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16. Abstract (Limit: 200 words)

This eight-chapter document is the second volume of a two-volume report that presents a comprehensive outline of coal mine electrical power systems from theory to practice. Together, the two volumes contain the vital aspects that go into planning and designing a mine power system. Building upon volume I, the subject of protective equipment and relaying starts volume II, first as an introduction in chapter 8, then by a treatment of device selection in chapter 9. Chapter 10 continues system protection in terms of transients and overvoltages. Chapter 11 describes the design of major power equipment, including power centers, switchhouses, and substations. Solid-state applications in mining are given in chapter 12, and batteries and battery charging are discussed in chapter 13. Chapter 14 covers electrical equipment in hazardous locations of mining operations. The report concludes with chapter 15, a discussion of electrical maintenance as well as some specific mine electrical problems. Information on surface and underground use is included in all chapters. An index finishes the documentation and is cross-referenced to both report volumes.

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FOREWORD

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As the contract report date, no inventions have been developed from contract J0155009. Consequently, no patents are pending.

The author is grateful to the many individuals and companies who have cooperated in this effort. Special thanks are given to the late Dr. Robert Stefanko. He originally perceived the need for these documents and provided guidance and encouragement throughout the entire project. Other individuals that deserve special mention are R. H. King, J. A. Kohler, T. Novak, F. C. Trutt and D. J. Tylavsky. Each has directly contributed to the text while on the faculty at The Pennsylvania State University. The author also would like to acknowledge all his students who, by taking his course on mine power systems and using the draft manuscripts, provided invaluable feedback for text refinement. Finally, the author wishes to thank his wife, JoAnn, for the many months she provided the back up necessary to write this work.

The author is also grateful to the several individuals and companies that supplied non-copyrighted material for use in this report. The material is noted by the various courtesies given throughout. Use of this material does not constitute an endorsement by the author, The Pennsylvania State University, nor the Bureau of Mines.

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Chapter 8

PROTECTIVE EQUIPMENT AND RELAYING

8.1 General

Even the best designed electrical systems occasionally experience faults and overloads; disturbances that cause abnormally high currents. These currents can exist in the ground system or in the phase conductors. Wherever the occurrence, the situation is most likely a hazard, be it to personnel or equipment.

Chapter 1 has established the "basic design criteria" behind mine power systems. Three of these are adequate interrupting capacity, current-limiting capacity, and selective-system operation. The first two provide protection to the system during a disturbance, while the purposes of the third are to locate the problem then minimize its effect. In Chapter 6, following the basic criteria, current limiting and selective relaying have been set aside as two prime purposes of grounding. Ground-fault-current limiting in mine power systems is made possible by inserting a resistance in series with the neutral conductor. However, even with the extensive reference in the foregoing material, not much has been presented about selective-system operation, other than its function. "Protective circuitry" and "protective relaying" provide the function and are the subject of this chapter.

The protective circuitry, associated with the power system, consists of sensors (or transducers), relays, and switching apparatus. Its role of safeguarding personnel and equipment can have manual or automatic operation. An instance of manual utilization would be to remove power from a system portion for maintenance. Through automatic operation, protective circuitry is employed to first sense then "clear" each hazardous current resulting from a disturbance. As might be thought, the process of "clearing" is to safely disconnect the affected circuit from the power source as quickly as possible with minimum interference to the system balance. In other words, protective circuitry must isolate a malfunction at a given location with minimum damage to circuits and equipment and with a minimum amount of shutdown to the mine's operation. The operation of protective circuitry to provide detection and isolation is termed "selective relaying."

All of the devices that comprise the protective circuitry in the mine power system thus play a vital role in safety. In fact, protective circuitry is likely the most important component of the power system and mandates a major portion of all power equipment. For example, a switchhouse, which has the principal function of protection, is simply a complex of protective devices.

Importance of Faults. The concepts of overcurrents and faults have already been presented in Section 4.6. Although the removal of destructive overcurrents (or overloads) is important, the main concern is the clearing of faults, because their occurrence can be catastrophic.

Because of cables, cable shielding, and grounded equipment, line-to-neutral faults are the most common in mining. Most of these are arcing with relatively short length and controlled distance, and ground-fault current is predominantly limited by neutral grounding resistors (in other industrial applications, ground-fault currents are often limited by fault impedance).

Phase-to-phase and three-phase faults can also occur, for instance, when a mobile machine severs a cable during a runover. Extremely large phase currents can result, limited in the mine system only by transformer and phase-conductor impedances. System components, such as couplers, cables, transformers, bus bars, and disconnect switches, must be capable of withstanding the momentary mechanical and thermal stresses created by the flow of fault current through them. Interrupting devices, such as circuit breakers, must be able to not only withstand these momentary "fault-through" stresses, but to "interrupt" (or terminate) these anomalous currents.

Consequently, the maximum magnitude of possible fault current existing in phase conductors must be known to select adequate ratings of protective equipment. The need extends to the coordination of protective-circuitry operation for the entire complex. Furthermore, minimum sustained fault currents may also be required to check the sensitivity requirements of the current-responsive protective devices. These fault magnitudes, both maximum and minimum, are usually estimated by calculation, and the equipment is selected using the calculation results.

Because of the many hazards that can occur, the system must therefore be capable of detecting overcurrent, short circuits (or phase faults), undervoltage, and ground-faults (as well as a compromise in ground-conductor continuity). With the use of resistance grounding in mine power systems, the protective relaying or sensing device associated with neutral faults or zero-sequence currents is usually handled separately from faults causing only anomalous positive- or negative-sequence currents. In addition, the relaying for overcurrent may be separate from that for faults. Interestingly, whatever the protection requirements in one location, except for fuse applications, the sensing devices for each function will cause the activation or tripping of the same circuit-interrupting device. The sensing devices may be part of the interrupting apparatus or separated from it, connected only through control wiring.

Chapter Format. This chapter builds upon the material covered in Sections 4.3-3 (mainly, device nomenclature), 4.6, and 4.9. The next two sections cover the main protection components, switching apparatus and sensing devices. Basic relay connections, relay terminology, and then kinds of protection follow. The "Arrangements for Mining" section illustrates typical assemblies and combinations of protective circuitry. All this material thus sets the stage for Chapter 9, which discusses fault calculations, device sizing, and coordination. Chapter 10 will introduce some additional protection devices, while Chapter 11 will apply Chapters 8, 9, and 10.

8.2 Switching Apparatus

A "switching apparatus" is defined as a device for making (closing), breaking (opening), or changing connections (5). Coupled to this classification, there are three basic types: switches, circuit breakers, and fuses.

8.2-1 Apparatus Ratings

All switching devices have certain design ratings which are a measure of the electrical stresses they can withstand. Obviously, the ratings must be correlated with the intended use or "duty." A listing of these, along with the definitions, follows but is restricted to those terms which have direct application to Chapters 8 and 9 (Chapter 10 will introduce some concepts which add to the list) (5).

1. Voltage. The maximum nominal system voltage (usually line-to-line for a-c devices), at a specified frequency, on which the device may be installed.
2. Continuous current. The maximum continuous current that the apparatus may carry.
3. Short-circuit current. Usually, the maximum current the device is capable of interrupting. This may be further qualified by an "interrupting-current" or "interrupting-capacity" rating.
4. Close-and-latch (or momentary). The maximum short-circuit current, during the few cycles after the fault occurs, which the device can withstand without severe mechanical damage (resulting in an inoperable device).

In the last two items, it can be seen that possible fault currents are input to the ratings of a switching apparatus. To help visualize the importance of these ratings, consider that a three-phase fault has occurred on a power system. Figure 8.1 illustrates the resulting phase current versus time, created by the flow of energy from the source (or sources) to the fault

(6). This asymmetrical waveform is made up of two components: direct current and a symmetrical alternating current. At any instant after the fault occurs, the total fault current equals the sum of the two. The d-c component decays to zero in a short time, with the total current gradually changing from asymmetrical to symmetrical.

Switching apparatus ratings, as a measure of the stresses involved during faulting, are based on the symmetrical value and applying multiplying factors. These concepts are presented in detail in Chapter 9. However, Figure 1 does provide a visualization of rating magnitudes, and these will be discussed in a following subsection along with each switching device.

8.2-2 Arcs and Circuit Interruption

After a switching apparatus receives a message that circuit current is to be interrupted, the device proceeds through definite steps to terminate the current (2). These are illustrated in Figure 8.2. Under normal operation, the contacts of the apparatus are closed (see Figure 8.2a), current flows through the interface, and the outgoing circuit is thus energized. To terminate current, the contacts begin to separate, and an electric arc is drawn.

The arc is composed of free electron and free positive-ion flow, as shown in Figure 8.3. To start this arc, free electrons and/or free positive ions must then be available between the contacts. The availability is dependent upon the environment.

1. If an air or gas, the conductive elements are generated prior to the arc by radiation and cosmic rays knocking off electrons from neutral gas molecules.
2. If a liquid, such as oil, they exist as impurities.
3. If a vacuum, they can be emitted from the cathode by a high-strength electric field with the process known as "high field emission."

The last case can add free electrons to any environment. Even though the voltage between the cathode and anode is low immediately after separation, the free electrons are attracted to the anode, with the positive ions towards the cathode. In terms of an arc, electron flow is more important because it accounts for about 90% of arc current (2).

If the voltage across the arc remains large enough, the movement of charge between the contacts initiates the mechanisms which can increase and sustain the arc. This again depends upon the environment. In a gas, the free electrons can collide with neutral gas molecules, producing additional free electrons and positive ions (termed "ionization by collision"). In any atmosphere, the collision of heavy positive ions on the cathode produces heat, which:

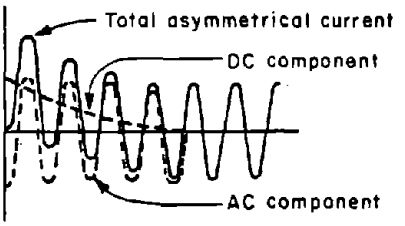

Figure 8.1. Typical System Fault Current.

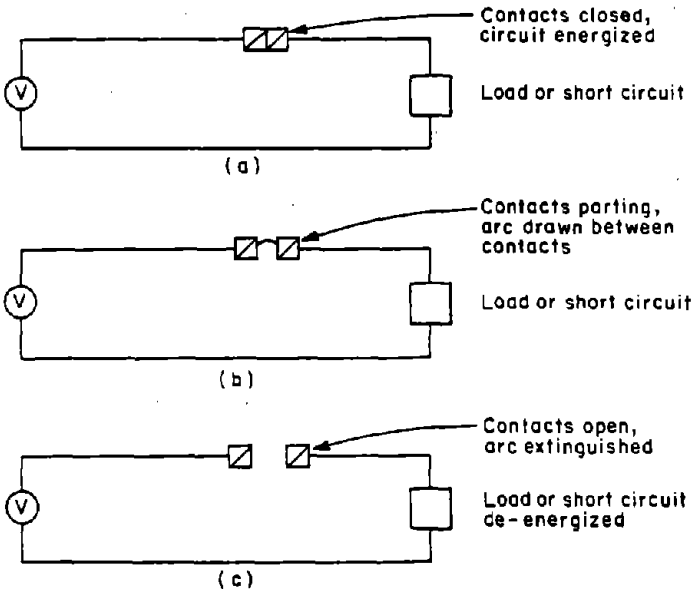

Figure 8.2. Circuit-Interrupting Steps.

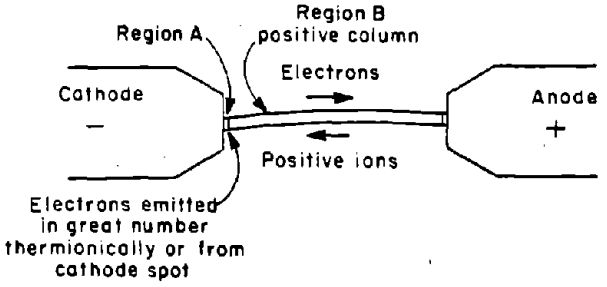

Figure 8.3. The Arc Between Two Contacts.

1. can augment field emission in low-melting-point materials, such as copper, creating intense electron discharge from a small area, called a "cathode spot;"
2. can cause "thermionic emission" in high-melting-point substances, such as carbon, where electrons are "boiled-out" by high temperatures.

Once the arc is established, processes must be brought into play to extinguish it, and these will be discussed soon. However, in general, the greater the arc current and the higher the voltage of the circuit, the more difficult is the problem of arc extinction. With a-c systems, the situation is made easier than with d-c systems, because the current waveform does pass through zero. However, the arc can "restrike" when the voltage again increases if the ionic conditions across the contacts still allow. For d-c, as a normal current zero does not exist, the arc is readily maintained.

Whatever the extinction process, the switching device will open the circuit successfully, provided that the current to be interrupted is within the rated value. However, when asked to terminate a current well above the design value, the arc between the parting contact may not extinguish or may continue to restrike, and the apparatus could be destroyed by the gas built up within it (3).

When a device is designed to interrupt fault current, it is often called an "interrupting device;" when not, it is commonly termed a "switch," being a device only to open and close a circuit. While some switching apparatus are intended to serve only one of these functions, others enable both duties.

8.2-3 Switches

A "switch" has exactly the same definition as that for switching apparatus, with the qualification of being a manual device (5). In other words, its operation is a normal or intended occurrence on the power system. The switch types usually applied to mine systems are disconnect and load interrupter. Both have the prime function of isolating (or "dangering off") outgoing circuits from the power source.

A "disconnect switch" is not intended to interrupt circuit current and can only be operated after the circuit power has been removed. Interlocks (see Section 8.5-5) must be provided to prevent manual operation under load and, oftentimes, latches may be needed to prevent opening from the stresses resulting from fault currents. Consequently, disconnect switches do not have an interrupting rating but beyond a continuous-current rating they may need a momentary-duty or close-and-latch rating irrespective of handling "fault-through" currents.

An "interrupter" or "load-break" switch differs from a disconnect in that it has an interrupting rating. Though not a normal operation, the device has the capability of terminating currents which do not exceed the continuous-current rating. They usually have a quick-made, quick-break mechanism which provides a fast switch-operation speed independent of the handle speed. The illustration shown in Figure 8.4 is a three-pole device; the mechanism on the right side of the connecting shaft provides the fast operation. Some units can be motor driven, allowing remote or automatic operation. In most mining applications, load-break switches need a momentary-duty rating. In the case where interlocks are not employed, the rating gives a margin of safety if the switch is closed into a faulted circuit.

For mining operations, switches are normally used as disconnects whatever their ratings. In fact, some states require load-break switches with interlocks for all disconnecting applications. These interlocks cause interruption of source power prior to contact separation (the operation is performed through the ground-monitoring circuitry, again see Section 8.5-5). In certain circumstances, load-break switches, used in conjunction with fuses, are employed as interrupters (see Section 8.2-5).

8.2-4 Circuit Breakers

A circuit breaker is primarily an interrupting device but in some cases is also used as a switch (5). A circuit breaker can be defined as a device designed to open and close a circuit nonautomatically and to open the circuit automatically at a specific current level without injury to itself when properly applied. Available as single-pole, double-pole, or triple-pole, the contacts may be operated manually or automatically. Manual operation, be it mechanically or electrically actuated, is again an intended occurrence, where the circuit current is not in excess of rated continuous current. Automatic operation is dictated by a system abnormality, such as a fault or an overcurrent. In this case the device may be called upon to interrupt current in excess of rated continuous.

Circuit breakers (in essence, interrupting devices only) must be used with sensing devices to perform their intended function. In medium- and low-voltage mining applications, the operation may be internally controlled by self-contained current-responsive elements, external protective relays, or a combination of both. In high-voltage situations, the sensing devices are always separate, with interconnections only through control wiring.

Circuit breakers can be generally broken into two classifications: those intended for systems over 1000 V and those for 1000 V and below. Devices in the first class are termed "power circuit breakers," while the second is divided into power circuit

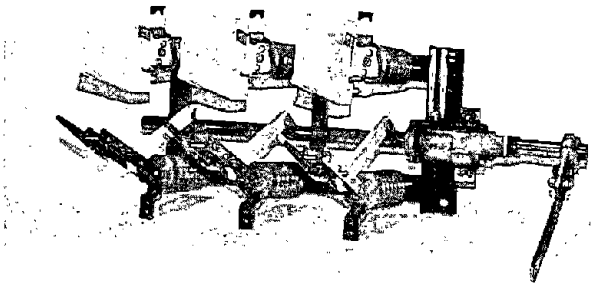

Figure 8.4. A Load-Break Switch (courtesy of Line Power Manufacturing Corp.).

breakers and "molded-case circuit breakers." Attendant with mining standards, circuit breakers for systems below 661 V are called "low voltage," for 661 to 1000 V, "medium voltage," and above 1000 V, "high voltage." (Note: IEEE Standards define above 1000 V to 72,500 V as medium voltage, below 1000 V as low voltage.) Low- and medium-voltage circuit breakers (usually lumped together) can find a-c and d-c service, whereas high-voltage breakers only involve a-c circuits. The next paragraphs will look at typical apparatus, and the operation of each will be discussed.

Low and Medium Voltage

Air Circuit Breakers. The term "air circuit breaker" is often used in referring to molded-case and power circuit breakers designed for low- and medium-voltage systems (6). Air circuit breakers employ the simplest method of interrupting current, extinguishing the arc in normal atmosphere by increasing its length (2). There are several processes which may be used to force the arc lengthening.

To illustrate one technique, consider Figure 8.5, where two circuit-breaker contacts, "a" and "b," have just separated. The horn-like arrangement of the contacts shown in the figure can be considered an "arc chute," a barrier to confine, cool, and extinguish the arc (3). By the ionization of the arc between the contacts, an arc is drawn, and heat is generated. Now, the arc extinction action commences; this is also called "deionization," as it serves to reduce the free electrons and positive ions in the gas (2). Air currents, created by the heat, force the arc upwards to form a loop. Electromagnetic forces within the loop

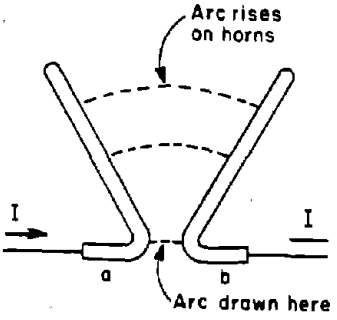

Figure 8.5. Extinguishing an Arc by Increasing the Length.

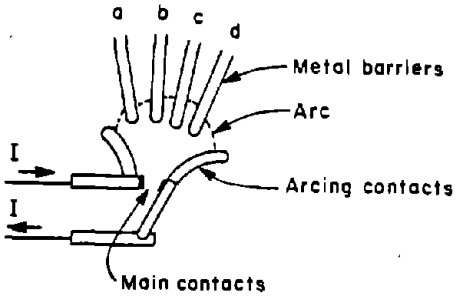

Figure 8.6. Metal-Barrier Arc Chute Assists Arc Deionization.

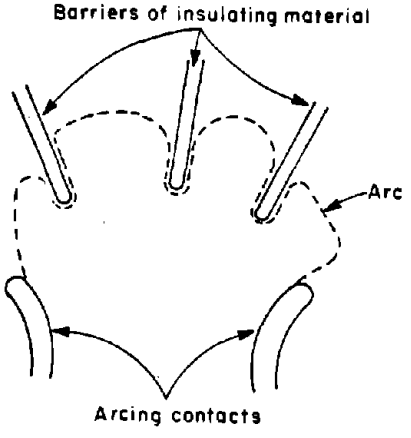

Figure 8.7. Insulated-Barrier Arc Chute Used with Magnetic Field.

further encourage the lengthing. Through "cooling" by radiation or convection, the longer arc requires a higher voltage, or "arc voltage," to sustain current flow.

As implied earlier, arc interruption in an a-c circuit occurs more easily than that for a d-c circuit. All voltages and current in an a-c system go through cyclic changes. Thus ion-producing effects for the arc are variable, falling as current become smaller, ceasing at current zero (2). However deionizing effects in the circuit breaker remain steady. Circuit breakers designed for a-c systems take advantage of this situation and often rely on the voltage required to establish a cathode spot. Because there is no natural current zero in d-c systems, the circuit breaker must force the current to zero. For this to happen, the arc voltage must be greater than the system voltage (7). In all circuit-breaker cases an enormous amount of heat can be generated while the arc exists, and an important function of the circuit-breaker assembly is to dissipate this heat safely.

The foregoing simple arc-lengthening technique works well for 240-Vac applications. Conventional practice is to use a single-pole device for 120 Vac and a double-pole breaker for 240-Vac single-phase circuits. The latter case employs one pole of the circuit breaker in series with each power conductor.

However for circuits 250 V and above, the direct arc-lengthening approach is not enough; special arc chutes, quenchers, or deionizing chambers are needed to assist in arc termination (3). Figure 8.6 illustrates one approach, where the arc is forced into metallic barriers by magnetic attraction. Thus the arc is broken into a series of smaller arcs. Each of these arcs is subjected to lengthening, cooling, and the problem of reestablishing a cathode spot if low-melting-point materials are used (2). Another approach is depicted in Figure 8.7. Because the arc establishes its own electromagnetic field, an external magnetic field can enhance arc lengthening. The process is termed "magnetic blowout;" breakers using the principle are called "air magnetic." Coils in series with the arc and carrying the circuit current can provide the magnetic field. As shown in the figure, the magnetic field forces the arc into insulated barriers or fins, creating further lengthening; recombination and cooling at the barrier surfaces accelerates deionization (2).

In d-c mine power circuits below 660 V, air-magnetic breakers are used extensively, especially on trolley systems. For a-c circuits below 1000 V, molded-case breakers are employed with very few exceptions. In addition, molded-case units are often called upon to protect low-voltage d-c face equipment.

Molded-Case Circuit Breakers. The molded-case circuit breaker is the most explicit example of interrupting apparatus with self-contained current-responsive elements. It is defined as a breaker which is assembled as an integral unit in a support-

ing and enclosing housing of insulating material (6). Depending upon the amount of protection desired, these devices can internally sense then clear undervoltage, overcurrent, and short-circuit conditions. Some "tripping elements," the actual components that cause the contacts to start separating are also externally accessible through control wiring so that other circuit protection can be added. Except for some power circuit breakers of low- and medium-voltage design, all other circuit breakers that will be discussed in this chapter rely solely on outside information to perform their prime function. It might seem that a more simple circuit-breaker type would be discussed first, but molded-case apparatus is placed here as it enables the easy introduction of many terms.

The application of molded-case circuit breakers in mining began with the conversion from low-voltage d-c power distribution in the 1950's to a-c power distribution and face rectification, further expanding with the trend toward a-c face equipment. In fact, Wood and Smith (8) attributed the introduction of low-height solid-state rectifier units in underground mines (which permitted the use of a-c distribution) to molded-case circuit breakers, citing the lack of high-speed, d-c circuit breakers of the proper height as the previous limitation. Molded-case breakers placed between the transformer and the rectifying bridge lowered the height limitation to that of the transformer, allowing a unit design complementary to the mining environment.

The largest mining application is trailing-cable protection in underground areas. The breakers are located in load centers and provide cable protection on each outgoing circuit as required by Section 75.900 of Title 30, Code of Federal Regulations, in addition to functioning as a switching device. The typical molded-case breaker, however, is not designed for repetitive switching. Mining use subjects them to many more operations than found in other industries, and a regular or "standard" circuit breaker generally cannot hold up to the stress. Several manufacturers, recognizing the situation, produce a special line of "mine-duty" molded-case breakers. To take the punishment, these have a stronger mechanical design.

Except for external adjustments, molded-case devices are usually not designed for field maintenance, and many are sealed to prevent tampering. Although some manufacturers offer a complete line of replacement components, repairs other than an exchange of easily removable parts such as arc chutes or trip units should only be made by qualified repair facilities. (Such facilities are critical, given the importance of the molded-case circuit breaker in personnel protection.)

All of the components of these circuit breakers are built into one insulated housing, the molded case. In addition to the case, there are five other main components: the operating mechanism, arc extinguishers (arc chutes), contacts, trip elements, and terminal connectors. Each of these is shown in

Figure 8.8 (11). Several accessories can also be included.

The function of the "molded-case" is to provide an insulated housing to mount all components. It is made of a glass-polyester or similar synthetic material that combines ruggedness and high dielectric strength in a compact design. Each different type and size of molded case is assigned a "frame" size or designation to facilitate identification. This nomenclature, loosely based on an old Underwriters Laboratories' standard, refers to a number of characteristics of the breaker, including maximum allowable system voltage, maximum allowable continuous current, interrupting capacity, and the physical dimensions of the molded case. Several trip units may be available for a particular frame size so a specific assembled breaker may have a lower continuous-current rating than the current designation of the frame. Table 8.1 lists the continuous ratings which are considered standard for mining service. The currents in parenthesis are the lower current settings available in that frame size from certain manufacturers. Unfortunately, manufacturers have varying design criteria and hence size their units to dissimilar specifications. For example, a 225-A, 600-V breaker supplied from two separate manufacturers may have different physical dimensions, and direct interchanging is difficult, if not impossible.

The circuit-breaker ratings listed in Table 8.1 are generally available as two-pole or three-pole units at 600 Vac/300 Vdc with only three-pole devices at 1000 Vac. The two-pole breakers are intended for d-c face-equipment or single-phase a-c applications. The convention is to use one pole for each ungrounded conductor in a circuit (3).

The arc chutes, in conjunction with the insulating and heat-dissipation properties of the molded case, define the interrupting-current capacity of the assembly. The chutes assist arc deionization by working on the same principle as was discussed for Figure 8.6. They are also termed "arc extinguishers" or "arc quenchers" by some manufacturers.

Circuit breakers designed for 1000 V and below are capable of clearing a fault faster than those constructed for high voltage (5). Often, the contacts begin to part during the first cycle of fault current. Consequently, the breaker must be rated to interrupt the maximum available first-cycle asymmetrical current and, thus, the momentary-withstand and interrupting ratings are the same (they are not in high-voltage breakers). However, the rating of these units is done on a symmetrical basis so multipliers accounting for the d-c offset need not be applied as long as the system X/R ratio does not exceed 6.6 (5) (see Chapter 9). Table 8.2 lists the interrupting ratings versus the system voltages (to which the breaker is used) for mining-service breakers; the a-c system values are on the symmetrical basis. Some manufacturers offer both "standard duty" and "high interrupting capacity" breakers. The table values presented

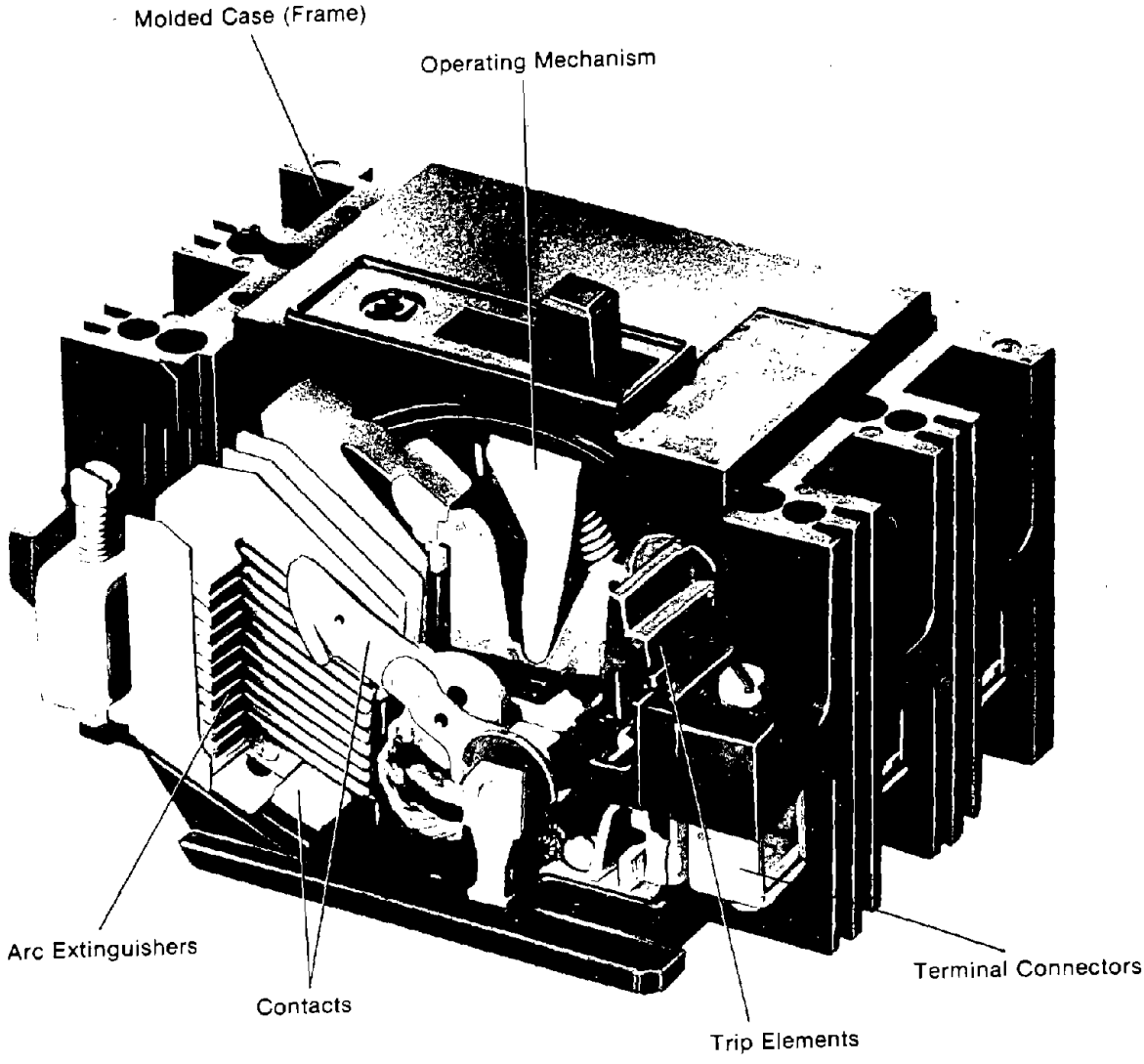

Figure 8.8. Molded-Case Circuit Breaker Components (courtesy Westinghouse Electric Corp.)

Table 8.1. Molded-Case Circuit-Breaker Ratings for Mining Service.

Frame Size, A*	100 (100, 70, 50, 30) 225 (225, 175, 150, 125, 100) 400 (400, 300, 225, 175, 150, 125, 100) 600 (600, 500, 400) 800 (800, 600) 1200 (1200, 1000, 800, 600)
Rated Voltage, V	
alternating current	600, 1000
direct current	300

*Note: Regular-duty breakers also available in 1600, 2000, and 2500 A frames.

parenthetically are for the superior construction, which incorporates sturdier contacts and mechanism plus a special high-impact molded casing.

The function of the "operating mechanism" is to provide a means of opening and closing the breaker. This "toggle mechanism" is the quick-make, quick-break type (again, meaning the contacts snap open or closed independent of how fast the handle is moved). The breaker is also "trip free;" it cannot be prevented from tripping by holding the breaker handle in the "ON" position. In addition to indicating whether the breaker is "ON" or "OFF," the operating-mechanism handle indicates when the breaker is "tripped" by moving to a position midway between the extremes. To reactivate the breaker, the handle first must be moved from the center position to "OFF" so as to reset the mechanism and then to "ON." This distinct trip point is particularly advantageous where molded-case breakers are grouped, as in load-center applications (see Chapter 11), because it clearly indicates any faulty circuits.

The function of the "trip elements" is to trip the operating mechanism in the event of prolonged overload or short-circuit currents. Two common types are used in mining, magnetic and thermal magnetic. When the circuit being protected involves portable or trailing cables, the thermal-magnetic combination is strongly recommended and is required by some state laws.

The "magnetic trip" protects against short circuits, where an electromagnet in series with the load current provides the trip action (9). "Short circuits" in this vein are actually phase-to-phase or three-phase faults on a-c or faults on d-c systems. When a short occurs, the high fault current causes the electromagnet in the breaker to attract the armature, initiating

Table 8.2. Interrupting Ratings Versus System Voltage.

Frame Size, A	Interrupting-Current Rating, A				
	240 Vac	480 Vac	600 Vac	1000 Vac	300 Vdc*
100	18,000(65,000)	14,000(25,000)	14,000(18,000)	10,000	10,000(20,000)
225	25,000(65,000)	22,000(35,000)	22,000(25,000)	10,000	10,000(20,000)
400	42,000(65,000)	30,000(35,000)	22,000(25,000)	10,000	10,000(20,000)
600	42,000(65,000)	30,000(30,000)	22,000(25,000)	10,000	10,000(20,000)
800	42,000(65,000)	30,000(35,000)	30,000(25,000)	10,000	10,000(20,000)
1200	42,000(65,000)	30,000(35,000)	30,000(25,000)	10,000	10,000(20,000)

* Actual d-c interrupting current dependent upon system inductance.

an unlatching action, in turn causing the circuit to open (see Figure 8.9). The action takes place within one-half second (usually within one cycle or 16 ms), instantaneously tripping the breaker. Since tripping takes place with no intentional delay, the magnetic-trip is often called the "instantaneous-trip" element. Screw-driver slots, located on the front of the trip unit, can be adjusted to specific requirements (see Figure 8.10). The maximum setting is mandated by the minimum conductor size in the circuit being protected.[1] Table 8.3 lists these maximum settings as applied to trailing cables. Figure 8.10b illustrates a family of time-current curves resulting from the adjustable range; to the left or below each curve, the breaker will not be tripped magnetically. Typical instantaneous-trip ranges versus frame sizes for mining service breakers are given in Table 8.4. This is not a rigorous listing, as some manufacturers will provide any desired trip range with most frame sizes upon request.

The other common molded-case breaker type is the "thermal-magnetic" variety. In addition to providing the short-circuit protection, the thermal-magnetic breaker also protects against long-term current overloads existing longer than roughly 10 s by incorporating thermal-trip elements (see Figure 8.11). The thermal action is accomplished through the use of a bimetal strip heated together, each with different coefficients of thermal expansion. A sustained overload causes excessive heating of the strip, resulting in deflection of the bimetal, which in turn causes the operating mechanism to trip the breaker. Because the bimetal deflection is dependent upon current and time, the thermal unit provides a "long-time delay" for light overloads with a fast response for heavy overloads. A representative current-time characteristic for the thermal unit alone is shown in Figure 8.12a (later in the chapter this will be described as inverse time). In comparison, Figure 8.12b shows the circuit-breaker response when both thermal and magnetic trip elements are incorporated. The shaded area for each curve represents a tolerance between the minumum and maximum total clearing times.

The thermal-magnetic unit shown in Figure 8.11 is ambient-temperature sensitive. Assuming the circuit breaker, cable, and equipment being protected are in the same ambient temperature, the element rerates in line with safe cable and equipment loadings which vary with ambient temperature (9). Thermal-magnetic trip elements are available that automatically compensate for ambient-temperature variations. The "ambient compensation" is obtained from an additional bimetal strip which counteracts the overload

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[1] Table 8, USBM Schedule 2G or Title 30, Code of Federal Regulations, Part 75.601-1. Sometimes minimum available fault current also affects this setting, see Chapter 9.

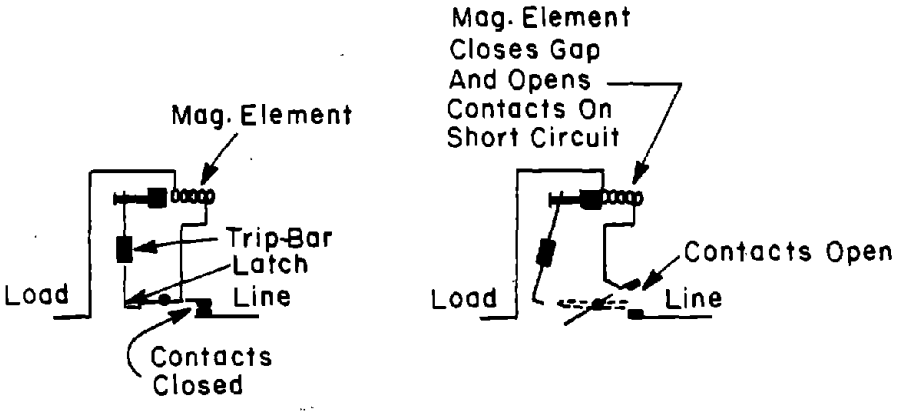

Figure 8.9. Magnetic-Trip Relay.

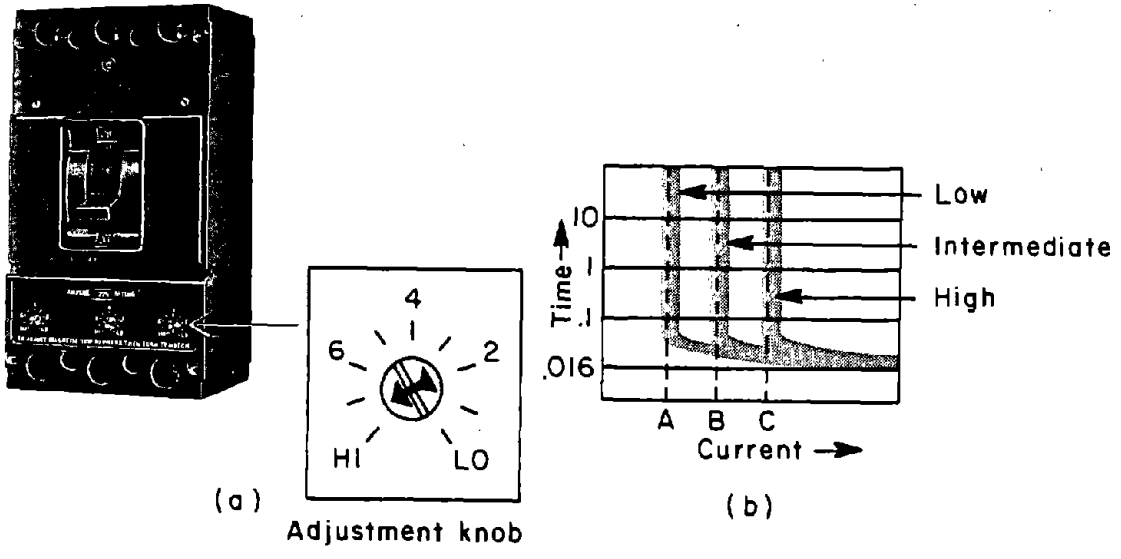

Figure 8.10. Adjustable Instantaneous Setting.

Table 8.3. Maximum Instantaneous-Trip Settings

Conductor Size, AWG or MCM	Maximum Allowable Instantaneous Setting, A
14	50
12	75
10	150
8	200
6	300
4	500
3	600
2	800
1	1000
1/0	1250
2/0	1500
3/0	2000
4/0	2500
250 to 500	2500

Table 8.4. Commonly Available Magnetic-Trip Ranges for Mining-Service Molded-Case Breakers

Frame Size, A	Magnetic- rip Range, A	Range of Allowable Conductor, AWG or MCM
100	50-180	14-10
	150-500	10-4
225	300-700	6-3
	500-1000	4-1
	300-1000	6-1
400	500-1000	4-1
	800-1600	2-2/0
	500-1500	4-2/0
600	900-3000	1-500
800	750-1500	2-2/0
	1000-2000	1-3/0
	1500-3000	2/0-500
	2000-4000	3/0-500
1200	1500-3000	2/0-500
	2000-4000	3/0-500
	2500-5000	4/0-500

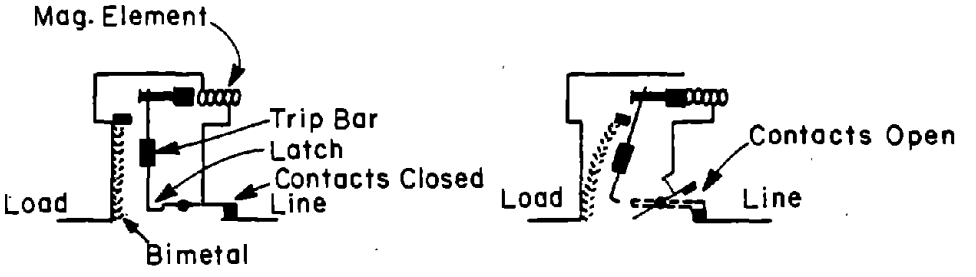

Figure 8.11. Thermal-Magnetic Action of a Molded-Case Circuit Breaker.

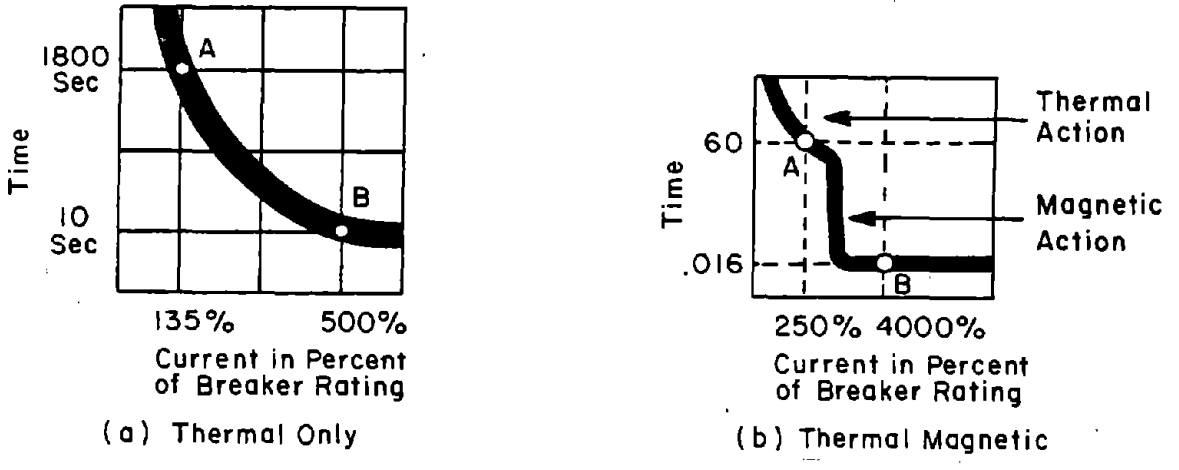

Figure 8.12. Time-Current Characteristics for Thermal-Magnetic Molded-Case Circuit Breakers.

the overload bimetal. Such trip units are recommended whenever the protected conductors and the circuit breakers are in different ambient temperatures (9).

Most (if not all) mining-service molded-case breakers with 225-A frame sizes and above have interchangeable trip units. For straight magnetic elements, these allow different instantaneous-trip ranges per frame size. However, thermal-magnetic units can be used to establish a lower continuous-current limit for the breaker. The National Electrical Code is used as a guide to define at what current the long-time-delay (thermal) element must initiate the circuit-clearing operation; 125% of the rated equipment or conductor ampacity is the specified point.[2] As seen in Figure 8.12a, the circuit breaker will take no action below this current. Hence, the thermal portion defines the continuous-current rating of the breaker, specified as 100% at 40°C for conventional (non-compensating) thermal-magnetic elements. Obviously the thermal-element current rating cannot exceed the frame rating. Because of the correspondence, some manufacturers recommend that the continuous current through the breaker be limited to 80% of the frame size (Chapter 9 - actual selections).

Electromechanical magnetic and thermal-magnetic trip elements in some molded-case breakers have been replaced by solid-state components. Although the solid-state counterparts may become popular in the future they have not yet achieved wide acceptance in the mining industry. Nevertheless these breakers are discussed in Chapter 12.

The last basic components are the terminal connectors. The function of these is to connect the circuit breaker to a desired power source and load. They are usually copper and must be constructed so each conductor can be tightened without removing another.

In addition to the basic components, several accessories are available, and the most common are the terminal shield, shunt trip, and undervoltage release. The terminal shields protect personnel from accidental contact with energized terminal connections. They are simply grounded metallic plates that shield the terminals. The other two accessories are used to trip the operating mechanism.

A "shunt trip" is employed to electrically trip a circuit breaker from a remote location. It consists of a momentary-rated solenoid tripping device mounted inside the molded case and is caused to activate when control power is applied across the solenoid coil. The magnetic field created by the solenoid moves a plunger, which activates a trip bar. At the same time,

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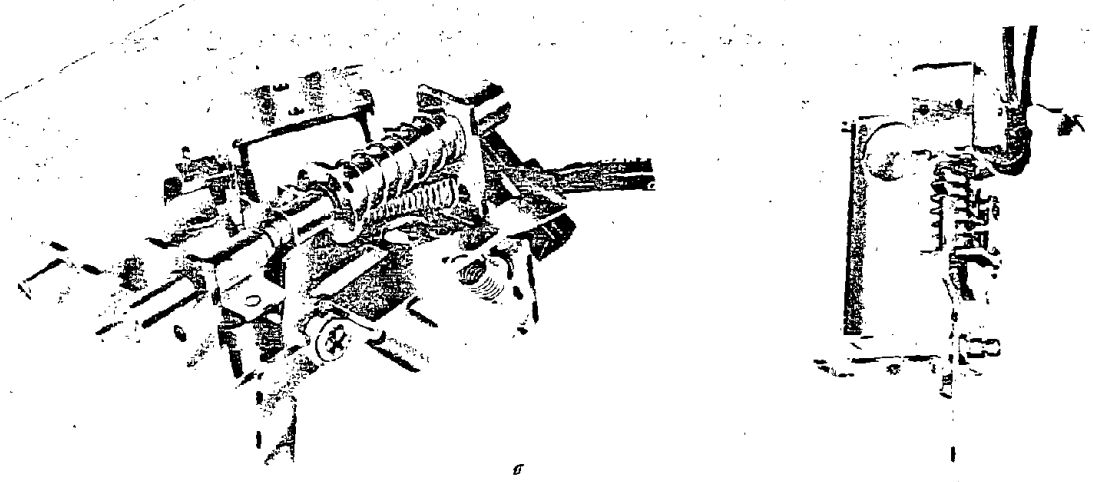
[2]National Electrical Code, ANSI C1-1981.



(a.) Shunt trip (b.) Undervoltage Release

Figure 8.13. Shunt-Trip and Undervoltage-Release Accessories.

a cutoff switch removes power to the solenoid coil, preventing it from burning up under continuous load. A typical shunt-trip assembly is shown in Figure 8.13a. The shunt trip can remotely trip the breaker but cannot remotely operate it. To reclose the breaker, the handle first must be moved to the reset position, then to the "on" position.

The purpose of the "undervoltage release" or "UVR" is to trip the breaker whenever control voltage (to the UVR) falls below a predetermined level (usually 35 to 70%). This device is also mounted inside the breaker frame and consists of a spring and solenoid. The spring is cocked or precharged by the operating mechanism when the breaker is closed; it is held in the cocked position by the solenoid after closure. If the voltage drops below the required level, the solenoid will release the spring, causing the circuit breaker to trip. Afterwards, the breaker cannot be turned on until the voltage returns to 80% of normal.

The importance of the shunt trip and UVR is far ranging, as they allow extension of protection to an outgoing circuit. The UVR adds undervoltage protection; in fact, undervoltage protection is normally required at the breaker location. (Undervoltage protection is required for all equipment, but it is not required on all circuit breakers as long as all equipment inby the breaker have undervoltage protection.) The undervoltage protection provided by UVR is actually "loss-of-voltage" protection since the drop-out level is well outside the recommended operating range of most motors (see Chapter 5). Through a specific combination of relays and sensing devices, any additional kinds of protection can be applied through shunt or UVR tripping. With a shunt trip, the relay completes the circuit between the control-power source and the solenoid coil. When a UVR is used, the relay removes the control voltage across

the solenoid coil. This circuitry will be discussed in detail in Sections 8.3 through 8.6.

Molded-Case Summary. The molded-case circuit breaker is the most widely used breaker in mining, even though its employment is restricted to low- and medium-voltage systems. The principal application is on a-c, where it provides a high interrupting capacity for short circuit in minimum space. On a-c or d-c systems, it is often the first protection device called upon to clear electrical problems existing on trailing cables and mining machinery. A clear understanding of the construction and rating of these breakers is required to assure adequate protection. The operating characteristics must be closely matched with that of the trailing cable to minimize hazards to personnel.

Power Circuit Breakers. Some industry engineers have found that molded-case circuit breakers cannot handle the available short-circuit currents on certain low-voltage applications. This is especially true for the outgoing d-c circuits of trolley rectifiers; other examples include d-c face equipment. The alternative is the low-voltage power circuit breaker.

Power circuit breakers for application to 1000 V and below are of open-construction assembly with metal frames. They are designed to be field maintained under planned periodic inspection, and all parts are accessible for maintenance, repair, and replacement ease (5,6). The design enables higher endurance ratings and repetitive-duty capabilities than available from molded-case devices. However, power circuit breakers are intended only for service inside enclosures with "dead front" construction (not accessible to unauthorized personnel).

Electromechanical units are available for long-time tripping, but mechanical displacement-dashpot types are normally used for this function, providing the same overcurrent protection as the bimetal thermal-tripping in molded-case breakers. Whereas long-time characteristics are not adjustable with bimetal strips, the dashpots allow changing the long-time-delay "pickup" current and operation time. This extends the capabilities of the power circuit breaker over the molded case by providing not only short-circuit but also overcurrent tripping adjustments, thereby allowing a broader range of application (6). Low-voltage power circuit breakers are available with or without direct-acting instantaneous units and with or without long-time-delay units. Furthermore, most manufacturers make available three different (separately adjustable) long-time-delay operation bands as well as three different short-time-delay operation bands. As with molded-case breakers, power breakers are available with either or both shunt-tripping and UVR units. For all tripping arrangements, solid-state devices are also manufactured.

Some typical ratings for low-voltage power circuit breakers are available in Table 8.5 (6). In addition to the listed values, frame sizes are available up to 6000-A continuous a-c current

Table 8.5. Some Typical Ratings for Low-Voltage Power Circuit Breakers.

A-C System Nominal Voltage, V	Rated Maximum Voltage, V	Frame Size, A	Three-Phase Short-Circuit Current Rating, Symmetrical, A	Range of Trip-Device Current Ratings, A
600	635	225	14 000	40-225
600	635	600	20 000	40-600
600	635	1600	42 000	200-1600
600	635	2000	42 000	200-2000
600	635	3000	65 000	2000-3000
600	635	4000	85 000	4000
480	508	225	22 000	40-225
480	508	600	30 000	100-600
480	508	1600	50 000	400-1600
480	508	2000	50 000	400-2000
480	508	3000	65 000	2000-3000
480	508	4000	85 000	4000

and 12,000-A continuous-current rating inside enclosures at 40°C.

In the low-current ratings, arc interruption can utilize arc-chute arrangements similar to those used in molded-case breakers. For high-current-interruption power breakers, full air-magnetic arrangements, like those described for Figure 8.7, are employed.

High Voltage

General. Power circuit breakers used in high-voltage mining applications include air-magnetic, oil, minimum-oil, and vacuum types. Vacuum circuit breakers (or VCB) are by far the most popular because of their small size and high efficiency. Oil circuit breakers (or OCB) were the most common, but their use has dropped substantially in recent years due to the unavailability of the interrupting sizes needed for mining. Air-magnetic types, at times, see service in surface installation and their use is normally limited to this application. The next few paragraphs will look at typical apparatus ratings; afterwards, the operation of each device will be described. Air-magnetic breakers are excluded as the operation is the same as was presented for lower voltage.

Typical Ratings. Typical voltage ratings, corresponding to nominal system voltages, are 4160, 7200, and 13,800 V, with 23,000 V seeing use in some strip mines. The system portions of interest are obviously a-c. Common continuous-current ratings are 400, 600, 800, 1200, and 2000 A. The majority of mine systems do not call for greater than 600-A continuous, and this has become the most used rating.

Interrupting and close-and-latch ratings are very important high-voltage parameters (5). For low- and medium-voltage circuit breakers, the two ratings are the same. However, high-voltage circuit breakers usually will not try to terminate current flow until a few cycles after the first-cycle peak; thus, the two values need not be the same (in fact, it is uneconomical to do so). Regardless, the interrupting-current rating must be equal to or greater than the maximum available short-circuit (or fault) current at the point of installation. A typical value found in mining is 12,000-A rms, symmetrical. The maximum close-and-latch rating is usually found by multiplying the maximum available short-circuit current by 1.6 (see Chapter 9) (5). This asymmetrical-current rating for many circuit breakers in mining is around 20,000-A rms.

High-voltage circuit breakers, beyond current ratings, are at times given an "interrupting-capacity class," expressed in MVA. The values often found are 250, 350, 500, and 750 MVA. Interrupting capacity, VA, is related to the interrupting-current

rating by: (3)

$$VA = \sqrt{3}\, V_{rated} I_{rated} \qquad (8.1)$$

where:

VA = interrupting capacity (MVA)
V_{rated} = rated system voltage (kV)
I_{rated} = rated rms interrupting current (kA).

However, rating circuit breakers by allowable current is now considered standard (in the past, volt-ampere ratings were used), and interrupting capacity is just used for identification (5).

Oil Circuit Breakers. Even though their popularity has been dropping, oil circuit breakers are still extensively used in surface installations, especially substations. The common type of construction is "dead tank." As sketched in Figure 8.14a, these have a steel tank, partly filled with oil; the cover has porcelain or other composition "bushings" or insulators through which the conductors are carried (2,3). The breaker contacts are at the bottom of the bushings and are bridged by a conducting crosshead carried by a lift rod. In most designs, the two bushings and crosshead provide two interruptions per pole. The majority of OCB's in mining have three such poles in one tank. The tank has an insulated liner to prevent the arc from striking the tank walls. The entire assembly is oil-tight; a vent with oil-separating properties permits the escape of any gases generated but prevents the escape of entrained oil.

Arc interruption in high-voltage circuit breakers employs the cathode-spot phenomena combined with arc lengthening and deionization of the arc path. In the case of the OCB, as the arc is established between the parting contacts, oil is vaporized to produce a bubble which surrounds the arc. The gases within the bubble are generally not conducive to ionization. However in most modern OCB's, an insulating chamber filled with oil surrounds the parting contacts (see Figure 8.14b). When the moving contact is lowered, the gas generated by that arc portion within the chamber forces oil out through the chamber throat (2). This oil blast is in intimate contact with the arc and accelerates cooling and ion recombination (see Figure 8.14c). The moving oil further assists by carrying away possible ions. Another arc-chamber approach is shown in Figure 8.15, where the chamber throat is made of laminations. Thus, during interruption oil may move radially into the arc path (sometimes termed a "turbo" action). In high-interrupting capacities, the gases developed within the chamber are at times used to blast oil horizontally across the arc path. Whatever the specific design, the chambers contain the developed high gas pressures, greatly reducing the pressure to which the main oil tank might be subjected (3). The generated gases, after being effectively cooled, are allowed to pass through the vent into open air.

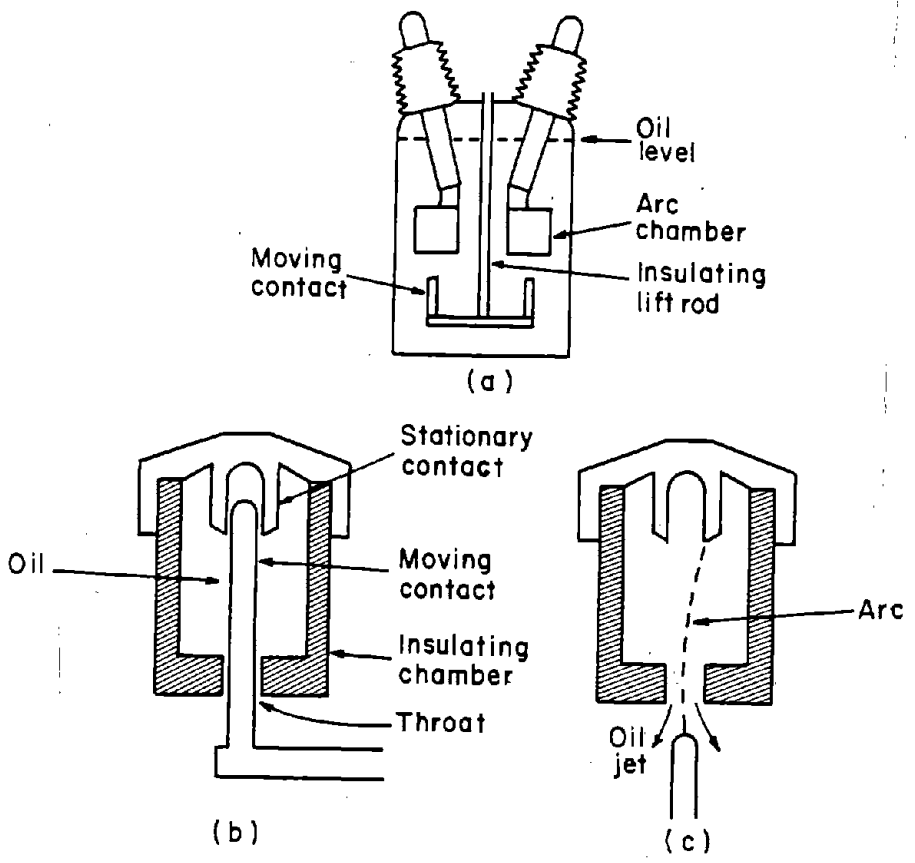


Figure 8.14. Construction and Operation of a Dead-Tank Oil Circuit Breaker.

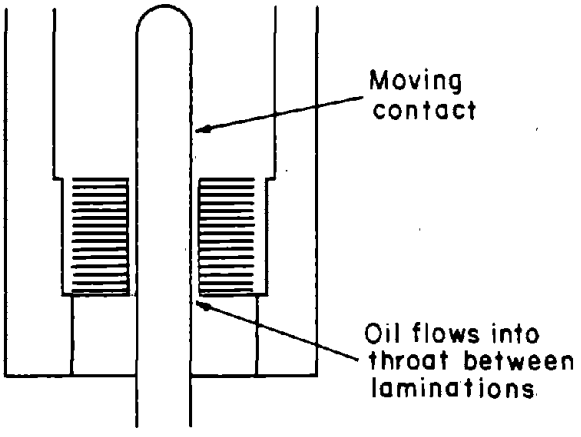


Figure 8.15. A Turbo-Action Arc Chamber for Oil Circuit Breakers.

The result of OCB construction and operation is a very effective arc interrupter. However, beyond availability, there are inherent disadvantages that discourage their use (2,3). The oil presents a fire hazard, particularly if the tank is ruptured due to unexpected pressure. The oil is bothersome to handle and creates maintenance problems including cleanliness. Finally, the inertia of the heavy operating mechanism severely limits operation speed, the time delay in opening the arc. The first of these, the fire hazard, has led to some states prohibiting OCB application in underground coal systems above 10,000 V. However, other advantages, most of which will be discussed in Chapter 10, still make the OCB desirable to many industry engineers.

When used underground, physical size of three-pole units usually limits the interrupting capacity to 100 MVA or less, with continuous-current ratings of 400 A. The operating mechanism on these small OCB's is typically spring-gravity/manual-reset; a handle-driven mechanism (quick break, quick make) is used to manually close the breaker while, at the same time, automatically tensioning an opening spring. With the breaker engaged, the spring becomes armed, by which a shunt-trip or UVR device can trigger the breaker opening by releasing the spring. A motor-driven system is also available, and used to close the breaker, but tripping is the same. The motor-driven OCB's, thus, can be electrically engaged as well as tripped. Larger OCB's, such as in substations, are typically motor driven.

Minimum-Oil Circuit Breakers. Minimum-oil circuit breakers, also termed "low-volume oil" or "live tank," have each pole in its own small-diameter tank (3). In modern versions, the tank is made of insulated high-strength, high-resistance material, and the top and bottom covers are high dielectric-strength insulators (see Figure 8.16). Contacts consist of a movable vertical rod and a stationary contact in the tank bottom. Oil volume is about one liter, and the top surface of the oil is at atmospheric pressure. Arc extinguishing is assisted by oil blast, and resulting gasses are vented to outside air. The operating mechanism can be either manual-reset/spring-trip or motor-reset/spring-trip. Some typical ratings of these breakers are listed in Table 8.6.

The arrangement of a three-pole minimum-oil unit (moving contacts mechanically interconnected) results in a smaller overall package than comparable dead-tank breakers. The smaller mass of moving parts (operating mechanism and rods) enables higher operating speeds, while the advantages of oil-interruption are maintained. However, the low volume of oil is such that after about five operations, the oil level must be checked. Even though oil-level indicators are available, this can create a maintenance problem in mining.

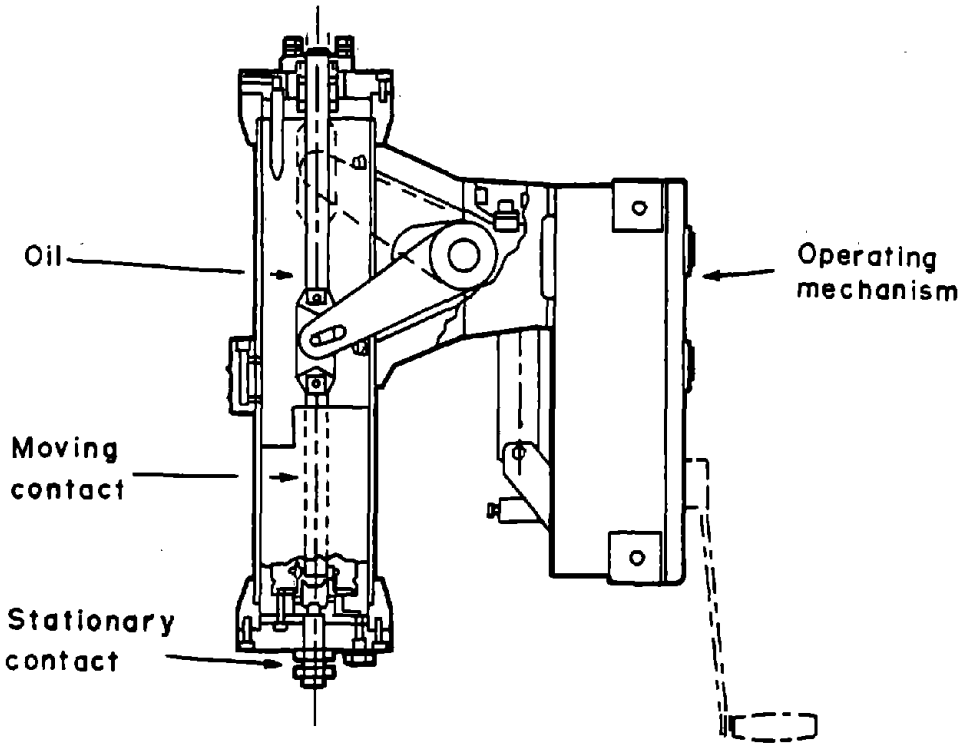


Figure 8.16. Cross-Sectional Drawing of a Minimum-Oil Circuit Breaker.

Table 8.6. Typical Minimum-Oil Circuit Breaker Ratings.

Rated Voltage, V	Interrupting Capacity, MVA	Continuous Current, A
5000	173	1000
15000	478	1000
25000	680	630

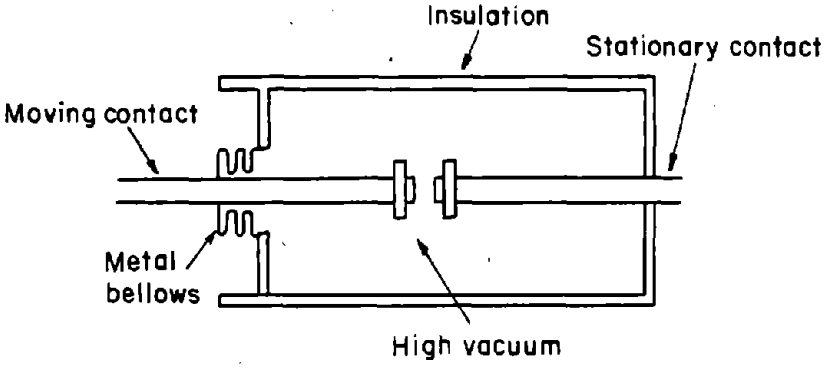


Figure 8.17. Cross-Sectional Drawing of a Vacuum Circuit Breaker.

Vacuum Circuit Breakers. With all circuit-breaker types covered so far, a gaseous atmosphere exists between the parting contacts. The gas is ionized by many processes and thus provides free electrons which move to the anodes, and positive ions that are attracted to the cathode (2). The positive ions, arriving at the cathode, assist thermionic or high-field emission of electrons. Almost all these phenomena cease to exist if the gas between the breaker contacts is removed; in other words, if the arc is drawn in a vacuum. Figure 8.17 shows a sketch of a vacuum circuit breaker (again, one pole).

For this reason, vacuum is considered an extremely good medium for switching, and there are resultant advantages.

1. Interruption usually occurs at the first zero current.
2. There are no "blind spots" in its interrupting range.
3. They have extraordinary life.
4. They are relatively maintenance free.
5. Recovery of dielectric strength (between the parting contacts) following interruption is extremely fast.

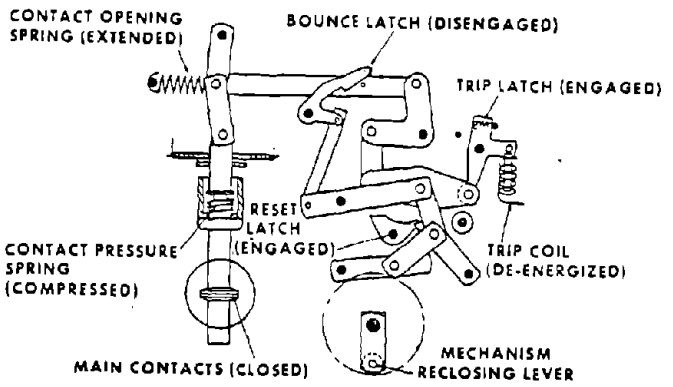
All these come from the fact that the vacuum totally discourages ionization.

An important aspect of VCB's is the long service. For instance, if a unit fails to clear a short circuit beyond its interrupting range, but another down the line does, the exceeded VCB can be employed again up to the full rating without difficulty. Coupled to small size with respect to capacity, they are extremely well suited to underground mining use. With regard to interrupting capacity for large currents, the vacuum circuit breaker can be utilized anywhere on high-voltage distribution, usually without reservation. These reasons have made these devices the most popular high-voltage interrupters in mining today.

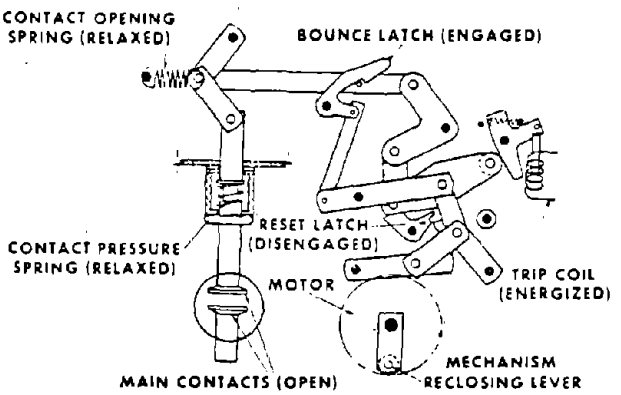
Further adding to the advantages is that the VCB does not have any physical orientation problems. This is a constraint with OCB's, as the tanks must always be vertical. Vertical placement of VCB bottles, however, is sometimes necessary to minimize dust accumulations.

The high efficiency of vacuum interrupters, which has in part led to their wide applications, is ironically the same property that can cause severe transients. If care is not taken with VCB installations, switching-transient related problems can occur throughout the mine electrical complex. Because of related phenomena, this important discussion is presented in Chapter 10.

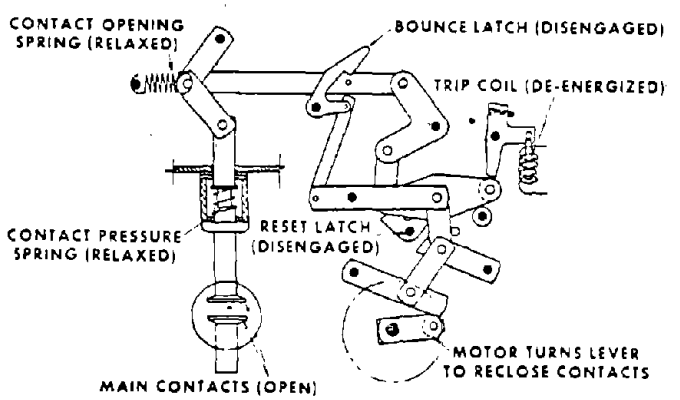
The operating mechanism is an important factor in proper vacuum circuit-breaker operation. Here, the mechanism includes the mounting structure for the vaccum bottles. (The same is true for minimum-oil tanks but dead-tank OCB construction



(a) Main Contacts Closed.



(b) Contact Travel Just Completed after Tripping.



(c) Main Contacts Open, Ready for Reclosing.

Figure 8.18. An Operating Mechanism for a Vacuum Interrupter (courtesy McGraw Edison).

is different.) There are four mandatory critera:

1. rugged construction to withstand the shock and stress of equipment movement;
2. a firm, smooth closure motion to prevent contact bounce;
3. forceful opening of contacts in case of contact welding; and
4. clean, smooth opening motion to prevent contact bounce and subsequent arc restriking.

In most cases, manufacturers rely on a motor-reset/spring-trip to meet items 2 through 4. Figure 8.18 illustrates one operating, mechanism approach. The trip solenoid can be shunt-trip or UVR device (in some cases, both are used). The importance of the above criteria is tied to the small contact travel distance, usually on the order of one-quarter inch.

In VCB applications, the compact size of the operating mechanism and mounting structure has made possible a substantial reduction in overall power-equipment dimensions. One manufacturer has even incorporated a disconnect switch in its design (see Figure 8.19).

8.2-5 Fuses

General

The "fuse" is the simplest and oldest device for interrupting an electrical circuit under short-circuit or excessive-overload current (3,6). They are installed in series with the protected

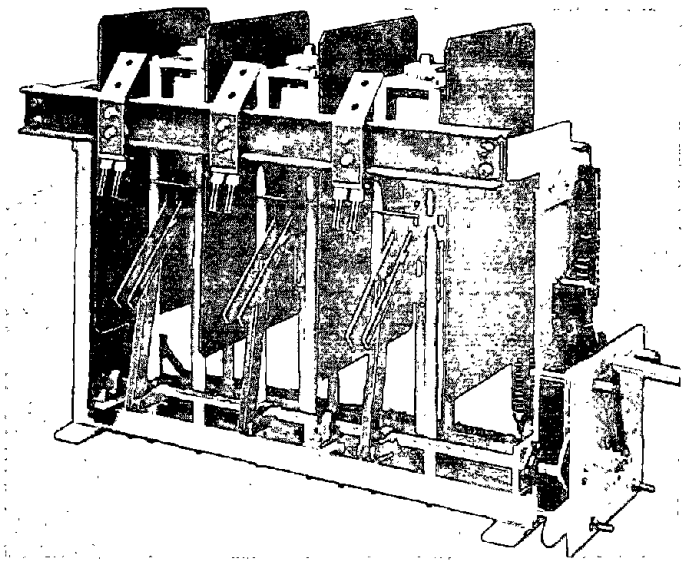


Figure 8.19. A Vacuum Circuit-Breaker Assembly Incorporating a Load-Break Switch (courtesy Ensign Electric).

circuit and operate by melting a "fusible link." The response is such that the greater the overcurrent, the shorter the time to circuit opening (again, an inverse-time characteristic). Fuses may be used in a-c or d-c circuits and have such a variation in these time-current characteristics that they are suitable for many special purposes. While circuit-breaker contacts rely on external sensing, the fuse acts as the sensing device and the interrupting device. Unlike circuit breakers, fuses are "one-shot," as their fusible element is destroyed in the circuit-protection process. Beyond the capacity of circuit breakers, fuses are available with interrupting-capacity ratings up to 200,000 A symmetrical rms. They are also available with current-limiting abilities to provide maximum protection for all circuit components.

Fuses are normally classified as low voltage or high voltage. The low-voltage types are intended for service in systems 600 V and below, while the high-voltage varieties are suitable for installations 2.3 to 161 kV (6).

Low-Voltage Fuses

Standard low-voltage fuses have two principal categories, plug fuses and cartridge fuses, and are classified by the following types: non-time-delay, time-delay, dual-element, and current-limiting.[3] There are also miscellaneous as well as non-standard fuse classes.

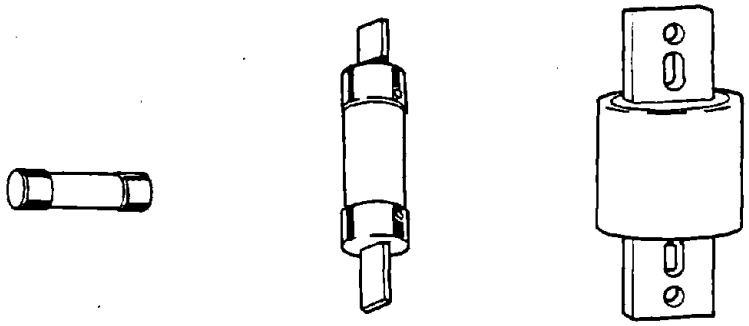
As with circuit breakers, there are three general fuse ratings (6):

1. current, the maximum d-c or rms a-c, in amperes, which the fuse will carry without exceeding a specified temperature-rise limit (available range: milliamperes to 6000 A);
2. voltage, the maximum a-c or d-c voltage at which the fuse is designed to operate (usual low-voltage ratings are 600, 300, 250, or 125 V a-c or d-c or both); and
3. interrupting, the assigned maximum short-circuit current that the fuse will safely interrupt (typical ratings are 10,000, 50,000, 100,000, or 200,000 A symmetrical rms).

Special ratings are also given to current-limiting fuses which deal with the maximum current and energy the device will "let through " to the protected circuit when clearing a fault (6).

Plug fuses are rated at 125 V and are available with current ratings up to 30 A. Thus their use is limited to circuits with

[3]National Electrical Code, ANSI C1-1981.



(a) Ferrule Type, 0-60 A (b) Knife-blade Type, 70-600 A (c) Bolt Type, 601-6000 A

Figure 8.20. Common Cartridge-Fuse Types.

this voltage rating or less, except they may be employed on systems having a grounded neutral where the maximum potential to ground of any conductor does not exceed 150 V (6). Plug fuses, therefore, have limited application in mine power systems (although an extensive popularity still exists for homes). Cartridge-fuse applications, on the contrary, are widespread to a point where the mention of a fuse implies a cartridge. Figure 8.20 shows the three standard low-voltage cartridge-type fuses (6).

Non-Time-Delay Fuses. As the name implies, these have no intentional built-in delay. They have a very simple construction, two end terminals joined together by a copper or zinc fusible element. The link is more current sensitive to melting than time. Non-time-delay fuses are available as "one-shot (or nonrenewable)" or "renewable;" the former is the oldest cartridge-fuse type in use today (6). With the one-shot, the link is in a sealed enclosure and after interruption the entire cartridge must be replaced. The renewable can be disassembled, and the link replaced. The lack of intentional time delay and a limited interrupting rating of around 10,000 A have substantially reduced the popularity of these fuses in recent years.

Time-Delay Fuses. The metal alloy used in time-delay fusible links is not only sensitive to overcurrent but also to the time period involved. In other words, a specific overcurrent existing for a specified time period is necessary to cause the heat-melting energy of the alloy. Such an arrangement permits harmless high-magnitude short-duration currents to exist, which are oftentimes necessary for proper system operation (e.g., motor starting).

Dual-Element Fuse. Originally designed primarily for motor-circuit protection, the dual-element fuse combines the features of non-time-delay and time-delay units. The time-delay or

"thermal cutout" is for overcurrent protection, blowing in a fraction of a cycle on heavy overcurrents. Figure 8.21 shows an internal view of a dual-element fuse, pointing out the components. The thermal cutout will allow the passage of currents as high as five times its continuous rating for up to 10 s. Therefore, they may be matched closely to protect the actual motor-running current and at the same time be sized to protect wiring and other equipment, providing both functions without nuisance blowing. In fact, properly sized dual-elements are required on all fuse-protected trailing-cable applications. They are available with up to 200,000-A symmetrical rms interrupting-current rating and, for further protection, most dual-element fuses also have a current-limiting feature.

Current-Limiting Fuses. Short-circuit protection requires that a fuse limit the energy the short-circuit can deliver to a faulted component. Obviously, the energy any interrupting device lets through under fault conditions cannot exceed the protected-component withstand rating. Current-limiting fuses provide this protection by restricting or cutting off fault currents before damaging peaks are reached. With very high fault currents, they are extremely fast, limiting current in less than one-quarter cycle with current interruption occurring within the first one-half cycle. Only a portion of the destructive available short-circuit energy is let through. By this, the current-limiting fuse allows the use of lower momentary and interrupting ratings by cutting-off current within equipment ratings (6). Figure 8.22 illustrates how the fuse operates. The large waveform represents the available short-circuit current on a faulted system and the performance of the fuse is superimposed.

The need to restrict energy relates to limiting the mechanical and thermal stress imposed on equipment carrying fault current. To illustrate this energy, consider Figures 8.22 and 8.23 and the "peak let-through current," I_p. It has been found that the magnetic forces, during a fault, vary as the square of fault current, I_p^2 (6). These forces translate to mechanical stress which can damage, for instance, transformer frames, bus structure, and cable supports. The "let-through energy," I^2t, represents a measure of the heating effect or thermal energy of the fault with or without the fuse (with the fuse, the value is I_p^2). I^2t actually equals $\int i^2 dt$, the time integral of the current squared for the time under consideration (10). Both I_p^2 and I_p^2t can be considerably reduced when current-limiting fuses are used (6). Furthermore, equipment with an I^2t withstand rating can be matched with energy let-through limit of fuses.

Standard Fuses. As implied by the foregoing, cartridge fuses come in a wide range of types, sizes, and ratings. Various classes for low-voltage units have been standardized by NEMA

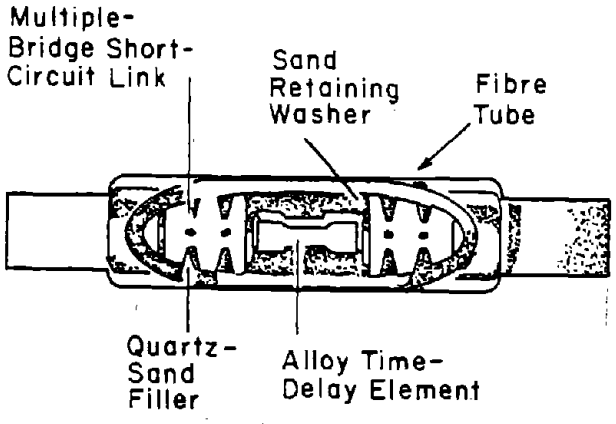


Figure 8.21. Inside View of a Dual-Element Fuse.

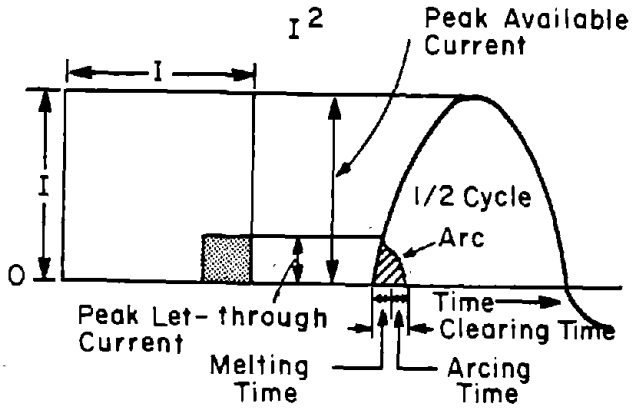


Figure 8.22. Current-Limiting Action of Fuses.

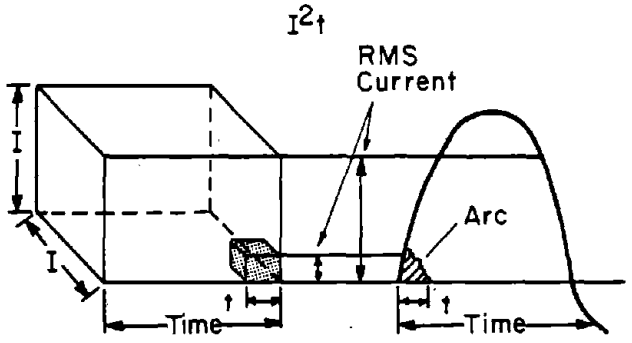


Figure 8.23. Energy-Limiting Action of Fuses.

and UL[4], and a listing of these follows (first value listed is range of continuous currents):

1. Class G: 0-60 A, 300 V to ground maximum, 100,000 A symmetrical rms interrupting, current limiting, fit only Class G fuse holders;
2. Class H: 0-600 A, 250 and 600 V, interrupting capacity up to 10,000 A, either one-time or renewable construction, commonly termed the "old NEC fuse;"
3. Class J: 0-600 A, 600 V, 200,000 A symmetrical rms interrupting rating, current limiting, will only fit a Class J fuse holder;
4. Class K: 0-600 A, 250 and 600 V, 50,000, 100,000, or 200,000 A symmetrical rms interrupting rating, have the greatest current-limiting effect of all low-voltage fuses (available as straight current limiting, dual-element current limiting, and dual-element time-delay current limiting), fit Class H fuse holder;
5. Class L: 601-6000 A, 600 V, 200,000 A symmetrical rms interrupting rating, current limiting, bolt-in mounting;
6. Class R: 0-600 A, 250 and 600 V, 200,000 A symmetrical rms interrupting rating, current limiting similar to Class K level-5 fuse, will fit only Class R fuse holder; and
7. Class T: 0-600 A, 250 and 600 V, 200,000 A symmetrical rms interrupting rating, current limiting but effect less than Class J fuses, fit only Class T fuse holder.

The above classes are sometimes referred to as "general-purpose fuses."

Non-standard Fuses. "Non-standard fuses" receive their name because of special applications or special dimensions; they are not general-purpose fuses (6). Of the many available, four have important application in mining and these are listed below.

1. Cable limiters. These fuses are for use in multi-cable circuits (paralleled cables) and placed in series with each cable in parallel. They are designed to provide short-circuit protection to each cable, removing it from power in case of failure. Cable limiters are rated according to cable size (4/0, etc.).
2. Semiconductor Fuses. These devices are available in two types: semiconductor protection fuses or semiconductor isolation fuses. Both are used in series with the application. The protection type is employed where solid-state devices are to be

[4] Underwriters Laboratories, Inc. (UL) fuse standards: UL 198.1-1973, UL 198.2-1970, UL 198.3-1970, UL 198.4-1973, UL 198.5-1973, and UL 198.6-1974.

protected rather than isolated after a failure and have lower let-through characteristics than other current-limiting fuses. A specific application is protecting a rectifier of SCR in case of an overload current. Isolation types are high-speed fuses, used to isolate a defective solid-state device in case of its failure. These are mandatory fuses for individual power diodes paralleled in large rectifier banks.

3. Capacitor Fuses. Capacitor fuses are applied in series with power-factor correction (or other type) capacitors and used to isolate a failed component by clearing short-circuit current before excessive gas is generated in the capacitor.
4. Welding Fuses. For use in welder circuits only, these are current-limiting fuses. The time-current characteristics are such that they allow a longer intermittent overload than general-purpose fuses, but still provide short-circuit protection.

High-Voltage Fuses

General

High-voltage fuses provide useable protection for 2.3 to 161 kV systems and fall into two general categories: distribution fuse cutouts and power fuses (6). Distribution fuse cutouts were designed for overhead distribution circuits, such as for the protection of residential distribution transformers. Even though their employment in utility-type systems is extensive, the use in mining is limited and, in some cases, restricted. Power fuses are another matter, however, as certain types are extremely practical protection in mine power systems. They can be applied to substation, distribution, and potential transformers (in series with the primary) and, occasionally, to distribution circuits. For surface mine systems, the fuses are often equipped with contacts, arranged so the fuse and its mounting acts as a disconnect switch (see Figure 8.24). There are two basic power fuses, expulsion and current-limiting types, and the next few paragraphs will discuss their operation, ratings, and application.

Expulsion Types. As with low-voltage fuses, high-voltage types start the current-interruption process by the melting of a fusible link but, as might be expected, deionization of the attendant arc becomes the most substantial part of current termination. To help the process, as shown in Figure 8.25, the link is held under tension by a coil spring; upon melting, the spring pulls the contacts apart, lengthening the arc (2). In "expulsion fuses," gases are liberated from the lining of the fuse interrupting chamber by the heat generating from the arc. The earliest form of expulsion fuse, and distribution fuse cutouts, uses a liner of organic material to deionize the generated gases by expelling them from the fuse holder tube

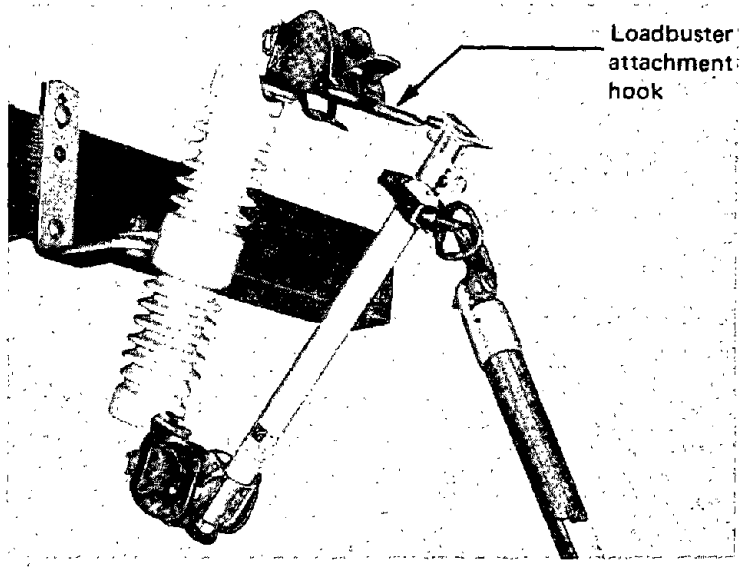


Figure 8.24. High-Voltage Power Fuse and Support (courtesy S & C Electric Company).

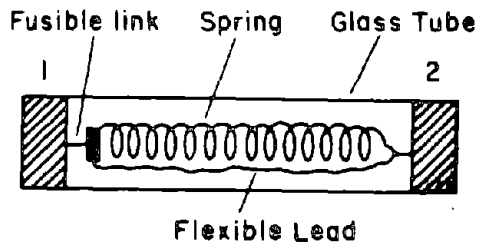


Figure 8.25. Fusible Element Under Spring Tension in a High-Voltage Fuse.

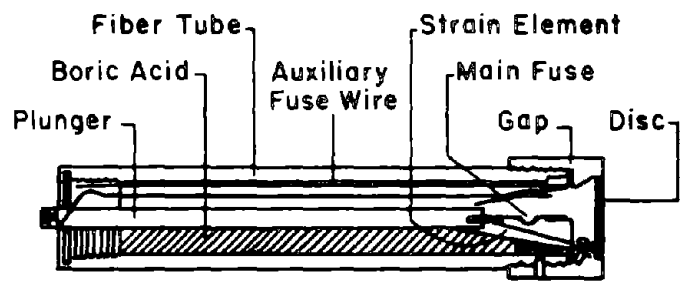


Figure 8.26. Cross Section of a Boric-Acid Power-Fuse Refill.

to the surrounding air. The problem with the operation is the attendant flame expulsion and loud noise. Hence, expulsion fuses are only for outdoor usage, generally in substations located remotely from human habitation (6).

The limited interrupting capacity (see Table 8.7) and unsuitable indoor use of early expulsion fuses led to the development of the "boric-acid" or "solid-material" fuse (6). Here, the interrupting chamber is made of solid boric acid. Exposed to arc heat, the material liberates steam, which can be readily condensed to liquid by venting the gas into a cooling device. The result is operation with negligible or harmless flame and gas emissions and noise levels. The range of voltage, continuous current, and interrupting ratings is also greatly expanded.

High-voltage boric-acid fuses are manufactured in two styles (6):

1. "fuse unit" (can be considered a one-shot typed), where the fusible unit, interrupting element, and operating element are all combined in an insulated tube; and
2. "refill-unit" or "fuseholder" (a renewable type). where only refill unit is replaced after interruption.

Figure 8.26 shows the internal components of a refill unit, while Figure 8.27 illustrates the construction of the entire fuse. Table 8.7 provides a listing of ratings for both styles. The fuse-unit style is intended for outdoor use at system voltages of 34.5 to 138 kV, while the refill unit can be used for indoors or outdoors (only on the surface) at 2.4 to 34.5 kV.

Current-Limiting High-Voltage Fuses. Realizing the same advantages as previously discussed for low voltage, high-voltage current-limiting or "silver-sand" fuses are of two different forms (6):

1. to be used with high-voltage motor starters for high-capacity 2400 and 4160 V distribution circuits, and
2. for use with 2.4 and 34.5 kV potential, distribution, and "small" power transformers.

The operation of either form is such that the arc, established by the fusible-element melting, is subjected to mechanical restriction of a powder or sand filler surrounding the fusible element. The technique provides three important features.

1. Current interruption is performed quickly without arc-product or gas expulsion. This allows use indoors or in small-size enclosures on the surface or underground. There is no noise from operation and, since there is no gas or flame discharge, only normal electrical clearances need be met.
2. Very high interrupting ratings are available so they can be applied on systems with very high

Table 8.7. Ratings of High Voltage Power Fuses.

Nominal Rating, kV	Expulsion-type Fuse		Boric-acid Fuse one-shot type		Boric-acid Fuse Renewable		Current-limiting Fuse	
	Maximum Continuous Current, A	Maximum Interrupting Rating, MVA[1]	Maximum Continuous Current, A	Maximum Interrupting Rating, MVA[1]	Maximum Continuous Current, A	Maximum Interrupting Rating, MVA[1]	Maximum Continuous Current, A	Maximum Interrupting Rating, MVA[1]
2.4	---[2]	---	---	---	200,400,720	155	100,200,450	155,210,360
4.16	---	---	---	---	200,400,720	270	450	360
4.8	---	---	---	---	---	---	100,200,300,400	310
7.2	100,200,300,400	162	---	---	200,400,720	325	100,200	620
14.4	100,200,300,400	406	---	---	200,400,720	620	50,100,175,200	780-2950
23	100,200,300,400	785	---	---	200,300	750	50,100	750-1740
34.5	100,200,300,400	1174	100,200,300	2000	200,300	1000	40,80	750-2600
46	100,200,300,400	1988	100,200,300	2500	---	---	---	---
69	100,200,300,400	2350	100,200,300	2000	---	---	---	---
115	100,200	3110	100,250	2000	---	---	---	---
138	100,200	2980	100,250	2000	---	---	---	---
161	100,200	3480	---	---	---	---	---	---

[1] Three-phase symmetrical rating.

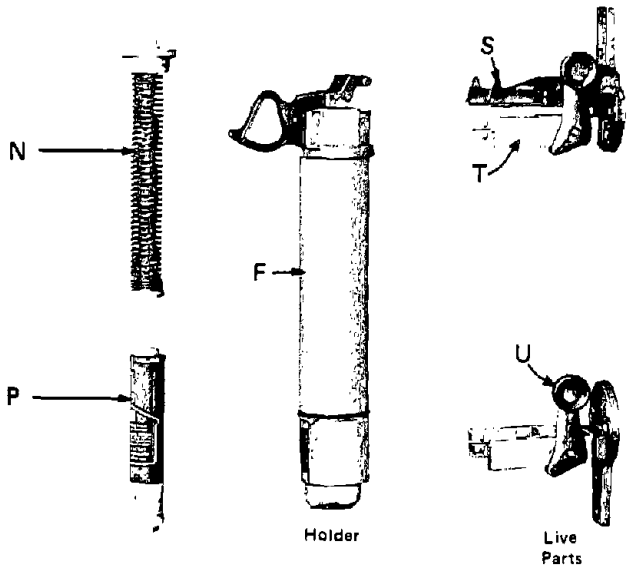
[2] Blank implies that standard fuses are not available in specific voltage rating.

short-circuit capacity (within their voltage rating).
3. All of the advantages of current-limiting action are available for high voltage.

Table 8.7 also provides a listing of ratings for current-limiting fuses. Instead of a current rating, these fuses can also be "E-rated" (for instance, 100 E instead of 100 A), "C-rated," or "R-rated." The specifications for E and C ratings are as follows:

1. E-rated fuses:
   a. 100 E and below, open in 300 s at an rms current within the range of 200 to 240% of the continuous rating of the fuse element,
   b. above 100 E, open in 600 s at an rms current within the range of 220 to 264% of the continuous (or E-) rating;
2. C-rated fuses, open in 1000 s at an rms current within the range of 170 and 240% of the C ratings.

E-rated fuses are considered as general-purpose or backup fuses, while R-rated devices are intended for use with high-voltage motor starters (6).



S, T = fuseholder upper contacts and latch

U = fuseholder lower contacts and latch

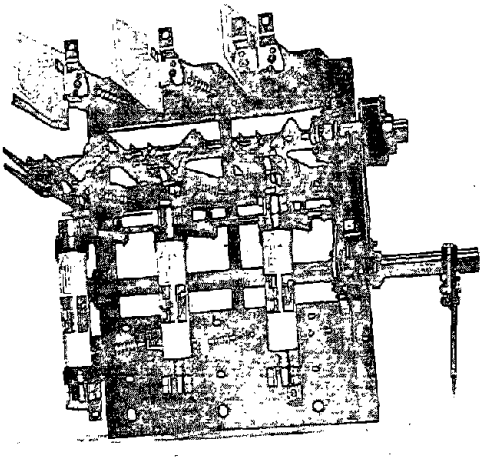
F = fuseholder

N = Spring-and-cable assembly (copper cable carries load current)

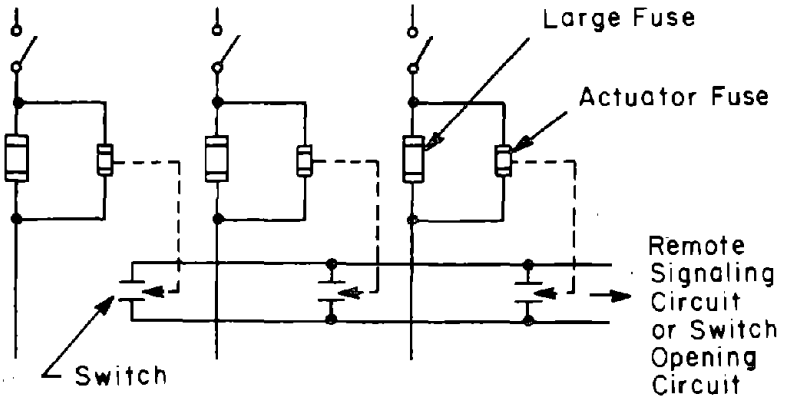
P = Refill unit

Figure 8.27. Refill-Unit Boric-Acid Fuse Disassembled (courtesy S & C Electric Company).

Load-Break Switches. After the occurrence of a short circuit on a fuse-protected three-phase system, only one fuse could open, substantially reducing fault current so the other two remain operational. This can cause serious damage to equipment, such as single-phasing motors. In a low-voltage circuit, dual-element fuses, closely matched to the overcurrent point, can usually handle the situation. On high-voltage systems, the problem is much more difficult in the case of protection by fuses alone. However, to take advantage of the lower cost of fuses and load-break switches versus that of a high-voltage circuit breaker, some manufacturers produce load-break switches with incorporated high-voltage fuseholders. An example is shown in Figure 8.28. The fuses are interlocked to trip the motor-driven operating mechanism of the switch if one or more of the fuses fail



(a) Fused Load-Break Switch.



(b) Schematic Showing Interlocks.

Figure 8.28. A Load-Break Switch with Interlocked High-Voltage Fuses (courtesy Line Power Manufacturing).

8.3 Sensing Devices

Purpose

As might be concluded, the major components of interest in protective relaying are relays. Relays are normally used with instrument transformers or shunt resistors to perform their intended function. These transformers and shunts have already been introduced in Section 4.9. This section will present basic relay types, and Section 8.4 will cover the combination of the two.

The reason relays are termed sensing devices is that they are used to detect a system abnormality. (Instrument transformers might be considered as sensing devices, but their function in protection relaying is solely as a transducer.) Relays must be used with an interrupting device to isolate an affected system portion. Be it a power or molded-case circuit breaker or motor-driven load-break switch, their final function is to supply or remove control power to shunt or UVR tripping elements. There are four basic relay types: thermal, electromagnetic attraction, electromagnetic induction, and static. (Note, d'Arsonval movements are actually considered another relay type, but the operation has been completely covered in Chapter 4.) The first three are electromechanical devices, and the following paragraphs will present their operation. Static or solid-state relays, because of related content, are discussed in Chapter 12.

Relay Terminology

The intended movement of electromechanical relays is to open or close contacts. In other words, when a relay operates, it is said to close or open its contacts (11). Most relays are restrained by spring control; they will assume a specific position when de-energized. A contact which is closed under this condition is termed a "normally closed" or "NC" contact; conversely, an open contact is called "normally open" or "NO" contact. Symbols for both situations are shown in Figure 8.29.

When a relay operates to open NC contacts or close NO contacts, it is said to "pick up," and the smallest actuating quantity to cause contact operation is referred to as the "pickup" value. (For instance, the relay is being energized to pickup the contacts.) When a relay operates to close NC contacts or open NO contacts, it is said to "reset" or "drop out" and, likewise, the largest actuating quantity to cause reset is the "reset" value of the relay. (For example, it could be said that the relay is de-energized to reset, but the reset value is almost always greater than zero, commonly referred to as a percent of normal operation.) Most relays have a range of adjustment (sometimes, tap settings) to make them adaptable to as wide a range of application circumstances as possible.

(a) Normally Open (b) Normally Closed

Figure 8.29. Relay Contact Symbols.

The word describing relay operation has definite meaning. The prefix refers to contact operation (9,12).

1. "Over-" means that the relay picks up to close a set of NO contacts when the actuating quantity exceeds the magnitude for which the relay is adjusted to operate.
2. "Under-" means the relay resets to close a set of NC contacts when the actuating quantity decreases below a reset magnitude.

Some relays have both over and under functions. The suffix refers to the actuating source for relay operation: voltage, current, or temperature. Consequently, an overcurrent relay picks up NO contacts (or opens NC contacts), at a certain current level, while an undervoltage relay closes NC contacts (or opens NO contacts) when voltage drops below a predetermined level.

Relays designed for protective circuitry usually are provided with some means of visual indication that a specific relay has operated to trip a circuit breaker. These "operation indicators" or "targets" are often brightly colored, being operated mechanically or electrically.

Relay Types

Thermal. Thermal relays most commonly employ bimetallic driven contacts, and this operation has been covered as part of the molded-case circuit-breaker presentation. For that application, the bimetal strip is direct sensing; circuit current is passed through it with the heat generated by its own resistance serving as the actuating agent. Another direct approach is to use ambient temperature; an example is the "temperature-monitoring protector" shown in Figure 8.30. This is a sealed bimetallic thermostat which opens or closes at a specified temperature. A use would be to sense motor overtemperature by mounting it against the end turns of a motor winding.

Another bimetallic approach is to employ a heater element, within the relay enclosure, connected in series with the circuit under consideration. As illustrated in Figure 8.31a, the relay trip point (opening or closing contacts), which is expressed in amperes but also a function of time, is determined by the

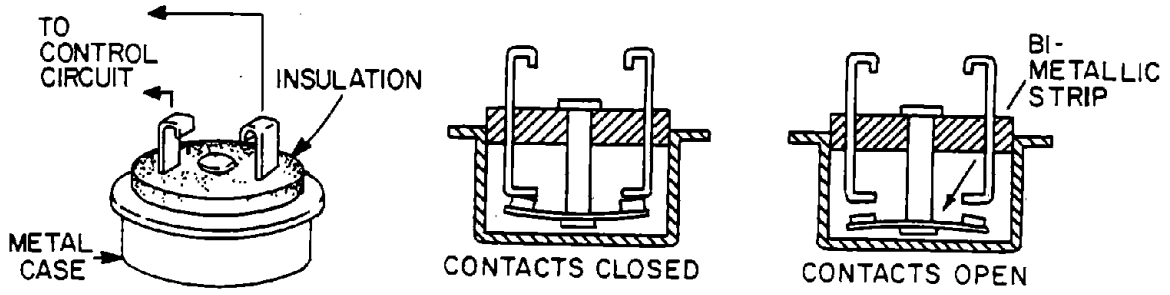
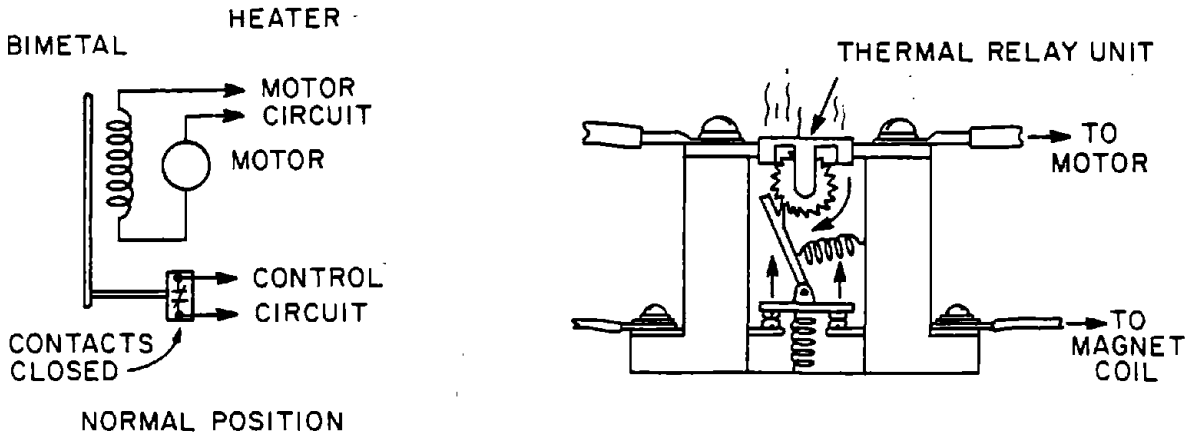


Figure 8.30. A Temperature-Monitoring Protector.



(a) A Bimetallic Relay (b) A Melting-Alloy Relay

Figure 8.31. Electromechanical-Thermal Relays.

heater rating. The trip setting is commonly based on a 40°C ambient temperature; however, the relay may be ambient or non-ambient compensating. After tripping, most relays of this type must be reset manually.

An electromechanical-thermal device not using bimetallics is the "melting-alloy" or "electric-alloy" relay. Being shock resistant and having high contact force, these are considered one of the most reliable thermal relays available, but because of cost they are not nearly as popular as bimetallics. The operation is presented in Figure 8.31b; the alloy melting point is extremely precise, again related to a specific current-time characteristic. After tripping and alloy solidification, the relay can be reset.

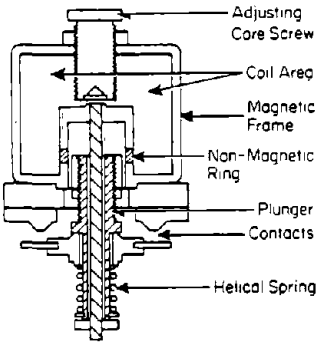
Two other thermal devices, resistance or "thermistor" types and "thermocouples," work with associated electronic equipment to provide very precise temperature sensing and relaying. Here, a probe can be inserted or imbedded in, for example, transformer or motor windings, providing spot-temperature response. These types of devices are often more popular than the preceding ones. especially where large horsepowers or capacities are involved.

Electromagnetic Attraction. There are three electromagnetic attraction relays in common use: the solenoid, clapper, and polar (12). Although their operational speed might vary, all of these are considered "instantaneous relays," as there is no built-in delay for pickup or reset. The solenoid and clapper types are available as a-c or d-c and voltage or current actuated, depending on coil impedance (high for voltage, low for current). Polar units are d-c sensing only, but may be used with a-c through rectification. All electromagnetic relays are available with normally-open or normally-closed or both types of contacts.

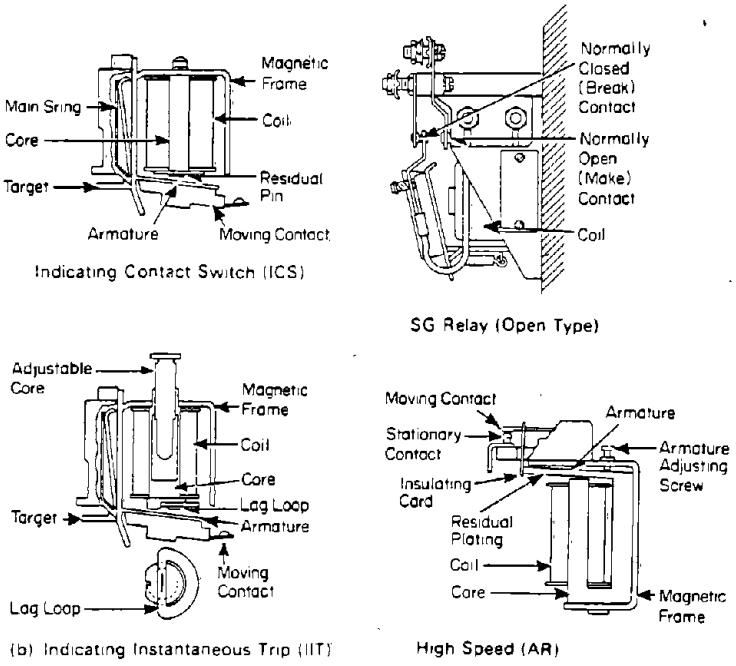
"Solenoid units" utilize a plunger being drawn into a cylindrical solenoid coil, the movement operating the relay contacts. Typical operating times are 5 to 50 ms, the longer times associated with operation near the maximum pickup value (12). A cross-sectional sketch of a solenoid relay is given in Figure 8.32a.

The construction of a few clapper-type units is shown in Figure 8.32b. These have a magnetic frame with a moveable armature and operate by the armature being attracted to an electromagnetic pole (12). The armature controls the pickup or reset of contacts.

As illustrated in Figure 8.33, polar relays have a hinged armature in the center of the magnetic structure (shown as an electromagnet but can be a permanent magnet); they operate when d-c is applied to the actuating coil (11). The polarity of the actuating source determines armature action, be it stationary or movement in either direction. In some units there is no



(a) Solenoid-Type Relay.



(b) Clapper-Type Relays.

Figure 8.32. Solenoid and Clapper Relays (courtesy Westinghouse Electric).

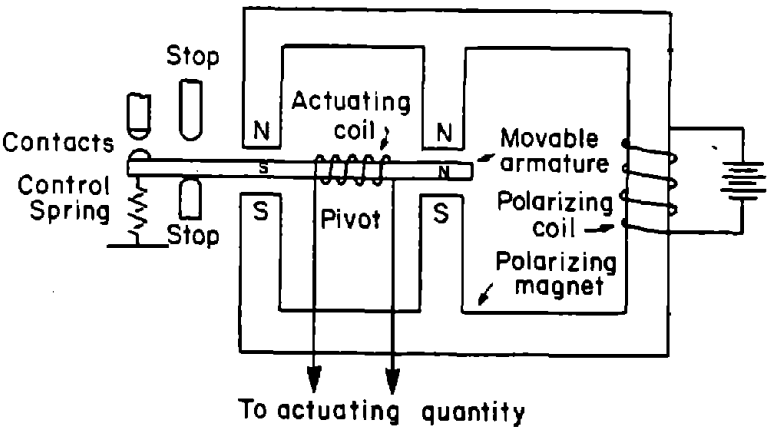


Figure 8.33. A Polar-Type Relay.

retaining spring and, with a combination of contacts, the relays can sense actuating-coil current in either direction (12).

The pickup and reset values of clapper units are less precise than available in solenoid and polar relays; thus, clapper relays are mostly used as auxiliaries of "go/no-go" devices (12). A common use for polar relays is in d-c circuit protection where the actuating source is obtained from a shunt or directly from the circuit (11).

A characteristic that should be considered when applying any electromagnetic-attraction relay is the large difference which can exist between pickup and reset values. When an attraction relay picks up, the air gap is shortened, which allows a smaller coil current to retain pickup than is needed to pick it up (11). The disparity is usually expressed as a percent ratio and is less pronounced in a-c than d-c relays. Alternating-current relays can have a reset up to 90 to 95% of pickup, where d-c ratios can range from 60 to 90% (11). This is no problem in overcurrent applications where relay-coil current drops to zero after pickup, but is a concern where reset values are important.

Electromagnetic Induction. Electromagnetic-induction relays are of two general types: induction disk and cylinder (12). Depending on construction, the induction-disk unit can be either a single-quantity or directional relay, whereas cylinder relays are intended to be directional. A "single-quantity" relay, as might be supposed, is actuated by a single a-c voltage or current source; a "directional" is actuated by and compares two sources (11). The most commonly used time-delay relays for system protection employ the induction-disk principle (6).

Single Quantity. Single-quantity time-delay relays of the induction-disk type use the same principle of operation as a-c

watthour meters, but the physical construction is quite different (12). A sketch of an elementary induction-type device is shown in Figure 8.34; most time-delay relays in use today use this arrangement. The disk, made of aluminum, is mounted on a rotating shaft restrained by a spring, and a moving contact is attached to the shaft (see Figure 8.35). On one side of the disk is a three-pole electromagnet; the other side has a common permanent magnet or "keeper." The operating torque on the disk is produced by the electromagnet, and the keeper provides a damping action or restraint after the disk starts to rotate. The retarding effect of the keeper creates the time-delay or desired time characteristic of the relay. Figure 8.35 is a front-view illustration of an actual induction-disk relay removed from its drawout case; all important components are pointed out. The unit pictured is for overcurrent. Overvoltage and undervoltage relays are also available, being identical in construction except for the electromagnet-coil rating.

The control spring carries current for the moving contact. If the actuating quantity (driving the electromagnet) is of sufficient magnitude, remaining for enough time, the disk will rotate until the moving contact touches the stationary contact. These main contacts trigger the "seal-in" or "time-delay" element, an electromagnetic attraction relay which has its coil in series and its contacts in parallel with the main contacts. Thus when activated, this relay picks up and seals in, lightening the current-carrying duty of the main contacts as well as operating a target indicator. After pick up, it usually must be reset manually.

The tap block at the top of the illustration is to enable different "tap settings" on the electromagnet coil. Table 8.8

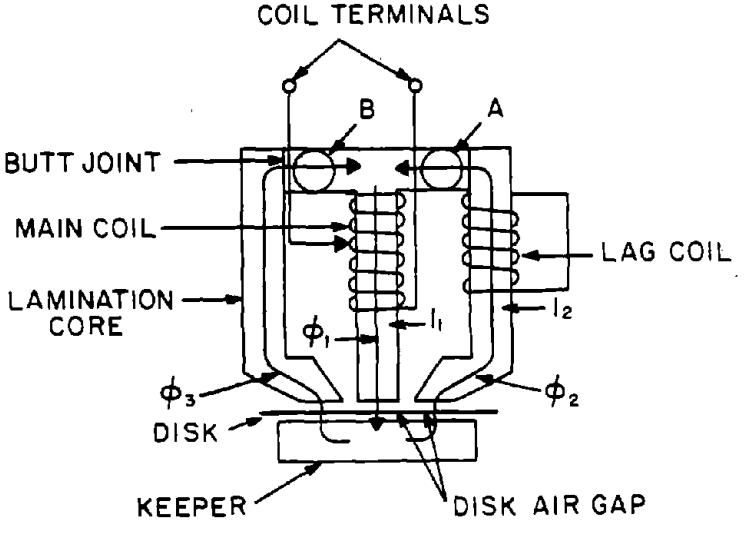


Figure 8.34. A Sketch of a Common Induction-Disk Relay.

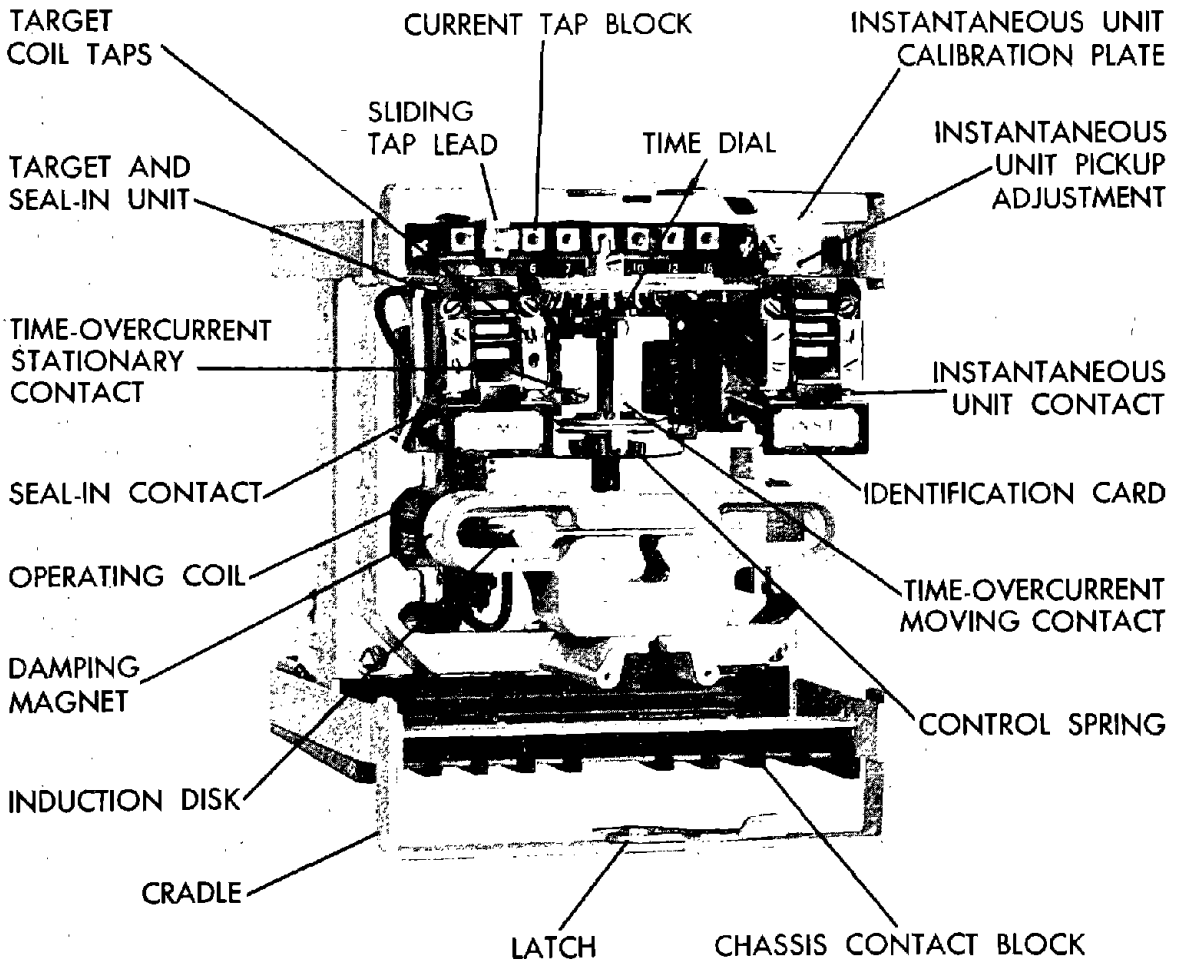


Figure 8.35. Front-View of an Induction-Disk Relay Removed from its Case (courtesy General Electric).

Table 8.8. Common Current Ratings of Induction-Disk Overcurrent Relays.

Time-delay Elements[1]		Instantaneous Elements[2]
Coil Range, A	Tap Settings, A	Adjustment Range, A
0.5-2.5	0.5,0.6,0.8,1.0, 1.2,1.5,2.0,2.5	0.5-4.0 2-16
1.5-6.0	1.5,2.2,2.5,3.0, 3.5,4.0,5.0,6.0	10-80 20-160
4.0-16	4.0,5.0,6.0,7.0, 8.0,10,12,16	

[1] Tap settings are for specific coil only.

[2] The instantaneous ranges listed are for each relay unit; different units are usually available for one time-delay range.

lists the tap settings generally available in overcurrent relays (6). Each range represents a different operating coil, and some relays have extended ranges to those shown. Voltage relays do not have as wide a range of adjustment, as they are usually expected to operate within a limited range from the normal magnitude of the actuating quantity (11). Be it a voltage or current relay, the coil and its tap settings are normally chosen with respect to the ratios of the potential or current transformer used.

As shown in Figure 8.35, overcurrent disk relays often have an auxiliary a-c operated instantaneous element, which is a clapper-type relay (6). The unit is continuously adjustable over a calibrated range, and Table 8.8 also lists some representative values. This relay operates in series with the time-delay operating coil and is usually set to instantaneously operate at a current pickup higher than the time-delay element. However, as the same actuating source drives both elements, the instantaneous relay setting must be coordinated with not only the same source but also the timed element. The instantaneous contacts can be in parallel with the time-delay contacts or connected to separate terminals. The unit also has a target indicator and normally must be manually reset after tripping.

The operation characteristic produced by the induction-disk principle is termed inverse time. Although mentioned earlier in this chapter, Figure 8.36 illustrates the inverse response: the operating time becomes less as the magnitude of the actuating quantity is increased (11). When this effect is more pronounced, the more inverse the curve is said to be. All relay time curves are actually inverse, except theoretically a definite-time response. "Definite-time" characteristics imply that the operating time of the relay is unaffected by the actuating quantity magnitude, but an actual definite-time is very slightly

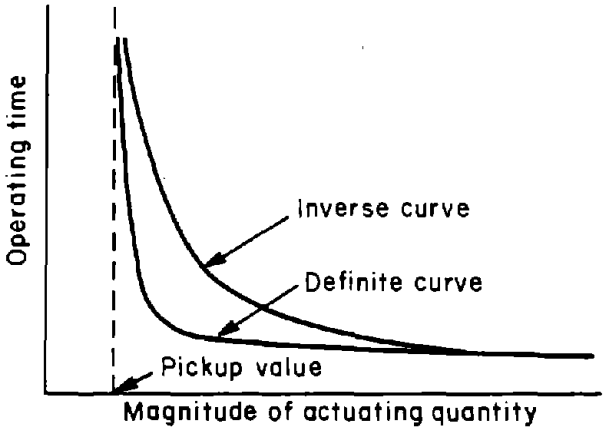


Figure 8.36. An Inverse-Time Curve Compared with a Definite-Time Curve.

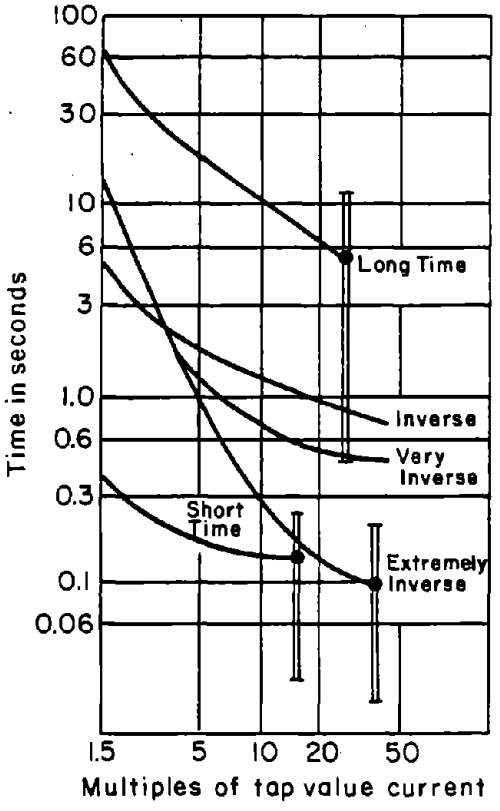


Figure 8.37. Various Time Characteristics of Induction Units.

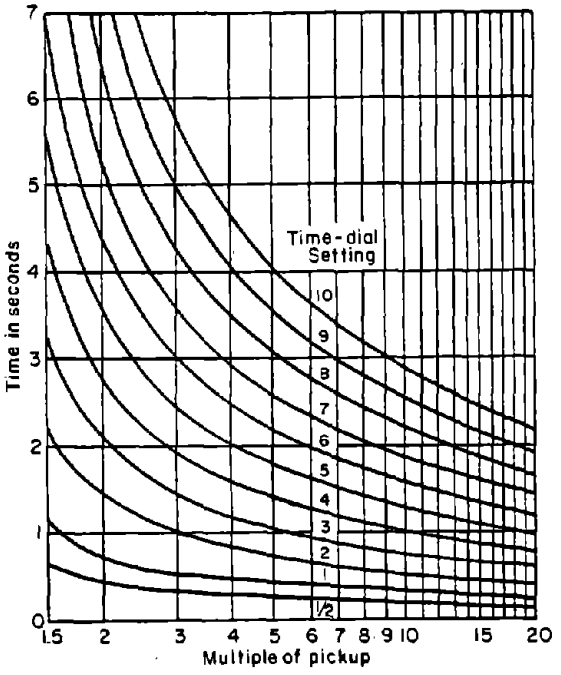


Figure 8.38. A Family of Inverse-Time Characteristics.

inverse (see Figure 8.36). Regardless, the term is applied to all fixed-time relays that approach this response.

The control-spring tension, the damping magnet, and the magnetic plugs (A and B of Figure 8.34) provide separate and relatively independent adjustment of the relay inverse-time characteristics. Preset by the manufacturer, the common responses are "inverse," "very inverse," "extremely inverse," "short time," and "long time," the first three being the most popular in mining. A comparison of these is given in Figure 8.37. The individual selection depends upon the application (5). A brief discussion of overcurrent relays follows.

When available fault-current magnitudes vary considerably, faster overall protection is usually gained with an inverse-time response. Very-inverse curves provide best overall protection where the fault current remains constant (detection of the fault, as seen by the relay, is mainly a function of fault location). Extremely-inverse relays are designed to coordinate rather closely with power fuses and distribution cutouts and are also used with systems that have large inrush currents. The actual application of these characteristics in the mine is given in Chapter 11.

The operating time of an induction relay is usually adjustable by selecting the amount of rotor travel from the reset to the pickup position (11). This is accomplished by adjusting the rest position of the moving-contact stop. The "time-dial," with evenly divided markings, facilitates positioning. When the response of the relay is plotted for different time-dial settings, the result is a family of curves, an example of which is shown in Figure 8.38. Current is plotted in terms of "multiples of pickup;" this enables the curves for a specific relay to be used with any tap setting.

Directional. The basic directional electromagnetic-induction relay commonly used, or "cylinder unit," is sketched in Figure 8.39. The operation is similar to an induction motor with salient poles for the stator, except the rotor iron is stationary and only the rotor conductor is free to rotate (11,12). The conductor is a thin-walled aluminum cylinder, and the two actuating quantities, causing I_1 and I_2, independently produce torque on the cylinder. A moving contact is driven by the cylinder, whose travel is restricted to a few degrees by the stationary contact and stops. Reset torque is established by a spiral spring.

Directional relays are used to distinguish between current being supplied in one direction or the other in an a-c circuit, by recognizing phase-angle differences between the two actuating quantities (7). (The d-c directional relay, or polar unit, recognizes differences in polarity.) To perform the comparison, one actuating value is used as a reference or "polarizing quantity." Therefore, the polarizing-quantity phase angle must remain fixed when the phase angle of the other fluctuates widely. One application of this technique is in power relays where the unit is polarized by circuit voltage and circuit current is the other actuating value. Through this, the cylinder will detect power flow in one direction or the other. Another important use is obtained when an a-c directional relay is combined with an overcurrent relay. This arrangement is provided in Figure 8.40. Tripping is such that it only occurs when current has a specific relationship to the voltage and power is flowing in the tripping direction.

8.4 Basic Relay Connections

8.4-1 General

In order to sense a malfunction then supply tripping energy to the appropriate circuit breaker, a relay must be attached in some manner to the power system. Circuit connections for protective relaying are basically not too different from that presented for instrumentation in Chapter 4. Here, however, the relay coil receives the input information; its contacts pickup or reset, affecting the control power to the circuit breaker. Direct circuit connections are often restricted to low-voltage,

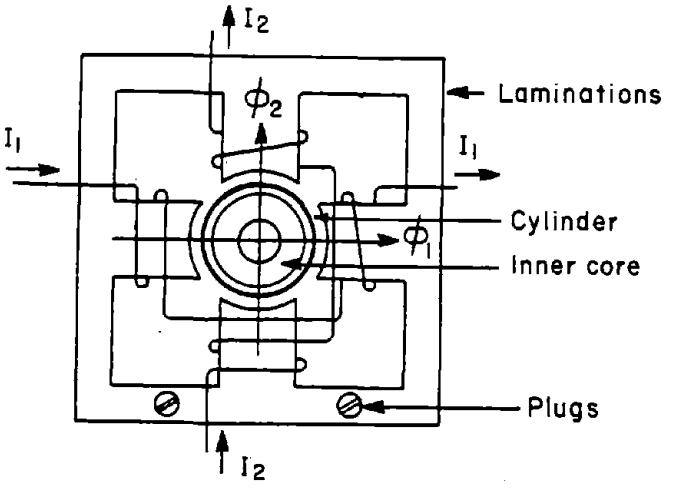


Figure 8.39. A Cylinder-Type Directional Relay.

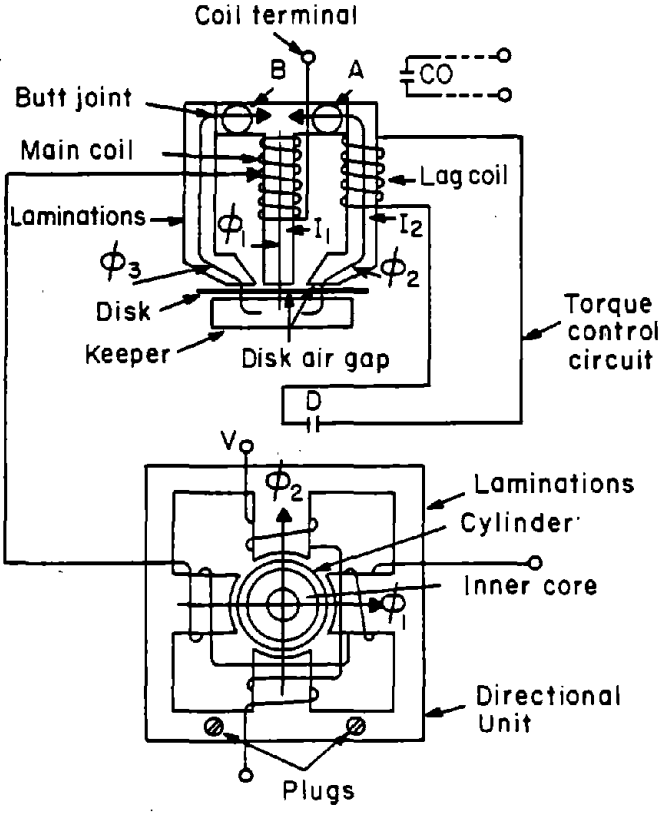
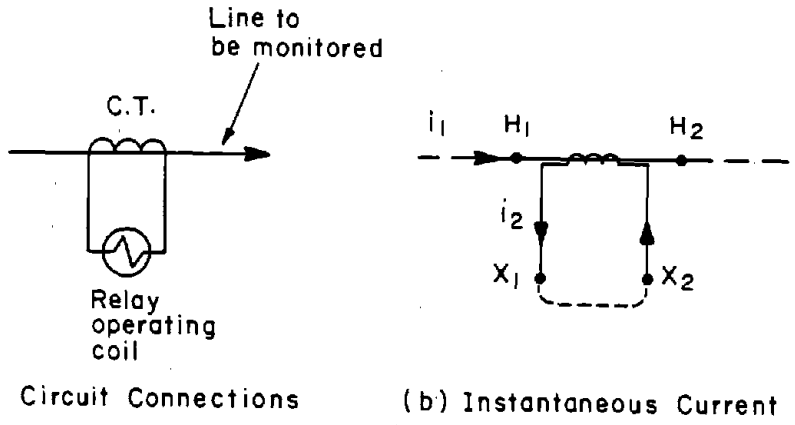


Figure 8.40. A Directional Overcurrent Relay using an Induction-Disk Relay and Cylinder Relay.



(a) Circuit Connections (b) Instantaneous Current

Figure 8.41. Direct Relaying in Alternating-Current Systems.

low-power circuits, as most relay current or voltage coils are designed to operate in the vicinity of 5 A or 120 V (2). Obviously, if power-system values exceed these levels, some interface is needed between the monitored circuit and the relays. Again, instrument transformers for a-c and shunts for d-c are used; the subject also has been introduced in Chapter 4.

There are five basic relay connections normally used for protective relaying in the mining industry. For a-c systems, these are direct, potential, and differential and, for d-c work, direct and potential are used. (Differential relaying for d-c is also available, but the circuitry is not considered basic.) Some of the techniques are employed much more than others, but this section serves to introduce all these connections.

8.4-2 Alternating-Current Connections

Direct Relaying. "Direct relaying" is used to sense the magnitude of current flow. As shown in Figure 8.41a, its most simple form consists of a current-transformer secondary connected to a relay operating coil. Relay pickup current is, thus, a function of line current. For instance, consider that the transformer ampere-turns ratio (or "current rating") is 50/5 A or 10/1 and the relay pickup setting is at 0.5 A. The relay would theoretically pick up its contacts when line current is [10][0.5] or 5 A. The purpose of this connection is, therefore, to provide current-protection relaying to any conductor.

The important items to consider in direct relaying are concerned with matching the performance of the CT with that of the relay. IEEE Standard 242-1975 provides most of these (6).

1. Ratios. An obvious starting point after the foregoing example. Standard ratios are provided in Table 8.9. The double-ratio and multiratio

Table 8.9. Standard Ratios for Bushing-Type Current Transformers.

Single-ratio Type, A	Double-ratio Type,[1] A	Multiratio CT[2]	
		Rating, A	Taps, A
10/5	25/50/5	600/5	50/5
15/5	50/100/5		100/5
25/5	100/200/5		150/5
40/5	200/400/5		200/5
50/5	300/600/5		250/5
75/5	400/800/5		300/5
100/5	600/1200/5		400/5
200/5	1000/2000/5	1200/5	450/5
300/5	1500/3000/5		500/5
400/5	2000/4000/5		600/5
600/5			100/5
800/5			200/5
1200/5			300/5
1500/5			400/5
2000/5		2000/5	500/5
3000/5			600/5
4000/5			800/5
5000/5			900/5
6000/5			1000/5
8000/5			1200/5
12000/5			300/5
			400/5
			500/5
			800/5
			1100/5
			1200/5
			1500/5
			1600/5
			2000/5

[1] Has centered-tapped secondary.

[2] Has multitapped secondary; higher current ratings than those shown are available.

types provide flexibility through secondary taps. These values are for bushing-type or window-type CT's which are the most popular in the industry. All these have the standard 5-A rated secondary current.

2. Secondary Current. The continuous-current rating of the secondary should be at least equal to the actual drain, but a full-load secondary current of three to four amperes is normal practice. An oversized CT is bad practice as the percent error is much greater than a correctly rated CT.
3. Short-Time Ratings. Both thermal and mechanical ratings should be considered. The thermal short-time value relates to the maximum symmetrical rms primary current that the CT can carry for 1.0 s without exceeding the maximum asymmetrical rms current the CT can withstand without damage. In both cases, the rating is made with the secondary short circuited.
4. Voltage Rating. Standard voltage ratings are 600, 2500, 5000, 8700, and 15,000 V, and are the same as insulation classes found in mine systems. The CT will operate continuously at 10% above rated without insulation failure.
5. Burden. As defined in Chapter 4, burden is the load connected to the CT secondary; expressions used are volt-ampere at a given power factor or an impedance with a power factor. The power factor is that of the burden. Table 8.10 lists standard values for current transformers at 60 Hz. Relay burdens are so varied they cannot be listed, but Chapter 9 shows how CT burden and relay burden can be compared.
6. Accuracy. Accuracy of a CT relates to its transformation ability. In protective-relaying applications, accuracy is not only important at normal circuit currents but also at fault-current levels. The problem with the CT is that core saturation leads to poor accuracy or ratio errors. Accuracy-class designations use a C or T identifying number. C states that percent ratio error can be calculated, whereas T means that the value has been found by testing. The classification number relates to a standard secondary voltage of 10, 20, 50, 100, 200, 400, or 800 V. At this voltage, the CT will deliver to a standard burden, 20 times normal secondary current with 10% ratio error or less, and it will not exceed 10% with any current from one to 20 times rated current with a lesser burden. (e.g., C200 relates for a 2.0-Ω burden, that (20)(5) or 100 A can be delivered from the CT without exceeding 10% error. Also, this error

Table 8.10. Standard Burden for Current Transformers.

Designation[1]	Characteristics		Characteristics for 60 Hz and 5-A Secondary Current[2]		
	R, Ω	L, mH	Z, Ω	ISI, VA	pf
B-0.1	0.09	0.116	0.1	2.5	0.9
B-0.2	0.18	0.232	0.2	5.0	0.9
B-0.5	0.45	0.580	0.5	12.5	0.9
B-1	0.5	2.3	1.0	25	0.5
B-2	1.0	4.6	2.0	50	0.5
B-3	2.0	9.2	4.0	100	0.5
B-4	4.0	18.4	8.0	200	0.5

[1] B-0.1, B-0.2, and B-0.5 usually considered for metering purposes, while B-1 through B-4 usually considered for relaying.

[2] At 5A, ISI = I^2Z or, for B-2, ISI = 5^22 = 50 VA.

can be calculated.)

7. Polarity. Polarity relates to the correct phasing of primary and secondary currents, and Figure 8.41b shows the relative instantaneous directions of current as per standard markings. This allows correct connections when more than one transformer is used, which is imperative in three-phase systems.

As can be seen in the foregoing listings, actual manufacturer specifications should always be consulted before attempting to match current transformers with relays for direct-relaying applications.

Potential Relaying. "Potential relaying" is as simple as direct relaying and enables circuit voltage to be monitored. Figures 8.42a and 8.42b show two applications: sensing voltage across a resistance and between two conductors. There is a potential transformer between the circuit and the relay. Figure 8.42c gives the polarity correspondence of instantaneous voltages between the primary and secondary windings as well as conventional transformer markings. Standard potential transformers are single-phase two-winding units constructed so the primary and secondary voltages always have a fixed relationship (6).

To visualize operation, consider Figure 8.42a. The transformer is rated 2400/120 V or has a 20/1 ratio, and the relay coil is rated at 120 V with the contacts set to pick up at 80% of rated (an overvoltage relay). The contacts will, therefore, pick up when 1920 V exists across the resistor.

IEEE Standard 242-1975 also provides guidelines for potential-transformer utilization, and a summary of these follow (6). In general, they are less rigorous than for current transformers.

1. Voltage. Standard voltage ratios are available in Table 8.11. When applied to sense voltage between two conductors, the nominal system voltage should be within ± 10% of the transformer nameplate rating. When used in three-phase mining systems, primary connections must be line to line. Special ratings, providing other than the standard 120-V secondary, are usually available.
2. Accuracy. Ratio and phase-angle errors of standard potential transformers are usually so small they can be neglected, and any standard transformer is satisfactory as long as it is used within its thermal and voltage limits. If the transformer load is within rated burden, the transformer is suitable over the range from zero to 110% of rated voltage. Regardless, standard accuracy classes do exist for potential transformers, ranging from 0.3 to 1.2. This value represents the percent ratio correction to obtain true ratio.
3. Burden. The burden of a potential transformer, or "thermal burden limit," is expressed in volt-ampere ratings of parallel loads arithmetically to obtain a total volt-ampere burden. Accuracy is usually satisfactory at burdens well below rated, but the transformer volt-ampere rating should not be exceeded.
4. Fusing. In some instances, fusing the primary of a potential transformer is not advisable, especially when the protective-circuitry duty is to sense a critical overvoltage condition (for instance, monitoring the voltage across a grounding resistor). Yet, when the PT is connected line to line, it must be protected in case of PT failure or secondary conditions which will lead to failure. General practice is to use current-limiting fuses, sized to the transformer full-load rating, installed in the primary circuit between each ungrounded conductor of the system. Fuses are preferred over circuit-breaker primary protection because of the inaccessibility to manual tripping. A prime use for

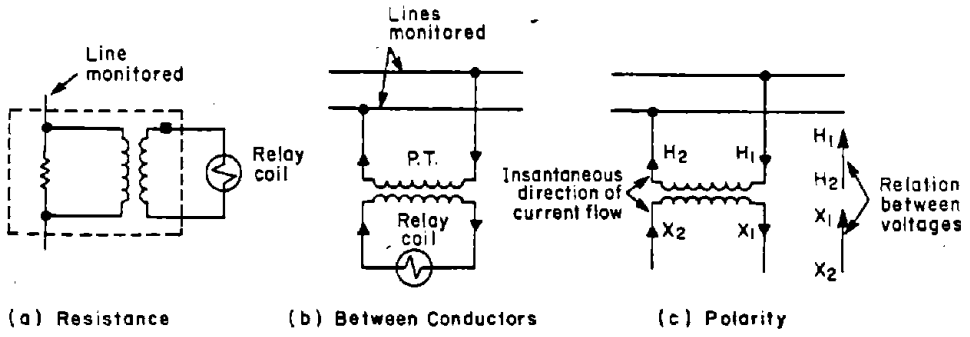


Figure 8.42. Potential-Relaying Connections.

Table 8.11. Standard Ratings for Potential Transformers.

Primary, V	Secondary, V	Ratio
120	120	1/1
240	120	2/1
480	120	4/1
600	120	5/1
2400	120	20/1
4200	120	35/1
4800	120	40/1
7200	120	60/1
8400	120	70/1
12000	120	100/1
14400	120	120/1
24000	120	200/1
36000	120	300/1
48000	120	400/1
72000	120	600/1

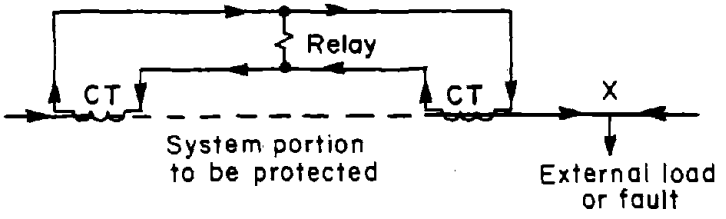
potential transformers in mine systems is to supply control power to protective circuitry; secondary protection in this case is unnecessary. For other loads, however, such as branch circuits for 120-V convenience outlets, the additional branches should be fused or protected by molded-case circuit breakers, the latter being general practice.

Differential Relaying. "Differential relaying" is where a relay is operated by the vector difference of two or more actuating quantities, and relay pickup is determined by a difference threshold (11). Most applications of this scheme are of the "current-differential" type, and a basic circuit is shown in Figure 8.43a. The dashed portion represents the area to be protected. Two matched current transformers are interconnected, and an overcurrent relay is inserted between. Under normal conditions, or even a fault occurring outside the protected zone, the CT secondary currents will circulate, not flowing through the relay coil. However, if the flow of I in both CT primaries becomes unbalanced, current will flow through the relay in proportion to the vector difference of the current entering and leaving the protected circuit (see Figure 8.43b).

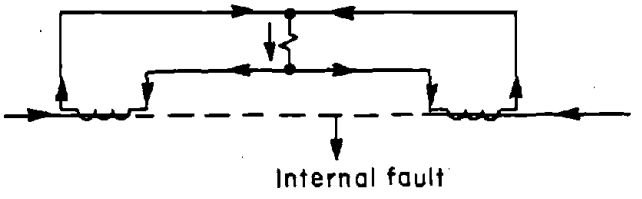
A problem with this basic circuit is that current transformers are very difficult to match; on identical units, the same primary current will not always give the same secondary current (6). Thus, the relay must be set to not pick up on maximum error current between the CT's. An approach to overcome the mismatch problem is the "percentage-differential" connection. As illustrated in Figure 8.43c, the main change is the relay, now an overcurrent current-balance type (12). Because of the relay restraining coil, the differential current required to operate the relay is a variable quantity, offsetting errors in the actuating sources.

8.4-3 Direct-Current Connections

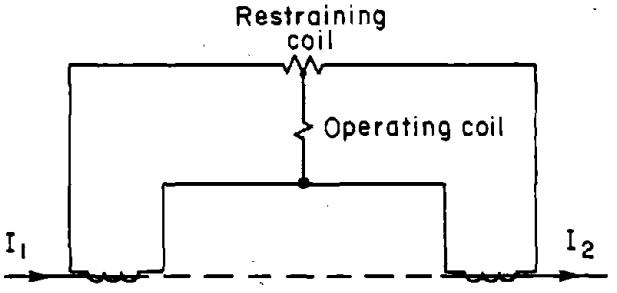
As is the case for a-c, direct relaying and potential relaying are also the two most used protective-relaying connections for d-c systems. Direct relaying (see Figure 8.44) consists of a d-c overcurrent relay connected to a resistance shunt. The relay operating coil is matched to the shunt voltage at the desired pickup level (shunt full-load current rating usually gives 50 or 100 mV across the shunt). For low-current applications such as sensing d-c current in a grounding conductor, current-relay operating coils are sometimes inserted in-line with the monitored conductor. Potential relays are also directly connected with the coils between the conductors of interest. Resistive dividers are at times employed to drop the d-c system voltage down to the coil rating (see Section 4.9).



(a) Basic Current Under Normal Conditions



(b) Basic Circuit Under Abnormal Conditions



(c) Percentage-Differential Relay Connections

Figure 8.43. Differential-Relaying Connections.

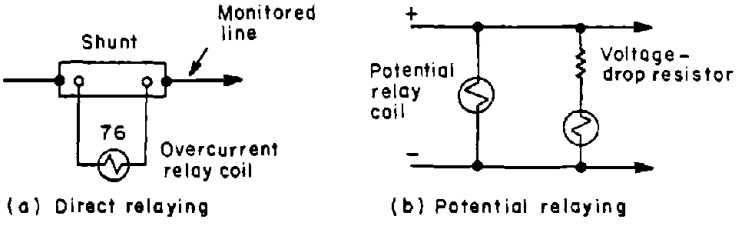


Figure 8.44. Direct-Current Direct-Relaying Connections.

8.5 Kinds of Protection

8.5-1 Quantities for Detection

In the preceding material, several relaying terms have been introduced; many of these fit into required protection classifications or "kinds of protection." A summary of these follows:

1. undervoltage,
2. overcurrent (also termed overload),
3. short circuit,
4. ground overcurrent (or ground fault),
5. ground continuity, and
6. overtemperature.

The first five are necessary protection on all portable and mobile mining equipment.[5] This section will expand upon this basic relaying material by covering how each kind of protection is facilitated in the mine power system. The content is mainly pointed at high-voltage three-phase a-c mining systems, in general restricted to sensing devices external from circuit breakers. Hence, the kinds of protection imply the following parameters:

1. line-to-line voltages for undervoltage,
2. phase overcurrent for overcurrent,
3. three-phase or phase-to-phase faults for short circuit,
4. faults causing zero-sequence current for ground overcurrent, and
5. grounding-conductor resistance for ground continuity.

Even though overtemperature is in the preceding list, it is usually applied to protecting a specific component; thus, its application is handled in Chapters 11 and 12.

8.5-2 Control Wiring

Figures 8.45 and 8.46 show simplified diagrams of typical control-wiring interconnections among the power source, relay contacts, and circuit-breaker tripping elements. In both, a potential transformer supplies 120 Vac with its fused primary connected line-to-line. Figure 8.45 relates instances where the tripping element is a UVR. The contacts can either reset to remove power from the coil (contacts in series with coil) or close to short it out (contacts parallel the coil). In the latter case, it can be seen that a resistance is placed in series with the contacts. (In fact, the UVR itself will trip the breaker if control voltage is decreased in the range of 40

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[5] Title 30, Code of Federal Regulations, Parts 75 and 77. There are exceptions to requiring all five kinds.

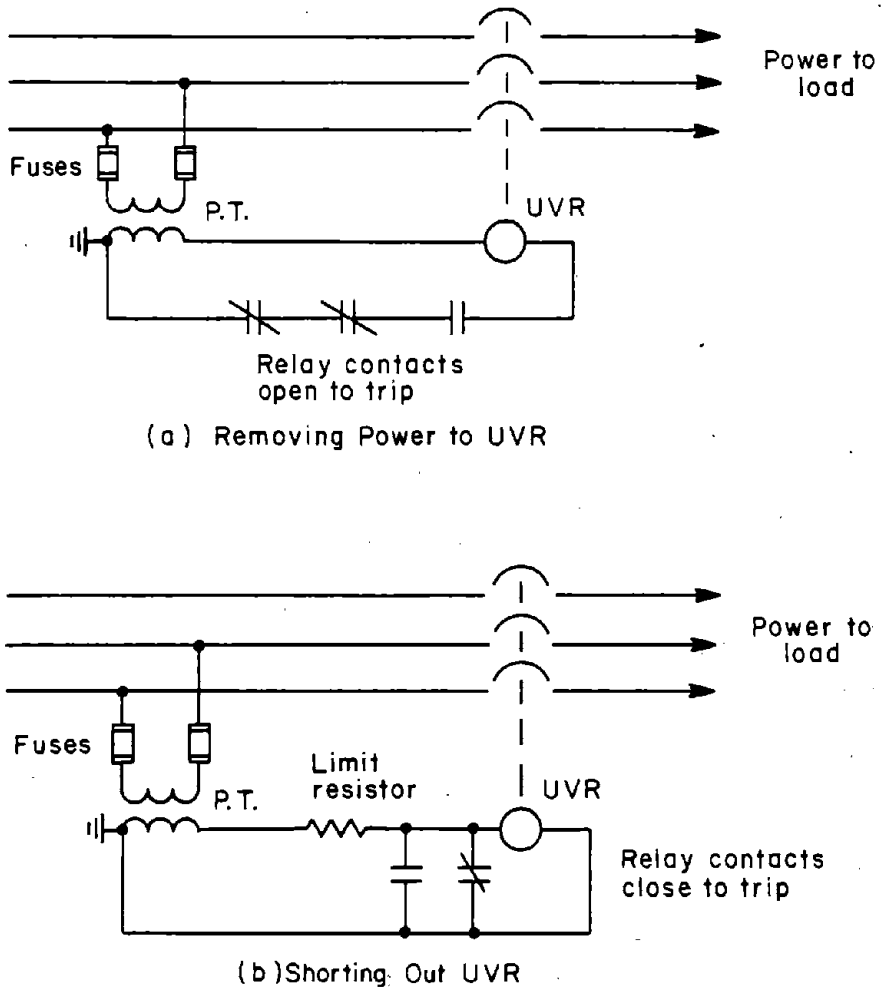


Figure 8.45. Typical Control Wiring for UVR.

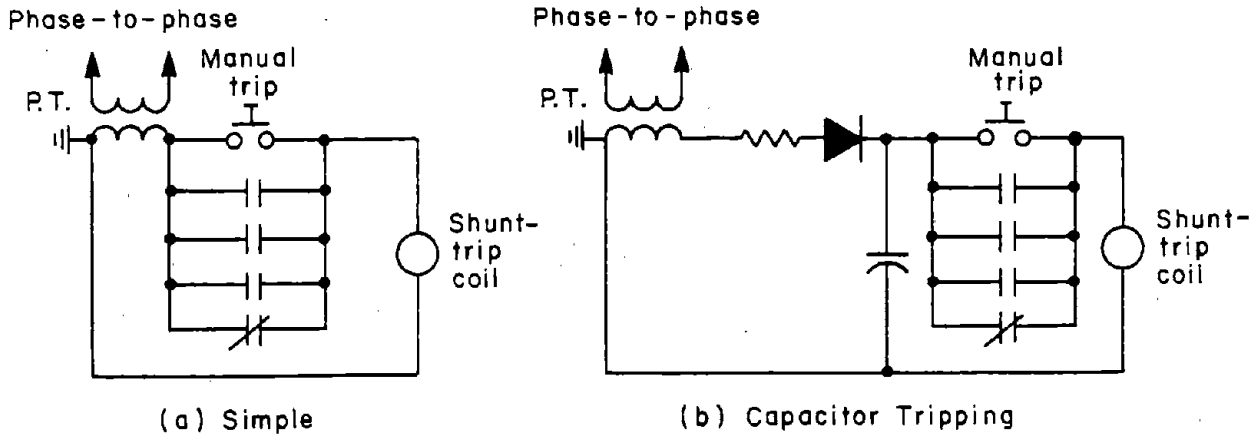


Figure 8.46. Typical Control Wiring for Shunt-Tripping Element.

to 60%.) Shunt-tripping connections are given in Figure 8.46, where power is supplied to the element to cause tripping. Here, the contacts for the various protective relays are paralleled, the combination being in series with the trip coil; closure of any contact trips the breaker. Although a-c is typical control, d-c is also used.

8.5-3 Phase Protection

General. Phase protection, as mentioned, can be overcurrent, short circuit, or both, depending upon the protective relays used. (Note: molded-case circuit breakers afford this same flexibility depending upon the internal tripping element used.) Time-delay relays (the device number is 51) are employed for overcurrent, with instantaneous units (device 50) for short circuit. Figure 8.47 illustrates the combined protection for three phase conductors, using an induction-disk relay (6). The three current transformers are placed in wye driving the wye-connected operating coils. The time-delay element is set on as low a tap setting as practical, enabling protection for sustained moderate overloads. The instantaneous units, however, are set to pick up on a current value slightly higher than the maximum peak load, thereby affording protection against short circuits or enormous overloads.

Two Versus Three Relays. With the connections as shown in Figure 8.47 and again in Figure 8.48a (but without the 50 elements), the secondary currents of each CT are in phase with the primary currents, neglecting transformer phase-angle errors, and each relay responds to abnormal conditions for its respective phase (11). If phase currents are approximately balanced, short-circuit protection for all three phases can also be afforded with open-delta connections, as in Figure 8.48b (11). This approach, as might be expected, is not as precise as with the straight wye connection, but a third overcurrent relay may be inserted in the CT common connection for backup protection (see Section 4.9 for a similar discussion on instrumentation). An advantage of the wye connection, lost when the open-delta approach is used, is the ability to sense zero-sequence currents through differential relaying. Thus, two current transformers are rarely applied as the only means of circuit protection.

8.5-4 Ground Overcurrent

General. To this point, the chapter has basically considered power-conductor protective relaying, and the extremely important subject of ground-fault protection has received only terse reference. Various relay configurations may be utilized to provide ground-overcurrent protection, some of which are quite elaborate. However, nearly all these techniques fall into

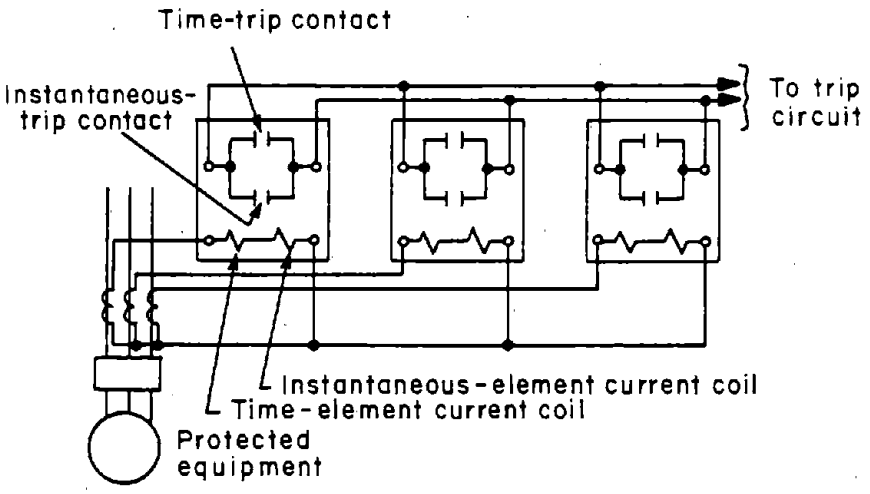


Figure 8.47. Three-Phase Overcurrent and Short-Circuit Connections.

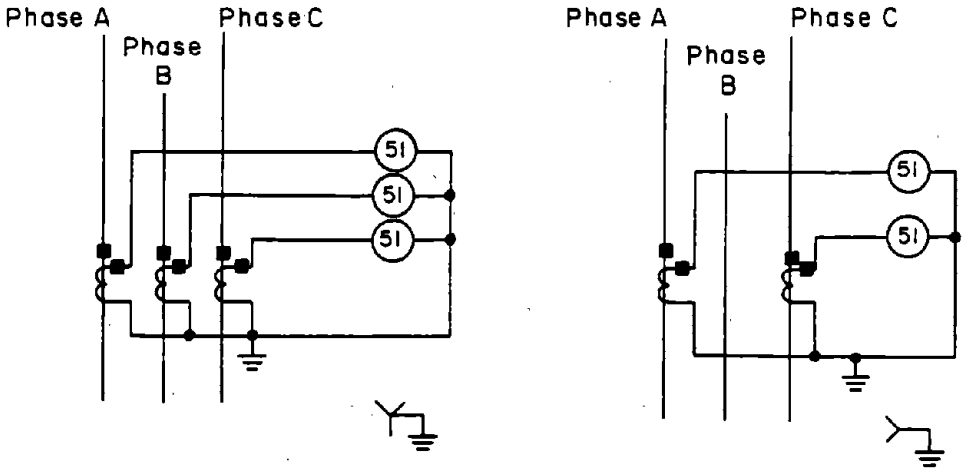


Figure 8.48. Two Current-Transformer Approaches.

one of five broad classifications (6):

1. direct relaying,
2. potential relaying,
3. residual connection,
4. zero sequence, and
5. broken delta.

Schemes 1, 2, and 4 are frequently used in resistance-grounded mine power systems, with zero-sequence relaying being perhaps the most popular. Unless otherwise clarified, the following discussion will assume that the system is resistance grounded.

The protection afforded by direct and potential ground relaying is usually restricted to use at the system neutral point or grounding resistor, whereas the other three techniques can provide protection anywhere in the system. Usually a combination is needed for complete assurance of clearing all ground faults.

Direct Relaying. In the simplest ground-overcurrent-detection approach, a current transformer can be placed about the grounding conductor. An example is illustrated in Figure 8.49, where the CT is between the transformer neutral and grounding resistor. Any anomalous flow of ground current indicates a malfunction. In many situations some ground-current flow is normal, due to system unbalance, capacitive-charging currents, or inductive-coupling effects, so the circuitry must be adjusted to pick up only when the normal level is exceeded. As will be seen, the pickup point, however, should always be less than the system current limit.

A problem with this neutral-conductor method is that should the grounding resistor, or the grounding conductors to it, become open, the relaying will never detect any ground-current flow. The system becomes essentially ungrounded, posing a personnel hazard especially where resistance-grounding is mandatory. Accordingly, although the technique does find application on some portions of the ground system, some states do not allow its use on substation grounding resistors, even for a second line of defense.

Potential Relaying. For monitoring current through a grounding resistor, an improvement can be made by replacing the current transformer with a potential transformer. The modification is shown in Figure 8.50, where the PT is placed in parallel with the grounding resistor. The flow of ground current generates a voltage across the PT, the secondary of which energizes the relay operating coil. Even if the resistor opens, protection is maintained (13,14,15).

Residual Connection. "Residual overcurrent relaying" is used in conjunction with current transformers placed on the phase conductors. An overcurrent relay is installed in series with the combined parallel secondaries of the transformers. As

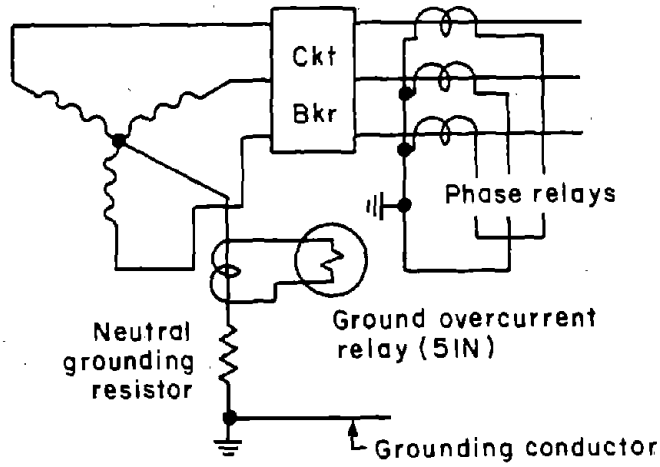


Figure 8.49. Neutral-Resistor Current-Relaying Scheme.

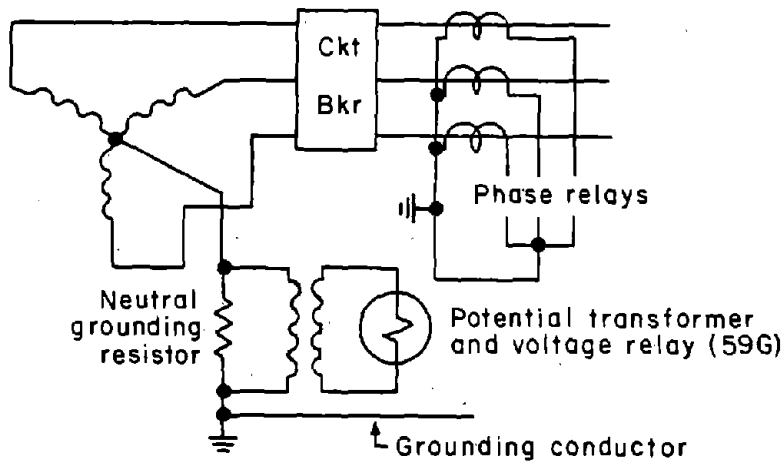


Figure 8.50. Neutral-Resistor Potential-Relaying Scheme.

shown in Figure 8.51, the protection can be conveniently added to the three-relay phase-overcurrent technique (5). The interconnection is such that the ground relay responds in proportion to ground-fault current. When a ground fault occurs downstream from the relays, neutral current will bypass the phase conductors directly back to the power source. Hence, the net current in the CT secondaries is not zero, and current flows through the residual-leg-relay operating coil (6).

Due to errors caused by current-transformer saturation and unmatched characteristics, residually-connected relays are often subject to nuisance tripping (5). Hence, they cannot have "sensitive settings" or very low pickup current (6). In many cases, the arrangement will not provide consistent repetitive tripping at the required current levels for mine power ground systems.

Zero-Sequence Relay. "Zero-sequence relaying," also termed "balanced-flux relaying," is the most reliable first defense against ground faults in mine power systems. Shown in Figure 8.52, the circuitry consists of a single window-type current transformer; the three phase conductors are passed through the transformer core, forming the CT primary (5). (Note: On four-wire systems which have line-to-neutral loading, the neutral conductor must also pass through the window but not the grounding conductor. As such loading is not allowed in mining, only the phase conductors can be used.) In a symmetrical-phase set, the vector sum of the three currents in the primary circuit will be zero, and no current will flow in the secondary. However, during a phase-to-neutral fault, the phase unbalance will produce current flow in the CT secondary, proportional to zero-sequence current.

The above phenomena can be easily demonstrated. In terms of symmetrical components, the three phase currents can be written as:

$$I_a = I_{a1} + I_{a2} + I_{a0}$$

$$I_b = I_{b1} + I_{b2} + I_{b0}$$

$$I_c = I_{c1} + I_{c2} + I_{c0}$$

The primary current, I_{prim}, for the CT can be considered the vector sums of the three phase currents, which is also the current flowing through neutral conductor (or that external to the CT window). Therefore,

$$I_f = I_a + I_b + I_c$$

$$= (a^2 + a + 1)I_{a1} + (a^2 + a + 1)I_{a2} + 3I_{a0}$$

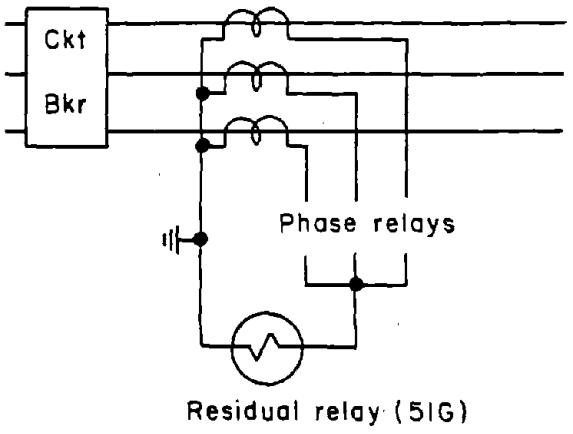


Figure 8.51. Ground Relay in Residual Connection.

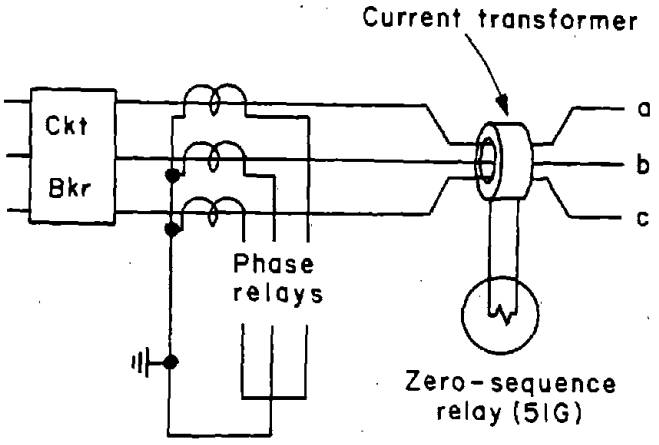


Figure 8.52. Zero-Sequence Ground-Relay Connections.

Because $a^2 + a + 1 = 0$,

$$I_{prim} = 3I_{a0}.$$

Thus, for an unfaulted or balanced condition,

$$I_{prim} = 3I_{a0} = 3I_{b0} = 3I_{c0} = 0$$

and no current is induced in the CT secondary. However, for a phase-to-neutral fault involving phase a, the primary current equals the ground-fault current, I_f, or

$$I_{prim} = I_f = 3I_{a0},$$

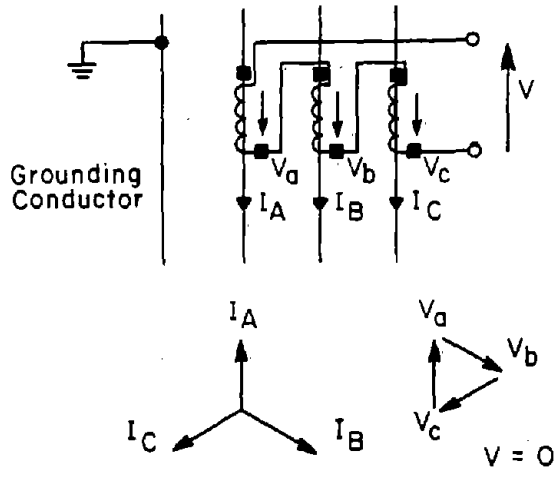
and a current is induced in the CT secondary to initiate tripping.

Zero-sequence relaying is not perplexed by current-transformer errors and therefore affords very sensitive tripping (5). The scheme is widely applied at all voltage levels in mining.

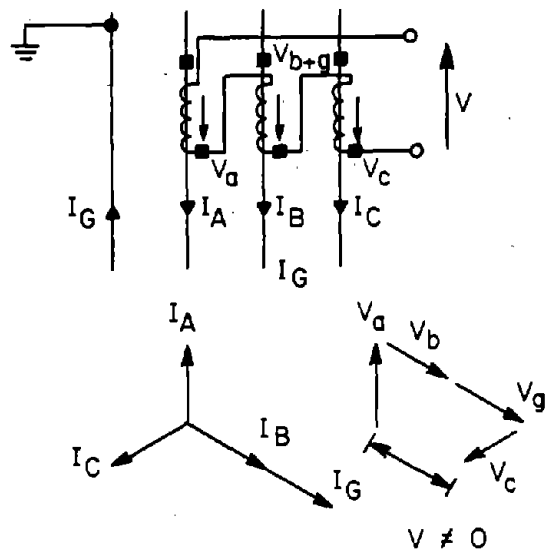
Broken-Delta Relaying. Broken-delta ground-fault protection is somewhat similar to the residual method, except that the three current transformers are wired in series, as shown in Figure 8.53. The resultant output voltages from the transformers form a closed delta if the load is balanced (see Figure 8.53a). An unbalanced condition, such as a line-to-neutral fault, will cause the formation of an open delta (see Figure 8.53b), and the resultant voltage causes current through the relay operating coil. The broken-delta is sensitive to any unbalance, but the zero-sequence relay only operates on faults involving the neutral (5).

Pickup. Most sources recommend that ground relays should pick up at no more than 30% of the maximum current limit of the ground system, to provide an ample margin of safety in resistance-grounded systems (13,14,15). For a 25-A current limit, this would be about 8 A. However, such a demand is beyond present protective-circuitry capabilities when electromechanical relays are used. The optimum arrangement, using induction-disk relays, is zero-sequence and shows approximately 12 A as best (reliable) pickup performance. The reason is connected to the fact that a window-type CT needs a large window in order to get the three phase conductors through. As a result, zero-sequence currents less than 12 A do not generate enough capacity for the CT to drive an induction-disk relay.

It might be thought that requiring relay operation below the ground-current limit is too stringent and that relays should only be required to operate at the fault current available on the system. The feeling is quite sound and relates that on a properly installed ground system, no potential greater than that allowed (100 V on high voltage) can ever exist between any metallic object and earth under fault conditions.



(a) Normal Operation



(b) Ground Fault

Figure 8.53. Broken-Delta Protection.

Nevertheless, in terms of personnel safety, setting relay pickup less than the limited fault current provides viable backup protection. In other words, machine frames would remain confidently below that allowed during any fault. Trending hazardous conditions can also be detected, although such trends involving the system neutral are infrequent on high-voltage distribution. Considering these thoughts and in-mine practice, ground-current pickup should not be greater than 60% of the system current limit. This level does provide reliable, repetitive operation of zero-sequence protective circuitry. In agreement with the literature (13,14,15), as technology improves, 30% pickup should be the goal.

8.5-5 Ground-Check Monitoring

General

The efficiency of all the ground-relaying methods just covered depends upon the integrity of the grounding system. A device which continuously monitors ground connections to verify continuity is termed a "ground-check monitor" (16,17, 18). If adequate conductivity is not present, it is the duty of the monitor to trip the circuit breaker that feeds power to the system with the defective grounding.

As has been shown in Chapter 6, the grounding conductor is not essential for mining-machine operation, but is imperative for personnel safety. The ground-check monitor thus ensures safety by making sure, via the grounding connections, the equipment frames are at near neutral potential. Again, the maximum frame potential to earth allowed on low and medium voltage is 40 V, with 100 V for high-voltage systems.

Ground-check monitoring is an extensive subject, and this subsection will only introduce basic systems. Several articles have been published which can be consulted for more detail (for instance, references 16, 17, 18, and 19).

Techniques

Although there are numerous possible methods of monitoring ground continuity, only a few are considered practical, mainly because of construction or high reliability (18). These can be divided into two general classifications: pilot and pilotless.

Pilot. Pilot monitors use a pilot or ground-check conductor (see Chapter 7) to perform the task, and there are three general kinds: simple loop, transmitter loop, and bridge (16).

In the most common "series-loop" circuit, a power supply, relay operating coil (instantaneous contacts or a minimal time delay), the pilot conductor, and grounding conductors are

connected as shown in Figure 8.54 (16). If the pilot or grounding conductor breaks the loop (or if the power supply fails), the relay contacts will reset. The circuit can be either a-c, using 60-Hz line frequency, or d-c.

The "transmitter-loop" concept is basically the same as the series loop, except the voltage source is installed in the machine (see Figure 8.55)(16). Here, the source must receive its power from the machine, and the relay cannot pick up until the circuit is energized. Therefore, the monitor must be temporarily bypassed in order to close the circuit breaker.

"Bridge-type" monitors use the series combination of the pilot and grounding conductors as one leg of a wheatstone bridge. Figure 8.56 shows a general circuit, where Z_3 is used to balance the bridge for a specific pilot and grounding-conductor impedance (16). Bridge output is sometimes amplified and, with or without amplification, the relay resets if a preset impedance level is exceeded. Bridge input can be 60-Hz a-c, d-c, or an audio frequency (for instance, 5000, 2500, or 900 Hz)(16,18).

Pilotless. "Pilotless" monitors, as the name implies, do not use the pilot conductor. Instead, as shown in Figure 8.57, an audio signal is placed on the phase conductors through a filter and removed at the machine (again, through filters), completing its path back to the source in the grounding conductor (16). Between the grounding conductor and the power-center frame is often a saturable reactor, which shows high impedance to the monitoring frequency. Its purpose is to restrict the monitoring signal to only the intended path. This presents problems in coupler grounding, as the coupler metallic shell is commonly grounded to the grounding conductor as well as physically connected through its receptacle to the power-center frame. In order not to bypass the reactor, the grounding conductor must be isolated from the shell ground.

Problems and Requirements

All of the basic configurations are plagued by some disadvantages, and achieving a reliable monitor has been a perplexing situation for the mining industry. The reason is tied to the uniqueness of the mine power system. The diagram in Figure 8.58 provides a conceptual view of some difficulties that can arise (18). One of the more pronounced problems is parallel ground paths established by contact through the mine floor or through grounding conductors on other machines. The alternate ground paths may have a resistance as low as the grounding conductor, but in the majority of cases these are very temporary in nature, and thus cannot be relied upon. Stray a-c and d-c and induced a-c are an ever present problem in many mines. With d-c rail haulage, substantial direct current can stray, for example, from the rail when a poor bond is present and end up flowing in the a-c ground system. If the cable, exemplified in G-GC and SHD-GC configurations, or system current is unsymmetrical, a-c can be

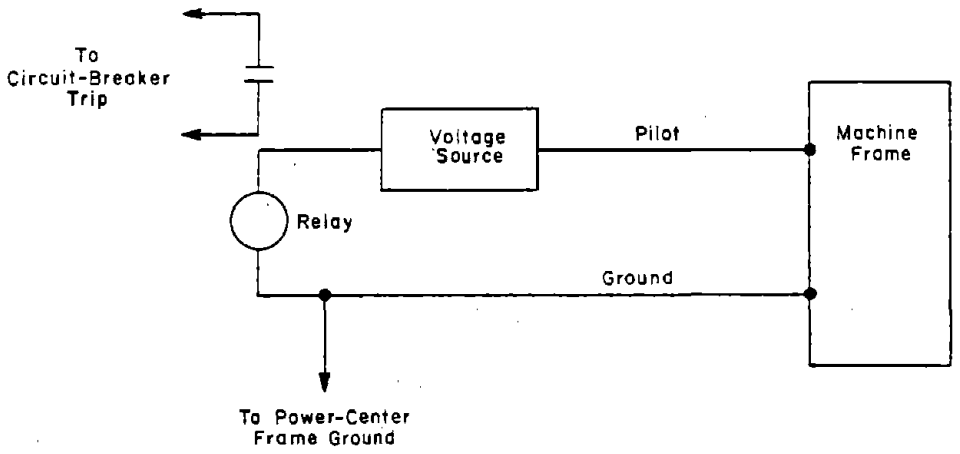


Figure 8.54. Series-Loop Ground-Check Monitor.

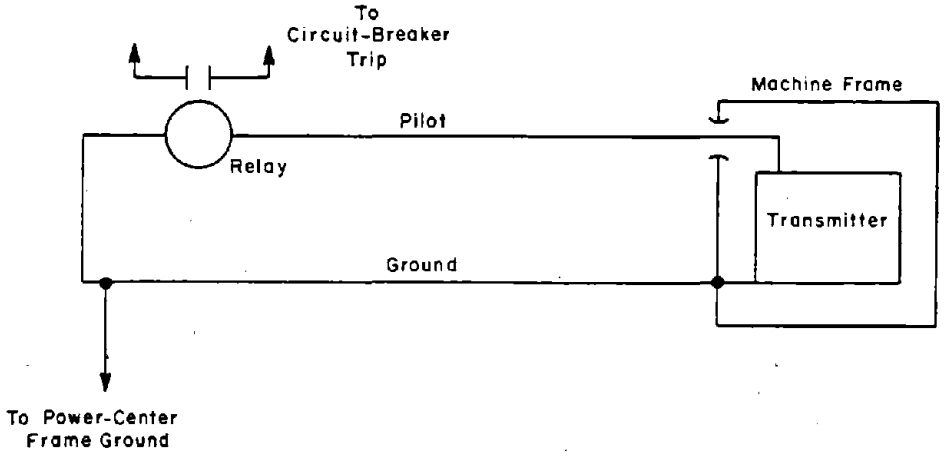


Figure 8.55. Transmitter-Loop Ground-Check Monitor.

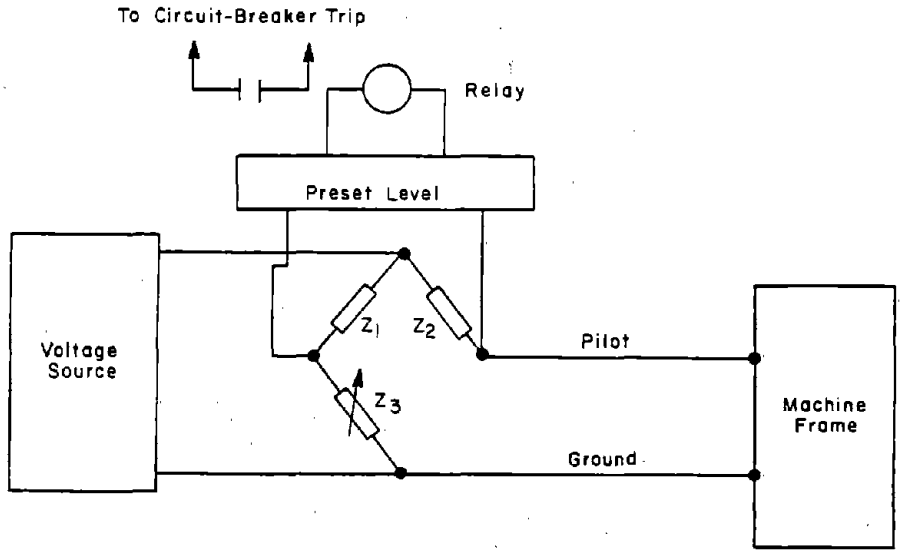


Figure 8.56. A Bridge-Type Ground-Check Monitor.

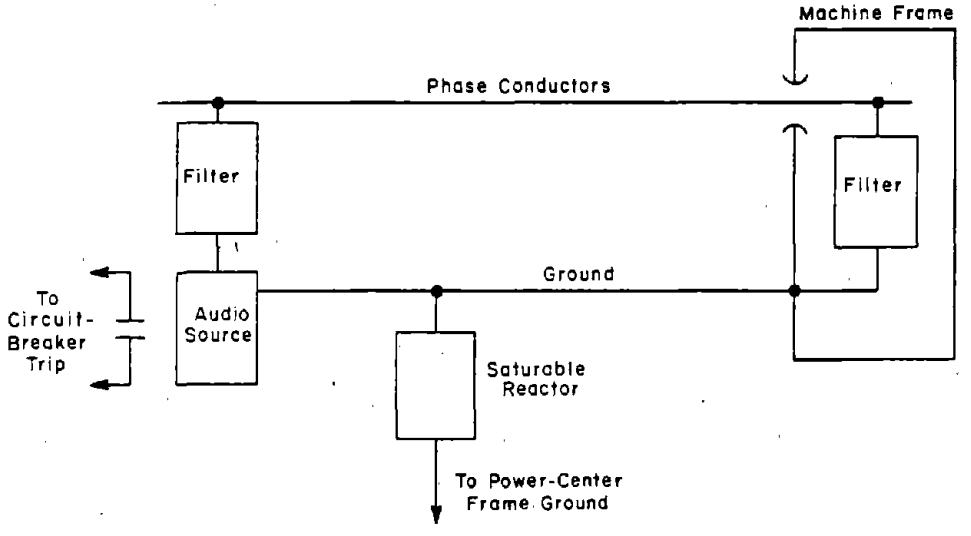


Figure 8.57. A Pilotless Ground-Check Monitor.

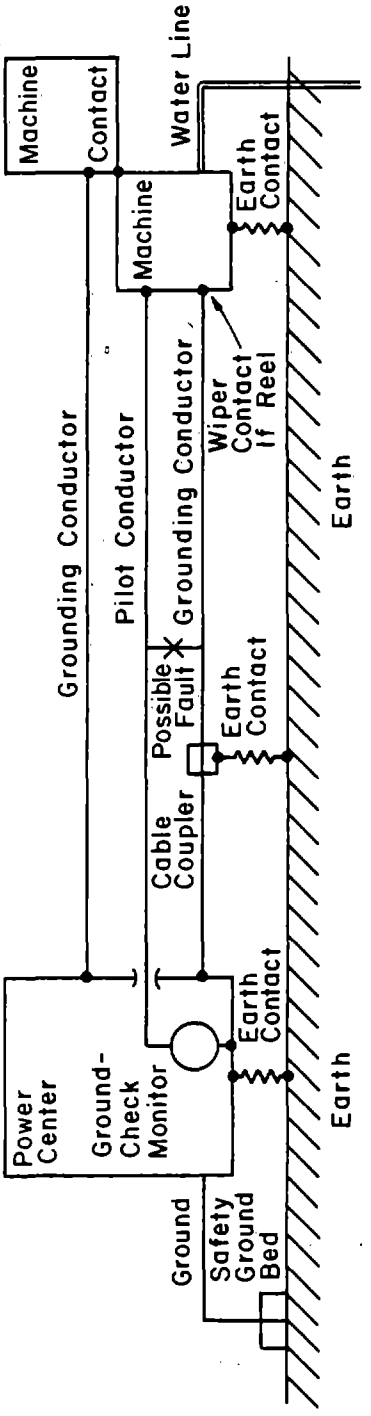


Figure 8.56. Some Difficulties with Ground-Check Monitoring in Mining.

induced in the grounding conductors, at times of significant magnitude, not only on underground loads but especially on surface excavating machinery. Another problem is in trailing-cable deterioration; say in a splice, there is a chance the ground-check conductor could short to the grounding conductors. Among the additional conditions that can be present, are power-system transients, occurring from lightning or switching surges, and wiper contacts on reeled units. All of these situations can affect ground-check monitors.

Accordingly, MSHA has several guidelines for low- and medium-voltage monitors which must be passed before they are approved. In these, two monitors are recognized: a continuity type and resistance type. A continuity-type monitor is one that meets the requirements of the Title 30, Code of Federal Regulations, Paragraph 75.902 (e.g., the series-loop technique). The resistance-type monitor is a unit that detects an increase of grounding-conductor resistance (e.g., the bridge). The requirements for both are as follows (16,18,19).

1. The monitor must be "fail-safe;" in other words, the failure of any component, other than the relay contacts, must make the trip-circuit contacts reset. (The relay must pick up its contacts when in normal operation.)
2. The monitor must not trip when:
   a. input voltage is varied by + 15% - 20%, or
   b. 5.0 V minimum to 25 V maximum, 60 Hz, or 10 A d-c is introduced in the grounding circuit.

   These conditions can substantiate that the unit stays operational, even when under the influence of power-line fluctuations, stray currents, or induced currents.
3. The open-circuit monitor voltage cannot exceed 40 V rms.
4. In terms of detecting grounding-conductor continuity,
   a. continuity monitors must trip the circuit breaker if the grounding conductor is broken at any point regardless of low-resistance parallel paths (75 Ω is considered an open connection), and
   b. resistance monitors must trip the circuit breaker if the impedance of the grounding circuit, external to the grounding resistor, increases to cause a 40-V drop under fault conditions (or, by Ohm's law, 1.6 Ω for 25-A limit).
5. Filters cannot cause a personnel hazard during normal operation or when the grounding conductor is opened.
6. The maximum time delay for contact reset, after an inadequate ground is detected, cannot exceed 250 ms.
7. When two or more monitors are operated in parallel

no interference must occur to cause incorrect tripping.

At this writing, similar guidelines for high-voltage ground-check monitors have yet to be established. However, by Title 30, Code of Federal Regulations, Parts 75 and 77, the maximum open-circuit monitor voltage is established at 96 V rms. Furthermore, continuity monitors must adhere to item 4a above, with resistance monitors conceivably tripping if the grounding circuit impedance causes a 100-V drop.

Advantages and Disadvantages

As mentioned, each basic ground-check has inherent advantages and disadvantages. A listing of these is rather informative (16,17,18).

Series Loop. Other than simplicity, the advantages of series-loop circuits are minimal. Designs using a d-c source are immune to stray a-c but not d-c. Further, a-c monitoring can be subject to nuisance tripping by stray d-c offsetting the signal current. However, when the relay operating coil is isolated by a blocking capacitor, an immunity to stray d-c is gained. In any case, the relay coil must have a very low impedance to be sensitive to grounding-conductor impedance. Two disadvantages of the circuit are substantial; parallel paths and grounded pilot conductors easily negate its operation.

Transmitter Loop. The advantages and disadvantages of this technique are basically the same as for series loop, except the circuit can detect pilot-to-ground shorts.

Bridge Monitors. Simple bridge monitors have the same problems as series-loop models, but they are very sensitive to changes in grounding-conductor and pilot-conductor impedance. The more elaborate designs can be made immune to a-c and d-c stray currents, yet even these often cannot distinguish between a sound grounding conductor and an illegal parallel path.

Pilotless. In general, these monitors are superior to pilot designs, except they are obviously the most expensive. Because the ground-check conductor is not needed, all associated problems are removed. The most elaborate models can distinguish parallel paths and are immune to stray currents; however, the simple designs are vulnerable to both.

Pilot Circuit and Interlocking. Pilot-conductor ground-check monitors also can serve the very important function of safety interlocking. This feature is required on many portions of the mine power system and used on almost all high-voltage systems. An example of the purpose is shown in Figure 8.59. The loop circuit, which the monitor senses, not only includes the pilot and grounding conductors, but also can involve a

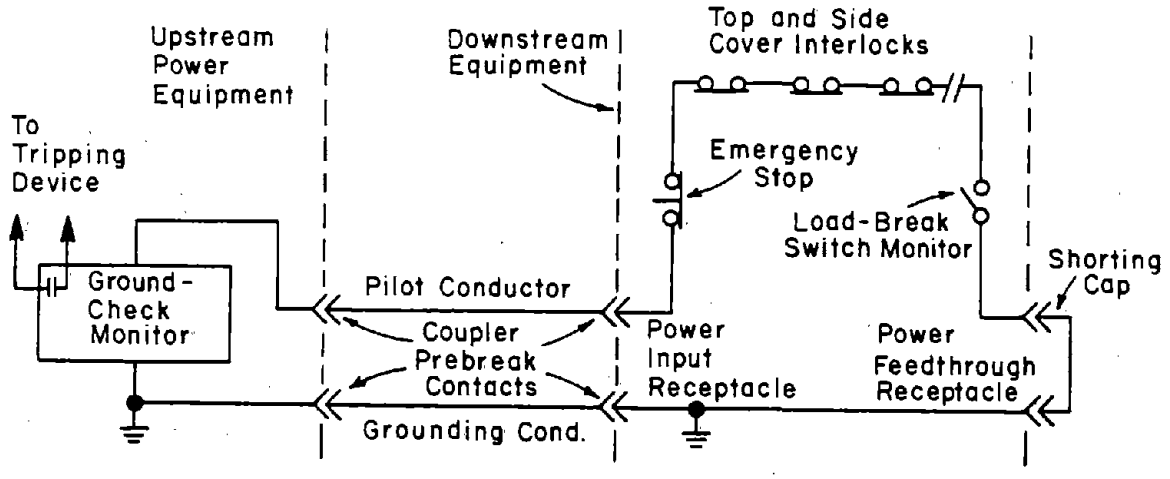


Figure 8.59. A Pilot-Interlocking Circuit Using a Ground-Check Monitor.

series of contacts and switches. Whenever one of these is opened, the continuity of the ground-check circuit breaker trips the power to that section. Included in the interlocks are top and side cover switches (open if cover is removed), the prebreak contacts on couplers, and pilot-break monitors on disconnect switches, to name a few.

When such interlocking is required, it is practically without exception that pilot-type monitors must be used. For instance, pilotless models cannot be employed when in-line couplers are on the circuit. However, a receptacle-coupler combination forms part of the monitored circuit on almost all equipment that uses low or medium voltage. Pilotless models must be wired into the ground-check and ground contacts of the coupler so that they trip the cirucit breaker prior to coupler removal.

8.6 Arrangements for Mining

8.6-1 Zones of Protection

There are two groups of protective-relaying equipment within a power system: primary and back-up. "Primary relaying" has the goal of clearing all faults and overloads. The general principle is to isolate offending power-system segments with minimum interruption to the system balance. The objective of "back-up relaying" is to operate only in the event of a primary relaying failure; its action is only for uncleared faults. In mining, be it phase or ground relaying, both groups are used extensively if not redundantly.

Protection to the entire system is mainly related to primary relaying and is accomplished by establishing "zones of protection." Each zone is associated with a circuit breaker, fusible disconnect, or fuses with the required sensing devices, and adjacent zones overlap (7). If a failure occurs within a zone, only the switching apparatus within that zone should open. If there is no overlap, a failure within the unprotected region would produce no tripping. The result could be broad outages to the system, rather than "sectionalizing" a specific zone or, at worst, two zones. The "coordination" of the protective relaying between zones is, therefore, extremely important. The intent is to isolate faults "downstream" from the power source without disturbing "upstream" zones. Unfortunately, obtaining coordination is perhaps the most outstanding problem of relaying.

By introducing the general arrangements of protective relaying in resistance-grounded mine power systems, this section actually serves as a transition between the basic relaying principles and Chapter 9. The objective is to show how primary and back-up relaying, zones of protection, and coordination are utilized in both surface and underground mines.

8.6-2 General Considerations

At all levels of the mine power system, protection against short-circuits, overloads, and ground faults holds priority. Because the majority of failures in mining involve line-to-neutral faults, ground-fault protection requires special interest, but does not negate the need to establish adequate phase relaying.

Coordination. The objective of coordination is to determine the optimum characteristics, ratings, and settings of the protective-relaying devices (6). Consequently, fault analysis of the system must be involved. However, the two common coordination schemes that are utilized are pickup setting and time. With the first, relay pickup settings for a specific actuating quantity are set progressively higher from the loads to the power source, such that a higher level is required to trip the circuit breaker in an upstream zone. For time coordination, pickup settings throughout the system, again for a specific kind of protection, may be generally the same, but the operating time to contact closure (at or above pickup) is set progressively higher towards the source. One technique or the other may be applied to coordinate between zones in the mine power system yet, at times, a combination might be needed. This can be a substantial problem, as exemplified by the fact that many engineers consider protective relaying more an "art" than a science.

Ground-Fault Protection. Except for capacitive ground current (see Chapter 10), ground-fault-current magnitudes are limited by grounding resistors. Recalling the material in Chapter 6, the maximum current is 25 A at low- and medium-voltage levels, but the level is seldomly limited below 15 A; whereas, it is very rare that a 50-A limit is exceeded on high-voltage grounds, with 25 A seen on many systems. Thus, ground-fault current is likely nearly constant throughout the system. Adding to this continuity is the use of delta-wye, delta-delta, or wye-delta transformers. At each transformation step, a new or separately-derived ground system is produced, each with its own ground resistor. Because the transformer configuration blocks zero-sequence components, a secondary ground fault raises primary current, but the vectorial sum of the phase current is zero (1).

From these thoughts, coordination of ground-fault relaying across transformers is unnecessary, and both primary and back-up protection must be established for each derived ground system. Selective coordination at each voltage level by pickup setting alone is typically impossible, and time settings must be relied upon when multistage protection is used (1).

It must be remembered that resistance grounding is not employed to preserve power to a fault, but used to reduce fault energy, frame potentials, or system potentials. If the first ground fault is not cleared, an alternate ground fault in another machine will be not only in a ground condition but also not limited by the grounding resistor (1). The result is dangerous frame potentials and powerful intermachine arcing. Consequently, ground-fault relays must always be arranged to trip circuit breakers. Fuses cannot be used.

Phase Overcurrents. The occurrence of a phase-to-phase or three-phase fault anywhere in the system, if not cleared downstream, can cause substantial outages. Not being restricted like ground faults, the anomalous positive- and negative-sequence currents can be passed across transformers to higher levels of the system. The resulting wide-range problems are especially evident on radial distribution. Coordination here is usually by pickup, using instantaneous relays, and the effort could involve fault currents from the machines to the substation. However, a maximum setting within a zone would be the minimum fault current at which thermal or mechanical damage to a protected device could occur.

The problems resulting from inadequate overload protection are as widespread. In most cases, this protection must be applied to the certain zone that the fuse or circuit breaker is protecting. For example, the pickup setting of a time-delay relay could be determined by the ampacity rating of the smallest conductor within the zone of the switching apparatus, whereas time settings might be employed to coordinate between zones. Overload protection can be critical in large mines

with numerous sections; when several machines are operating simultaneously, the designed maximum current demand for an upstream conductor could become overloaded.

8.6-3 Surface Mines

To illustrate the foregoing thoughts, consider Figure 8.60, a one-line diagram (including grounding) of a simple surface mine power system (1). The diagram is drawn to show the various combinations of protective-circuitry that can be found. Each protective device is installed to trip the closest circuit breaker, "52."

In terms of ground overcurrent for the low-voltage machines, zero-sequence relaying (50G, usually instantaneous) establishes primary protection. Back-up protection could be afforded here by adding timed direct relaying (51N) about the grounding conductor of the grounding resistor. For high voltage, remembering that the transformer configuration blocks zero-sequence current, ground-overcurrent primary protection is again provided by zero-sequence relaying (50G, instantaneous or minimum time-dial setting), establishing a zone of protection for each outgoing circuit (the excavator, loader, and a-c power center). The time-delay zero-sequence relay (51G) in the substation can be considered to give both back-up protection for the downstream 50G relaying, as well as primary ground-fault protection for the zone between its location and the switchhouse. In any event, back-up protection is the principal duty of the 51N direct relaying about the neutral conductor of the substation. (N is used to signify neutral relaying but G can be used.) All this relaying is normally coordinated by time setting, the pickup setting being specified as a percentage (say 50%) of the ground-current limit.

The use of the grounding-conductor direct relaying, shown in Figure 8.60, is restricted to situations where a main circuit breaker, that it trips, sees total ground current. In the a-c power center, this means that the back-up relaying must cause tripping of both circuit breakers. Because here there is no "main" breaker, some states require potential relaying of the grounding resistor as back-up. Potential relaying does afford more safety than direct relaying, as previously mentioned.

Ground-check monitoring is illustrated in Figure 8.60 in its most extensive form for surface mining, where every grounding conductor in the system is measured. Ground-check conductors are shown connected to each monitor, and these are not needed in instances where pilotless devices are applied. In cases where conductors from the substation form an overhead ring bus, such as in some open-pit operations, ground-check monitors are often not used because of the circular nature of the distribution. In any overhead distribution arrangement, monitors

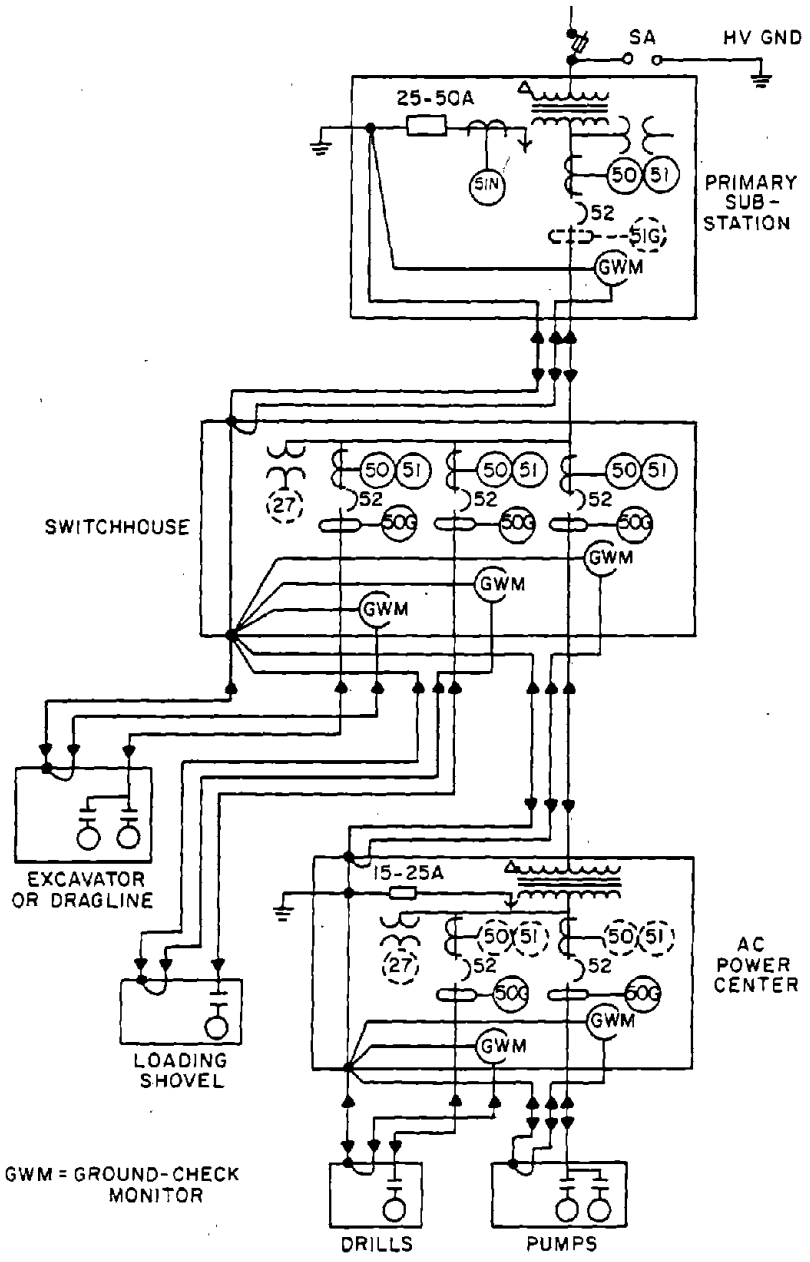


Figure 8.60. A Simple Surface Mine Power System Illustrating Protective Relaying.

are susceptible to extensive failures due to lightning strokes.

Phase overload and short-circuit protection in the distribution portion is provided by phase current transformers connected (usually) in wye to time-delay relays, normally induction-disk types with both instantaneous (device 50) and time-delay (51) elements. Each 50/51 combination establishes a zone of protection downstream from its location. As shown, the same kinds of protection can be afforded at utilization with low-voltage power circuit breakers in conjunction with external current transformers and relays. Normally, this location (the device numbers have dashed circles) is protected by molded-case units. (Note: all 50/51 phase protection could also be by fuses or fusible disconnects, but circuit breakers or power-driven load-break switches are needed for ground-fault protection.)

Figure 8.61 shows a three-line diagram of a typical molded-case arrangement. These components are in place of the 50, 51, 50G and 27 devices associated with each low-voltage breaker in Figure 8.60. The molded-case circuit breaker provides short-circuit protection with its magnetic trip units (not shown) with overload tripping given by the internal thermal elements. (Overload protection may not be required on low- and medium-voltage circuits; see Chapter 9 for discussion.) External protective circuitry is commonly a zero-sequence relay and pilot-type ground-check monitor, the contacts of both tripping the undervoltage release. Notice that here the ground-fault relay shunts the trip coil, while the ground-trip relay is in series with it. The UVR itself gives undervoltage protection. Thus, all necessary kinds of protection are available for the resistance-grounded trailing-cable installation.

An undervoltage relay (device 27) is also shown in the switchhouse of Figure 8.60. Again, it is not needed at this (or any) location as long as all equipment downstream have undervoltage protection.

8.6-4 Underground Mines

Alternating Current. For comparison, Figure 8.62 illustrates a simple one-line diagram of an underground-mine power system. The a-c portion is very similar to Figure 8.60, with the reasoning and arguments behind the protective devices being the same. Differences, however, are in the disconnect switch, relaying in the substation, and possible extra outgoing circuits from the substation; all these are also possible in surface mines.

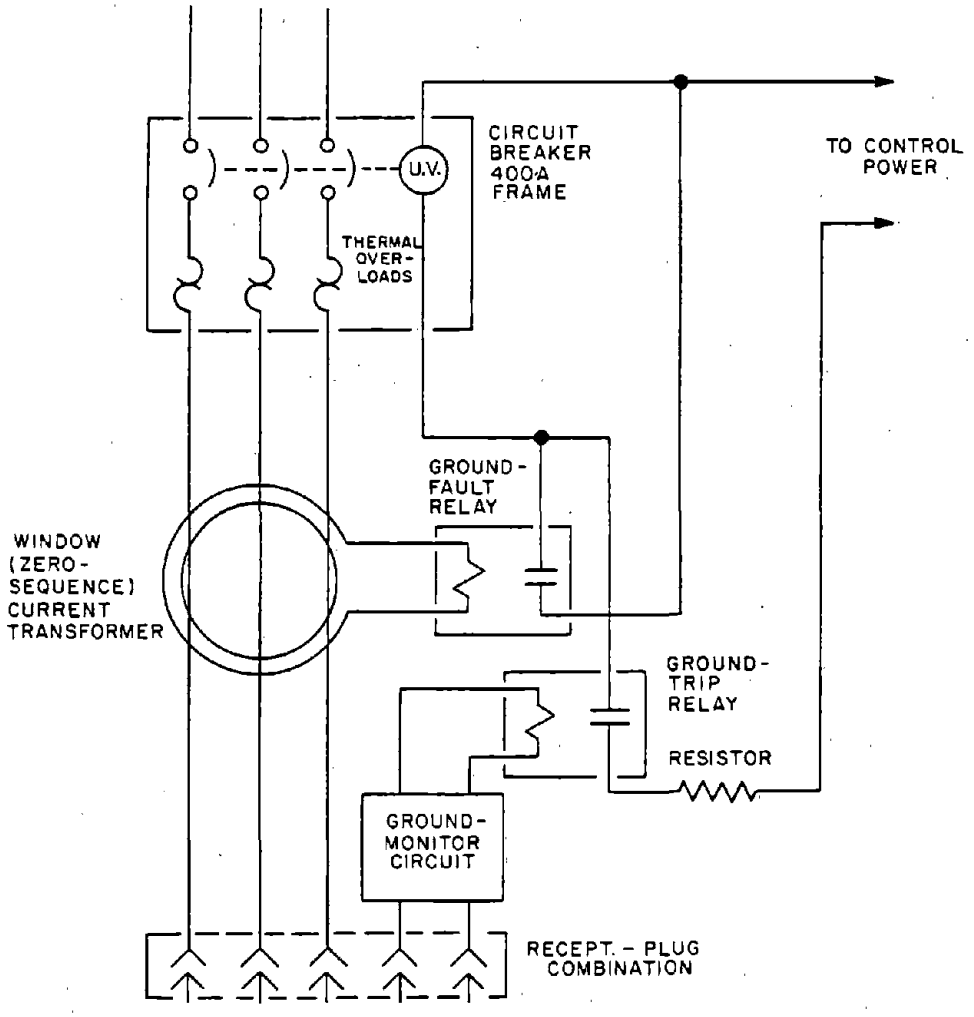


Figure 8.61. A Typical Three-Line Molded-Case Schematic with Ground-Overcurrent and Ground-Check Protection.

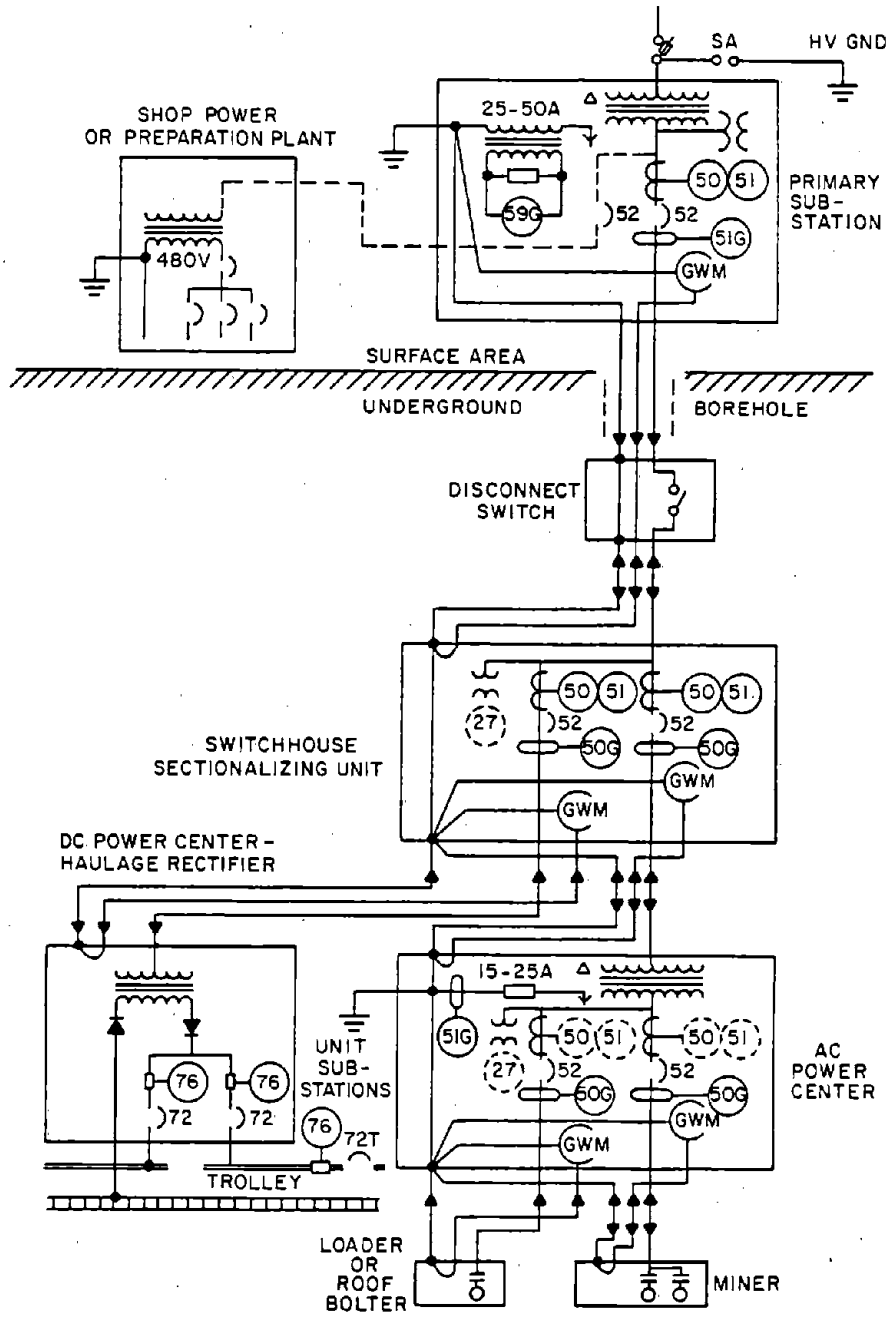


Figure 8.62. An One-Line Diagram of a Simple Underground Mine Power System Illustrating Protective Circuitry.

As stated in Chapter 2, some means of visible disconnect is required within 500 feet of the point power enters the underground workings. A separate switch is shown in the diagram for this purpose. Actually, it is advisable, if not required, to place visible disconnect switches on incoming high-voltage (distribution) circuits within all power equipment (these have not been included in Figures 8.59 and 8.61 for clarity). Consequently, it is not uncommon to find the first disconnect in the mine as part of a switchhouse.

Ground-fault back-up relaying located in this substation is mainly by the potential technique. Here, the relay operating coil is placed directly across the resistor and, in addition to relaying, the transformer is used for resistor impedance matching for current limit. Although not shown, the outgoing circuit to the surface equipment has basically the same relaying as for underground (see Chapter 11 for the implications of such loads).

Direct Current. Only one form of relaying for d-c equipment is provided in Figure 8.63, overcurrent for rail-haulage systems, consisting of a d-c overcurrent relay (device 76) driven by the voltage drop across an in-line shunt. For off-track d-c machinery, the protective-relaying arrangement is directly tied to the power source. Here, five basic systems of d-c ground-fault protection are presently being used in the U.S.:

1. diode grounding,
2. basic grounding conductor,
3. relayed grounding conductor,
4. neutral shift, and
5. differential current.

The grounding philosophy for all but the last has been introduced in Chapter 6. The neutral-shift and differential-current systems can be used only when the machine is powered from the output of a rectifier, such as contained in a section power center whereas the first three systems are more commonly employed when a trolley system is the d-c source.

When d-c equipment is powered from the trolley system, short-circuit and overcurrent protection is normally provided by a dual-element fuse. The device is mounted in a holder or "nip," which is clipped to the trolley wire. The other trailing-cable power conductor is connected to the rail. Fuses are rarely applied to trailing-cable protection in load-center rectifiers. Here, air-magnetic power breakers, molded-case devices, or d-c contactors (see Chapter 11) are employed, the former being preferred. In practice, these are usually tripped only for short-circuit conditions, with overload protection not used.

Diode Grounded. The diode-grounded system is often found with d-c vehicles that employ cable reels. This permits using a two-conductor cable, which is less expensive and uses less space on the cable spool than Type-G cables. A simplified diagram of the system is shown in Figure 8.63. The machine frame is tied to the grounded (negative) conductor by means of the grounding diode (D_1). The grounded conductor is connected to the power-center frame or trolley-system rail, depending on the power source. The series with the diode lead is a ground-fault device, G, a mercury-magnetic switch or the operating coil of an electromagnetic-attraction relay. The pickup setting of this device can be no greater than 25% of the forward-current rating of the diode.

If a positive-conductor to machine-frame fault occurs (location 2 of Figure 8.63), current flows through the grounding diode and the ground-fault relay. When the fault current exceeds the pickup setting of the relay, the fault is then isolated by de-energizing the M_1 contactor with opening of the G contacts. Actually, this sequence of events only occurs if the fault exists between the load side of the M_1 contacts and the motor. This leads to some of the basic drawbacks of the diode-grounded system, as location 2 is the only "safe" area for a ground fault to occur.

Location 1 of Figure 8.63 includes the length of ungrounded conductor from its entrance point on the machine to the main contacts of the M_1 contactor. Since these machines normally utilize cable reels, slip-ring assemblies are required for connecting the incoming power conductors to the machine circuit. Thus, it is difficult to locate a circuit-interrupting device at the immediate cable entrance of the machine. If a fault occurs at location 1, the fault current will flow through the machine frame, causing diode D_1 to become forward biased,

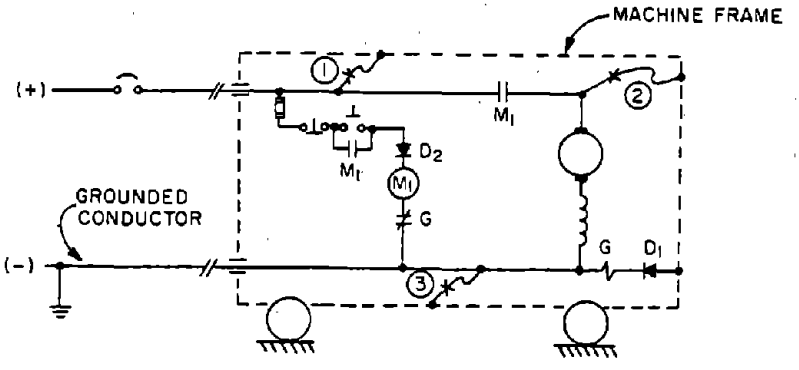


Figure 8.63. Diode-Grounded System with Possible Fault Indicated.

and current then passes through the ground-fault relay. When the relay operates, the M_1 contactor resets, and the motor circuit is de-energized. However, this does not result in isolating the fault. Isolation is solely dependent upon the opening of the M_1 interrupting device, and the fault is located on the line side of its contacts. In this case, fault current can only be terminated by the switching apparatus on the source side of the trailing cable (dual-element fuses for a trolley nip or fuses or a circuit breaker for a power center).

Location 3 of Figure 8.63 covers the entire length of the grounded conductor within the machine. A fault here renders the diode-grounded system unreliable, since it effectively provides a parallel path from the frame to the grounded conductor. The purpose of diode D_1 is to block the voltage drop across the grounded conductor from the machine frame. Therefore, if D_1 is bypassed, the frame potential is raised. A fault at location 3 can easily go undetected. As a result, a simultaneous fault at any location of the ungrounded circuit must again rely on isolation on the source side of the trailing cable.

Failure of the grounding diode is a common problem associated with the diode-grounded system. With D_1 in shorted mode, the situation is the same as for a location-3 fault. However, when the grounding diode fails in an open mode, all ground-fault protection is lost. Faults occurring in location 1 or 2 can cause the frame to become raised to a value equal to the supply voltage.

The D_2 diode is referred to as the "polarizing diode." Its purpose is to protect against having the positive and negative conductors switched. This situation can occur while installing a new trailing cable or while making a cable splice. Thus, if the polarity of the supply voltage is inadvertently reversed, the polarizing diode will block the current flow, and the motor circuit cannot be energized. However, if D_2 fails in the shorted mode and the d-c circuit is under reversed conditions, the diode-grounded system would be rendered totally inoperative, but the machine would still operate.

Grounding Conductor. Other methods of grounding d-c machines require the use of a separate grounding conductor and Type-G cable. Of these, the basic grounding-conductor system (Figure 8.64) and the relayed grounding-conductor system (Figure 8.65) are the simplest. (Again, these are commonly used when the source is a trolley system.) With the first, a ground fault is detected only by the overload protection on the source side of the trailing cable, and the result is extremely poor sensitivity with respect to ground faults. The ground-fault sensitivity can be improved by adding a ground-fault relay in series with the grounding conductor, as shown in Figure 8.65. However, the current flowing through the relay may not be the total ground-fault current, since a parallel path may be established through the earth.

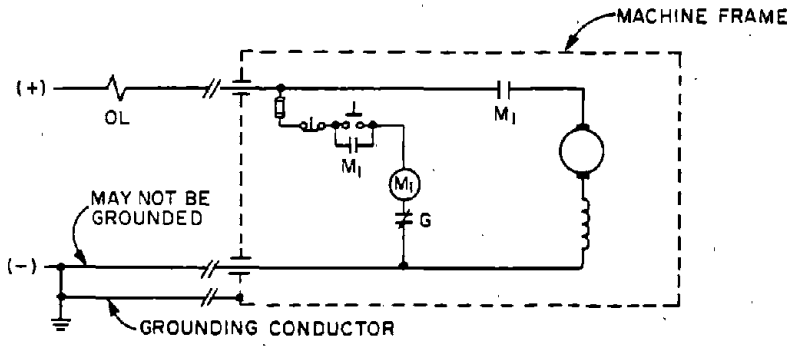


Figure 8.64. Basic Grounding-Conductor System.

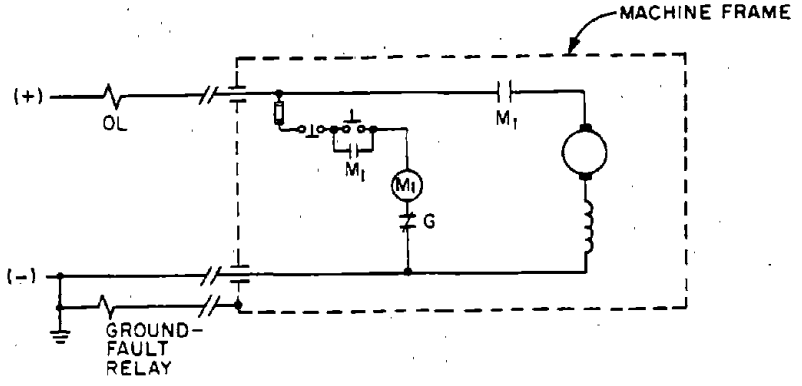


Figure 8.65. Relayed Grounding-Conductor System.

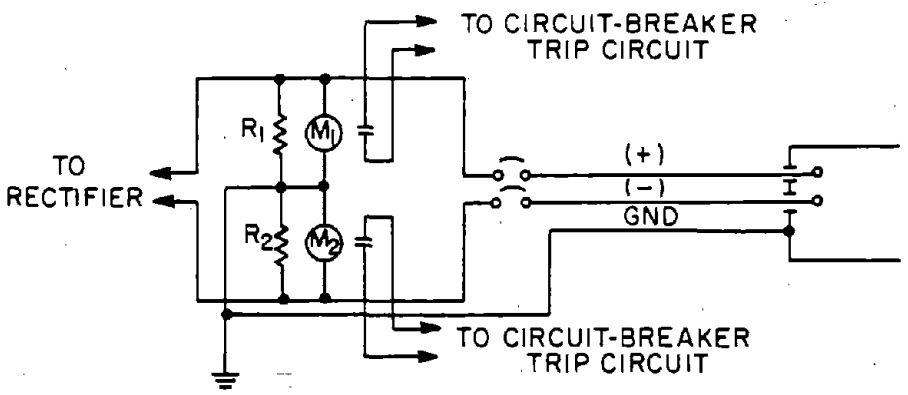


Figure 8.66. Neutral-Shift System.

Neutral-Shift System. The neutral-shift system is illustrated in Figure 8.66. The resistors R_1 and R_2 create a d-c neutral point for the system as well as limiting the ground-fault current. A ground fault on either the positive or negative conductor will cause the neutral point to shift, which results in detection by the voltage-sensitive relays M_1 and M_2. (The relays are usually given the device number 64, a potential relay, also termed a "d-c unbalance" relay.) The primary limitation of this system is that it cannot discriminate ground faults for individual pieces of equipment fed by the same rectifier. If a ground fault occurs on one machine, all circuits are interrupted.

Differential Current. As shown in Figures 8.67 and 8.68, differential-current d-c ground-fault protection utilizes the neutral of the wye-connected secondary feeding the rectifier. With a delta-connected secondary, a neutral connection can be provided through a grounding transformer. A grounding resistor is inserted in the neutral circuit to limit d-c ground-fault current typically to 15 A. (Actually, this results in an additional method of grounding d-c off-track equipment to that presented in Chapter 6.) Ground-faults are then detected using either a saturable-reactor or saturable-transformer system.

With the saturable-reactor system (Figure 8.67), a voltage-sensitive a-c relay is placed in series with the winding of a reactor, which encircles the positive and negative outgoing conductors. The relay and reactor are excited by a 60-Hz control voltage. Under normal conditions, the current through the positive conductor equals that through the negative conductor,

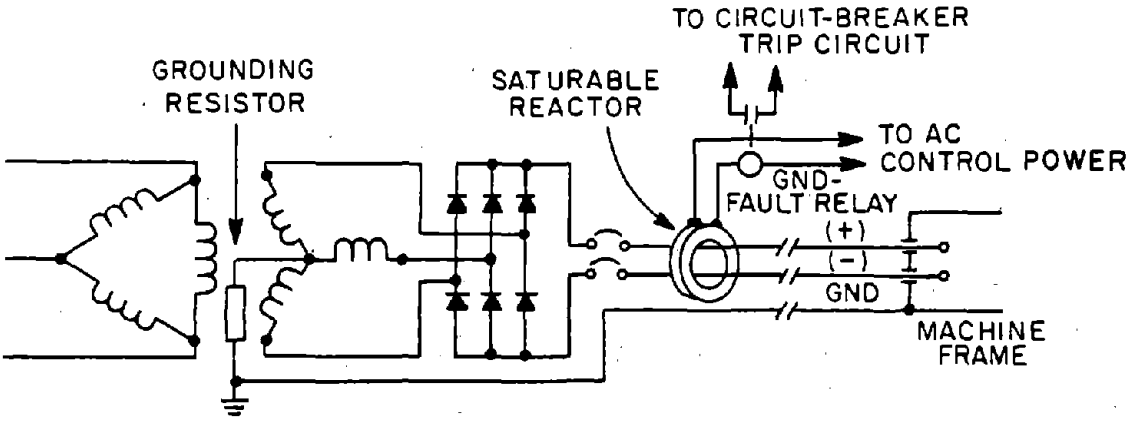


Figure 8.67. Current-Balance Direct-Current Ground-Fault Relaying Using a Saturable Reactor.

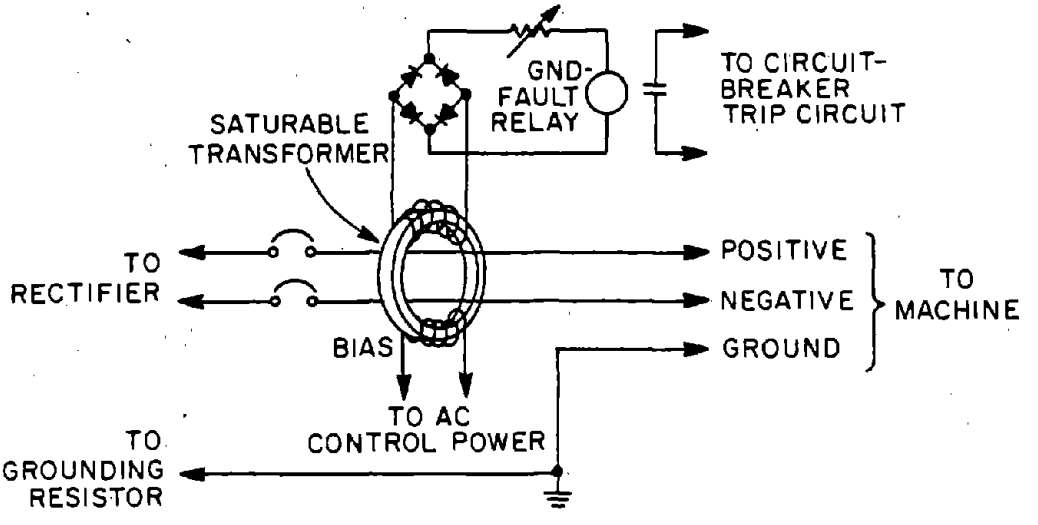


Figure 8.68. Current-Balance Direct-Current Ground-Fault Relaying Using a Saturable Transformer.

and the magnetic fields about both conductors tend to cancel each other. Thus, the reactor winding exhibits maximum impedance and prohibits the ground-fault relay from operating. However when a ground fault occurs, the currents in the positive and negative conductors become unequal in magnitude, as current is flowing in the grounding conductor. The magnetic fields about each power conductor are no longer equal, and the resultant magnetic field causes the reactor core to saturate. This in turn reduces the impedance of its winding, causing the a-c control voltage to be impressed across the relay. Typical relay pickup is from 4 to 6 A of ground-fault current.

The saturable-transformer system (Figure 8.68) operates on the same concept. Here, the a-c control voltage excites the primary ("bias") of a two-winding torodial transformer. The transformer secondary is connected to a rectifier bridge that has its output feeding an adjustable resistor in series with a d-c relay. Although the relay could be a voltage-sensitive electromechanical device, solid-state relays are normally used (see Chapter 12). The relay has N.O. contacts when de-energized. Under normal operation, a-c is induced in the transformer secondary, and the rectified d-c causes the relay to pick up its contacts. During a ground-fault, the core again saturates, but in this case the saturation stops transformer action. In turn, the d-c is removed from the relay, and it resets its contacts to cause circuit-breaker tripping. The resistor enables adjustment of the pickup setting.

In addition to providing sensitive relaying for d-c ground faults, another advantage is available as either technique only senses d-c unbalance in the conductors passing through the core. By using a detection system for each outgoing d-c circuit, each relay system is only sensitive to ground faults existing downstream from its reactor or transformer. Thus, selective d-c ground-fault relaying can be realized, an advantage not available with the neutral-shift system.

8.7 Summary

The foregoing material has served to introduce the complexities of protective equipment and relaying. The discussion has culminated with Figures 8.60 and 8.62, where it is shown that protective relaying in a mine power system can be mainly divided into the various power equipment used. The application of this circuitry is the subject of Chapter 11, and some variations of these basics will be detailed there. A careful study of the overall mine power system is needed to properly coordinate the various protective devices, and Chapter 9 provides the necessary tools.

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Chapter 9

PROTECTIVE-DEVICE SIZING

9.1 Important Parameters

In Chapter 8, it has been shown that circuit breakers, fuses, and switches are rated in terms of the nominal circuit voltage, the continuous currents they may carry, the short-circuit currents they may interrupt, and the fault-through currents they must withstand. Furthermore, in order that interrupting devices promptly and correctly operate to disconnect faulted equipment, it is necessary to have a protective system that recognizes the presence of a fault, determines what is faulted, and supplies energy to the mechanisms which will terminate current flow. Consequently, the maximum fault currents in the mine power system must be calculated and, in many cases, the minimum sustained overcurrent values are needed to check the sensitivity requirements of the current-responsive protection devices (1). In multistage time-delay devices, the operating time of each device as well as the time difference between devices must be known. All these parameters are mandatory in the selection, installation, and coordination of protective equipment and relaying.

9.2 Fault Current

The fault current at any point in the mine complex is limited by the impedance of circuits and equipment from the source or sources to the fault point, and the level is not directly related to the load on the system (1). When a mine is in development, system additions are often made to increase the capacity to handle the growing load. These changes most often will not change the normal load on pre-existing system portions, but may substantially increase fault current during three-phase and phase-to-phase faults. Yet ground-fault currents, except for some special cases, remain relatively constant in resistance-grounded applications. Whatever the situation, the available fault currents must be determined to ensure adequate protective-device operation.

9.2-1 Fault-Current Sources

To properly apply fault calculations, all sources of fault current should be known. The main sources in mining are electrical utility systems, synchronous motors, induction machines, and capacitors (and capacitance). Synchronous generators are also a significant source, but these are only a concern if the mine generates its own power. Of the others, because of negligible

contribution to fault current, some can be eliminated, with caution, depending upon the installation.

Utility Systems. In most mine systems, the generators of the electric utility system are the principal source of short-circuit current. Because these generators are often remote from the mine, the current resulting from the fault within the mining operation usually appears as just a small increase in their load current, and the contribution remains rather constant (1,2). For these situations, the electric utility can be represented at the mine as a single-value equivalent impedance referred to the point of connection. Even in proximate locations such as mine-mouth electric plants, this approximation usually gives adequate calculation results.

Synchronous Motors. Synchronous motors can be a substantial contributor to fault current, but because the prime coal-mining application is in M-G sets for excavators, they are a concern mainly to surface mines. The current supplied to a fault can be described as follows (1,2). After the occurrence of a fault, system voltage tends to decrease. The motor receives less power to rotate its load and simultaneously the inertia of the motor and load, as the "prime mover," causes the motor to act as a generator. The motor thus supplies fault current, which diminishes as motor field excitation and kinetic energy decay.

Induction Machines. Induction motors can also contribute fault current to the system by inertia driving the machine as a generator (1,2). In this case, however, the presence of field flux in the rotor is produced by induction from the stator; this decays rapidly with motor terminal voltage, disappearing completely after a few cycles. Accordingly, the effect of induction machines, except for large horsepower ratings, can sometimes be neglected but should always be considered.

Capacitance. Because of the widespread use of shielded cables, power-factor-correction capacitors, and surge capacitors, this parameter is found in great abundance in mine power systems. Although power-frequency fault currents come from rotating machinery (including the utility) and commonly result in the most destruction to equipment, capacitance can produce very high transitory overvoltages and fault currents (2). However, these are usually of short duration and of a natural frequency much higher than the power frequency. The result can be insulation damage, and this subject will be discussed in Chapter 10.

Stored charge of the capacitance acts as the prime mover. Because the fault-current contribution is of such short time (less than one cycle), it can often be neglected in terms of phase current (2). The main worry in fault conditions is more in the area of ground overcurrent during phase-to-neutral faults. For instance, most high-voltage resistance-grounded distribution systems have a 50-A ground-current limit or less. If the system voltage is 12.47 kV, vacuum circuit breakers are used in practically every switchhouse, and common practice is to have at least one set of surge capacitors associated with each interrupter (see Chapter 10 for the reasons). Yet, the standard 0.25-μF surge capacitor, at this voltage level, adds about 5-A capacitive ground-charging current, directly translating to ground-fault current during a line-to-neutral mishap. Adding to the current is the charging of high-voltage feeder cables, typically 0.2 A per 1000 ft. With just 10 capacitor banks on the distribution system, corresponding to a moderate-size mine, a 50-A limit is exceeded. If a phase-to-neutral fault occurs, the capacitance could discharge, feeding the fault with capacitive current in excess of ground-current limit. As this could happen within the distribution circuitry, there is a possibility that the grounding resistor would not see it. Because the duration could be less than one cycle, the protective circuitry might not react.

9.2-2 Fault Calculations.

Fault Types. Many times in the foregoing material, the basic fault types, three-phase, phase-to-phase, and phase-to-neutral, have been mentioned. Each affects system voltages and currents differently, the first of these being symmetrical while the other two are asymmetrical or unbalanced. In Chapter 4 it has been shown how the method of symmetrical components could be used to solve asymmetrical three-phase problems. Symmetrical situations, of which the balanced three-phase fault is one, are no more difficult in solution than single-phase work.

In specifying equipment or checking protective-circuitry performance, there are certain simplifying assumptions that are normally made to determine fault current. An important one for finding phase currents is that the fault is three-phase, because this type generally causes the maximum short-circuit current to flow (as opposed to asymmetrical types). Perhaps the only exception is on utility systems, where a line-to-neutral fault can cause current up to 125% of a three-phase fault (1). Of course, such fault currents are normally substantially limited in mining. Regardless, the significance of assuming a three-phase fault is that symmetrical-component methods are not needed in the solution. (This is true for most routine calculations, but detailed fault investigations sometimes require looking at asymmetrical problems.)

Because most mine power systems are radial (even in secondary-selective distribution, they are operated radially), calculating a three-phase fault is a rather simple task. Basically, all that is required is Ohm's law and an equivalent circuit. Even during a phase-to-phase fault, positive- and negative-sequence impedances are essentially equal, and a good estimation can thus be made by applying a fixed fraction of the three-phase case (3). This value has been found to be about 0.87 (1).

Second, the fault is customarily assumed to be bolted; that is, it has zero impedance (1,2). Such not only simplifies calculations, but also applies a safety factor since the results are a maximum and equipment is rarely stressed beyond its full rating. For instance, analytical studies on low-voltage systems have shown that minimum arcing-fault currents, expressed as a factor of bolted faults, are typically (1):

1. 0.89 at 480 V for three-phase arcing faults, and
2. 0.74 at 480 V for phase-to-phase arcing faults.

As the voltage level is increased, the arcing current level approaches, but it is always less than, the bolted case.

Source Equivalent Circuit. The representation of equivalent circuits is the principal difficulty in the calculation of fault currents. An equivalent circuit for the most important source (typically), the utility system connection, has already been presented. Rotating machinery are also a concern, and the fault current contributed by each machine is limited by the machine impedance, which is unfortunately a rather complex and time-dependent variable. However, to simplify calculations, a constant driving voltage in series with a variable reactance is again assumed.

The reactance has three specific values to establish the fault current delivered at three points in time (1):

1. X''_d, the subtransient reactance, for current during the first cycle after the fault occurrence;
2. X'_d, the transient reactance, for current after several cycles at 60 Hz; and
3. X_d, the synchronous reactance, which determines current flow for the steady-state region.

Subtransient reactance is assumed to last about 0.1 s. Then the machine impedance increases to the transient-reactance value; after 0.2 to 0.5 s, the value again increases to the synchronous reactance. With each increase, current contribution decreases.

Depending on the maintenance of field excitation, synchronous motors could use all three values, but X_d and sometimes X'_d are not needed in mining applications (the values approach infinity). Because of rapid current decay, X''_d is the only value used for induction motors. In other words, the motors do not

contribute significant fault current beyond the first cycle after the fault. Table 9.1 lists some typical motor reactances, given in per unit based on the machine kVA rating (1). Nevertheless, following the previous statement and considering the type of rotating machinery, calculations on underground-mining systems can sometimes ignore motor contribution. However, surface mines and surface facilities (especially when thermal dryers are involved) generally cannot.

Calculations. IEEE Standards 141-1976 and 242-1975 detail extensive fault-calculation recommendations, most of which are directly adaptable to mine power systems (1,2). A summary of these follows; after which an example will be discussed. In both, specifics about sizing high-voltage switchgear will be presented; however, low- and medium-voltage applications also apply.

Again, by assuming a bolted three-phase fault condition, the power-system parameters remain symmetrical, regardless of the neutral conditions or even delta-wye connections. The balance is especially close in resistance-grounded systems as line-to-neutral loads are not allowed. Therefore, the balanced fault current can be calculated from a single-phase equivalent circuit, which has only per-phase impedance and phase-to-neutral voltage. All major impedance elements should be included: the utility, transformers, conductors, cables, and rotating machines. The procedure is to find the Thévenin's equivalent impedance of the system (Z) then solve for fault current. Ohm's law is the basic relationship used, or:

$$I = \frac{V}{Z} \qquad (9.1)$$

where,

V = the driving voltage of the circuit

Z = the impedance from the sources to the fault, including source impedances

I = the fault current.

Calculations may use real, percent, or per-unit values. As shown in Chapter 4, per-unit methods have the advantage of greatly simplifying the work when the system has different voltage levels. The "prefault voltage," the level existing just prior to the fault, is assumed to be the nominal system voltage at the fault location. With this, fault current will approach maximum and, when using the per-unit system, if the

Table 9.1. Some Typical Reactances for Induction and Synchronous Motors.

Motor Type	X''_d	X'_d
Synchronous Motors:	0.15	0.23
6 poles	0.20	0.30
8 to 14 poles	0.28	0.40
16 poles or more	0.24	0.37
Synchronous Converters:[1]		
600 Vdc output	0.20	--
250 Vdc output	0.33	--
Individual Induction Motors[1,2]	0.17	--
Groups of Induction Motors, each less than 50 hp[1,3]	0.25	--

The above values are in per-unit referenced to the motor kVA base. Approximate power bases can be determined from the motor horsepower rating:

0.8 pf motor, kVA base = hp rating;
1.0 pf motor, kVA base = 0.8 (hp rating).

[1] Transient reactance not usually needed in calculations.

[2] Induction motors generally above 600 V.

[3] Motor voltage usually 600 V and below. Subtransient reactance is increased slightly because of very rapid current decay. A lower value of X''_d would be in order for groups of larger motors.

voltage bases are equal to the system nominal voltages, the driving voltage, V, is simply equal to 1.0 pu. The resulting symmetrical fault current may be compared, realizing some constraints, with equipment ratings, capabilities, or performance characteristics which are given on a symmetrical-rms-current basis.

Because of the high mobility of mine power equipment, any specific unit, say a switchhouse, may be installed anywhere, the location controlled more by the operations than engineering personnel. It is often desirable that portable apparatus be able to withstand or interrupt the worst fault conditions. Further, equipment should have a uniformity in design (there are other underlying reasons here which are detailed in Chapter 11). Application instances would be circuit-breaker and disconnect-switch duty ratings. Consequently, repetitive fault calculations must be performed, assuming various fault locations throughout the mine system, to arrive at a worst-case fault current. The situation is usually more pressing at distribution levels than at utilization. Such intensive fault computations sometimes call for computer analysis, which will be discussed subsequently.

The first step in fault calculations is always the preparation of a good one-line diagram, showing all fault-current sources and all significant elements. All necessary impedances, both resistance and reactance, should be included, the collection of which is perhaps the principal difficulty in fault calculations. Impedances for cables and conductors can be assembled from Chapter 7. If transformer impedances are not known, the values can be estimated from the standard values given in Table 9.2 (other impedances are given in Chapter 11) (1).

In terms of system impedance, fault current has been shown to be mainly dependent upon the reactance between the sources and the fault. This holds true except for extensive use of cable, overhead lines, and buses, which is the case for mining. Regardless, if the reactance-to-resistance ratio, X/R, for the entire system from the source to the fault is greater than 5.0, negligible error is introduced by neglecting resistance. This actually provides a small safety factor; thus, it is common practice in other industrial applications.

For most cases, it is recommended that the per-unit system be used in calculation. Therefore, after the one-line diagram is complete, all parameters must be converted to per unit on a set of consistent bases. Normally, base power, kVA_b, is selected, then the current base, I_b, and impedance base, Z_b, are derived using the nominal voltage at each system level as the other base, V_b. Accordingly, the base voltages must be related

Table 9.2. Three-Phase-Transformer Impedances.

High-Voltage Rating, V	kVA Rating	Per-Unit Impedance[1]
Distribution Transformers, including Load Centers:		
2400 to 13,800	112.5 to 225	not less than 0.02
2400 to 13,800	300 to 500	not less than 0.045
2400 to 13,800	750 to 2500	0.0575
22,900	All	0.0575
34,500	All	0.0625

Liquid-Immersed Transformers, 501 to 30,000 kVA:

	Low-Side Rating, 480V	Low-Side Rating 2400V and Up
2400 to 22,900	0.0575	0.055
26,400, 34,500	0.0625	0.060
43,800	0.0675	0.065
69,000		0.070
115,000		0.075
138,000		0.080

[1] Actually a reactance, the value is normally expressed as a percentage. The per-unit values given use the transformer self-cooled kVA and voltage ratings as a base. Transformer resistance is usually well below 0.01 pu.

to the turns ratios of the interconnecting transformers. The power base may be any convenient level, but the main substation kVA is often selected. Details of the per-unit technique may be found in Chapter 4.

The next step in the calculation procedure is to reduce the system to its Thévenin equivalent by combining all impedances. The best way to visualize these calculations is through an example, which will follow shortly. The result of the reduction is a single driving voltage in series with a single impedance and the fault. Equation 9.1 can then be used to compute the per-unit fault current, which can be converted to amperes using the base-current multiplier.

This calculated fault current is an alternating symmetrical quantity, because the sources are rms voltage. It can be used to compare equipment ratings that are expressed in symmetrical rms currents. However, the fault calculations must recognize the asymmetry of typical fault currents and account for it. Fault-current waveforms have already been discussed in Chapters 4 and 8, but the typical asymmetrical type is again reproduced in Figure 9.1 for discussion convenience (1). The compensation for asymmetry considers current composed of two components:

1. the a-c symmetrical component, taken as the calculated symmetrical value, and
2. the d-c component, with its initial maximum magnitude taken as the peak of the a-c symmetrical component.

The time period in which the d-c component decays is related to the reactance-to-resistance ratio, X/R, of the system. Hence, the first cycle maximum fault current is estimated as 1.6 times the symmetrical rms value. Depending on the X/R ratio, various other multiplying factors are used to approximate maximum asymmetrical levels throughout the d-c decay. These resulting estimates of asymmetrical rms current can be used to compare ratings that are based on total (asymmetrical) rms current.

Because fault current varies with time, there are several different results that are commonly desired from the fault calculations. To obtain these might require carrying simultaneous impedance reductions accounting for X''_d, X'_d, and X_d of the rotating machinery. However, when the system has just induction motors or synchronous converters as loads, these usually only contribute fault current within the first cycle and, at most, only two reductions are necessary: one with the motors as sources, the other with just the utility system. As mentioned, oftentimes motor contribution is practically negligible but, in marginal situations, this might be the extra current that could result in equipment destruction during phase faulting.

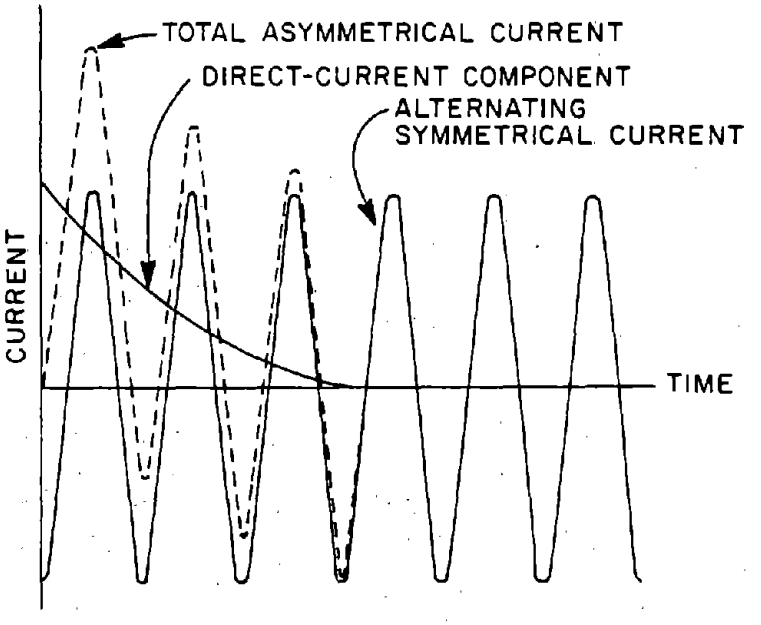


Figure 9.1. Fault-Current Waveform Showing Asymmetrical Nature.

With these thoughts, the desired computation results could be listed as shown in Table 9.3 with the implication towards mining phase-current applications. The first-cycle maximum symmetrical current is always needed. The maximum value, existing between 1.5 and 4.0 cycles after the fault, is required for sizing high-voltage circuit breakers. Fault-current levels, possibly existing beyond 6.0 cycles, are necessary to estimate the performance of time-delay relays and fuses. The "calculation result," listed in the table comments, refers to the a-c symmetrical value of fault current. Figures 9.2 and 9.3 are mentioned in the table and relate the system reactance-to-resistance ratio with circuit-breaker contact parting time, to obtain multiplying factors for momentary or close-and-latch rating comparisons (1). To help use these curves, typical breaker speeds are 3, 5, and 8 cycles, having respective contact parting times of 2, 3, and 4 cycles (a two-cycle circuit breaker has 1.5 cycle contact parting). The application of the material given in Table 9.3 is shown in the next section.

1. Express all impedances between the sources and the fault in per unit on a set of consistent bases. (In rare cases where the sources and fault are at the same voltage level, such conversion is not necessary.)
2. Reduce the system to one equivalent impedance.

Table 9.3. Possible Desired Results from Fault Calculations.

Application	Operation	Fault Current	Comments
1. Fuses and low-voltage circuit breakers	Contact parting and momentary withstand	First Cycle Maximum	a. Machine subtransient reactance X''_d, must be included. b. If ratings are symmetrical rms current, calculation results are directly used.
2. High-voltage switching apparatus excluding fuses.	Momentary rating or close-and-latch rating	First Cycle Maximum	a. Machine subtransient reactance, X''_d, must be included. Use values given in Table 9.1, except use $1.2X''_d$ for individual induction motors 50 to 250 hp, neglecting those below 50 hp. b. Multiply calculation result by 1.6 to obtain total short-circuit current.
3. High-voltage circuit breakers	Interrupting duty	From 1.5 to 4 cycles after fault	a. Multiply all motor X''_d from Table 9.1 by 1.5, except use $3.0X''_d$ for individual induction motors 50 to 250 hp, neglecting those below 50 hp. b. Determine X/R ratio of Thévenin's equivalent impedence. c. Select appropriate multiplying factor from Figures 9.2 or 9.3.
4. Time-delay relays	Operation under short-circuit currents	Beyond 6 cycles	a. All motor contributions omitted. b. Procedure same as Application 1.

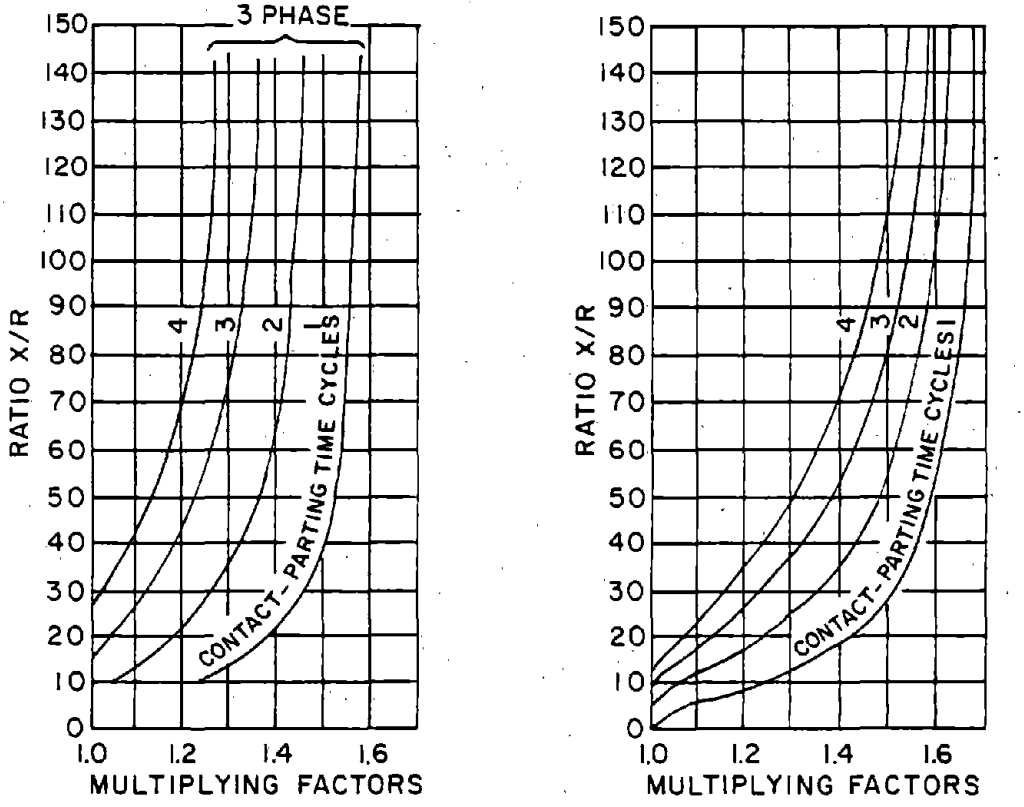
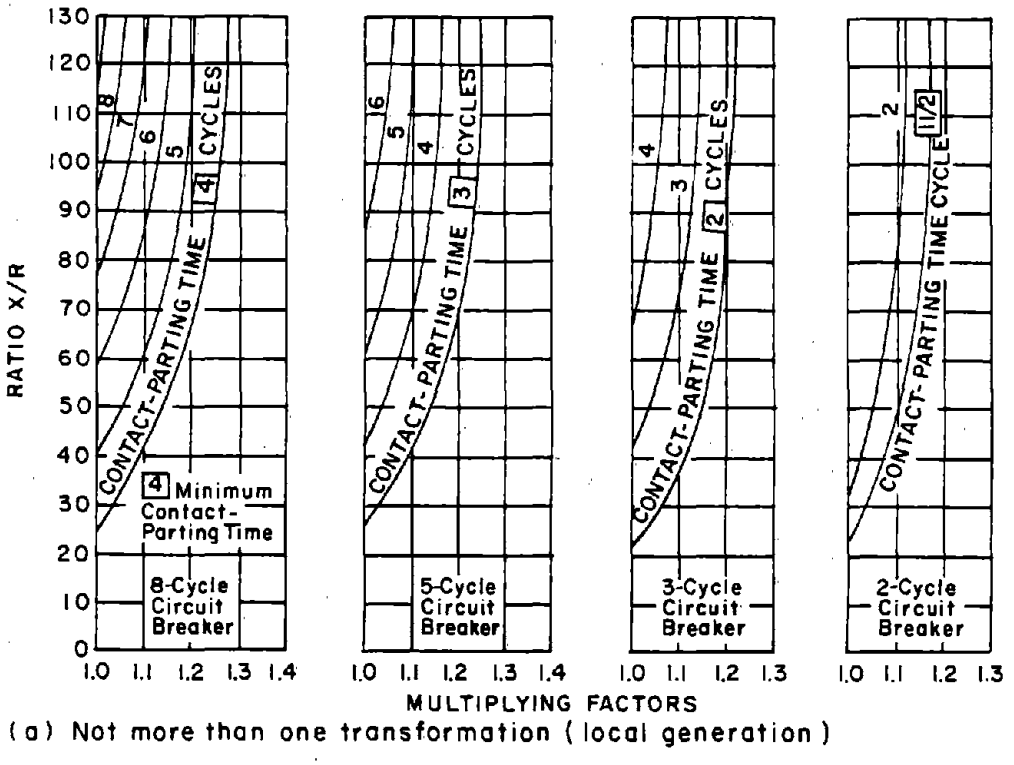
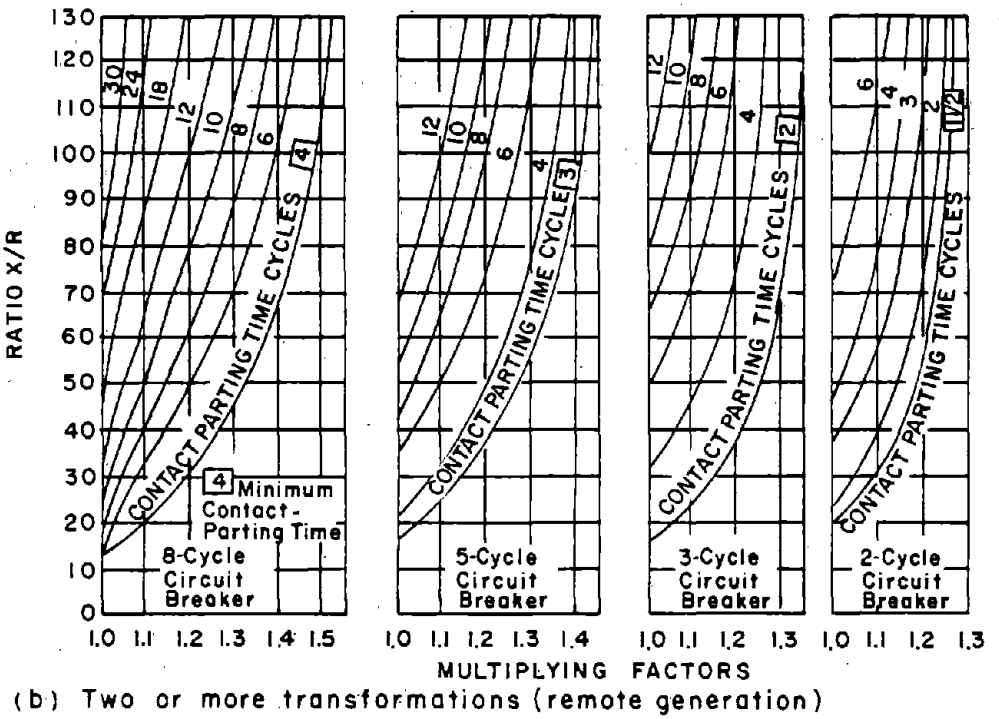


Figure 9.2. Multiplying Factors of Three-Phase Faults for Momentary Ratings of Switching Apparatus.



(a) Not more than one transformation (local generation)



(b) Two or more transformations (remote generation)

Figure 9.3. Multiplying Factors of Three-Phase Faults for Close-and-Latch Ratings of Switching Apparatus.

3. Calculate the three-phase bolted-fault current, I_{sc}, by:

$$I_{sc} = \frac{V_{pu}}{Z_{pu}} \; I_b \tag{9.2}$$

in which

V_{pu} = the driving voltage of the circuit, 1.0 pu, if nominal voltages are taken as the prefault level

Z_{pu} = the magnitude of the equivalent impedance (per unit)

I_b = the base current for the system portion in which the fault exists (A)

I_{sc} = the symmetrical rms fault current (A).

4. Apply appropriate multiplying factors to account for fault-current asymmetry.
5. If phase-to-phase fault current is desired,

$$I_{pp} = \frac{I_{sc}\sqrt{3}}{2} = 0.87 \; I_{sc} \tag{9.3}$$

where,

I_{pp} = the approximate symmetrical rms fault current resulting from a bolted phase-to-phase fault (A). (NOTE: this is derived from the fact the positive- and negative-sequence impedances are basically equal for phase-to-phase faults.) For phase-to-phase-to-neutral faults, equation 9.3 also approximates the phase-current level if the system is resistance grounded.

6. If ground-fault currents are desired on resistance-grounded systems,

$$Ig = \frac{V_{Ln}}{Rg} \tag{9.4}$$

where,

I_g = the symmetrical rms ground-fault current (A)

V_{Ln} = the line-to-neutral voltage of the circuit (V)

R_g = the ground system resistance, including the grounding resistor and conductors (Ω).

The last item is highly significant in mining as phase-to-neutral faults are by far the most common. During such occurrences, the current in a resistance-grounded system is limited to a level lower than typical load current in the phase conductors; phase-to-phase-to-neutral faults cause about the same current levels. As there are no neutral-connected loads in these systems, fault-current contribution is only from generating stations and capacitance (i.e., motors have no effect). The result is that fuses cannot be used to protect against ground faults; in fact, their use in series with the grounding conductors can create a serious personnel hazard if they open. As was discussed in Chapter 6, ground-fault currents in ungrounded or solidly-grounded systems can be substantially greater; thus, phase devices including fuses can provide ground-current protection. For instance, sizing fuses to item 5 (above) would likely cause interruption during two different phase-to-neutral faults in an ungrounded system. However because of asymmetry, symmetrical-component methods are required for precise calculations of ground-current levels in systems which are not resistance grounded and, in general, the above approximations are not satisfactory. On the other hand, the following phase-current techniques are adequate regardless of system grounding.

To illustrate an example of bolted three-phase fault computations consider the one-line diagram in Figure 9.4. This is suggestive of an underground coal mine in its early stages of development. All cables are given by their conductor size; transformers by the voltages, capacity, and percent reactance; utility supply by its ability to deliver short-circuit current (a kVA capacity); and motors by the horsepower. Transformer resistance and power-equipment bus-work and interrupting-device impedances are assumed negligible. Three possible fault locations are suggested, but suppose Fault 1 has occurred. To ensure correct results, the contribution of rotating machinery is not neglected.

The initial direction is to compute the first-cycle maximum fault current. Following the recommended procedure, the first concern is to convert all impedances to per unit. For calculation convenience, a base power, kVA_b, of 5000 kVA is chosen; the level is also not too large to make the per-unit values of any component insignificantly small. Prefault voltages are taken as nominal system voltages and define the second required base

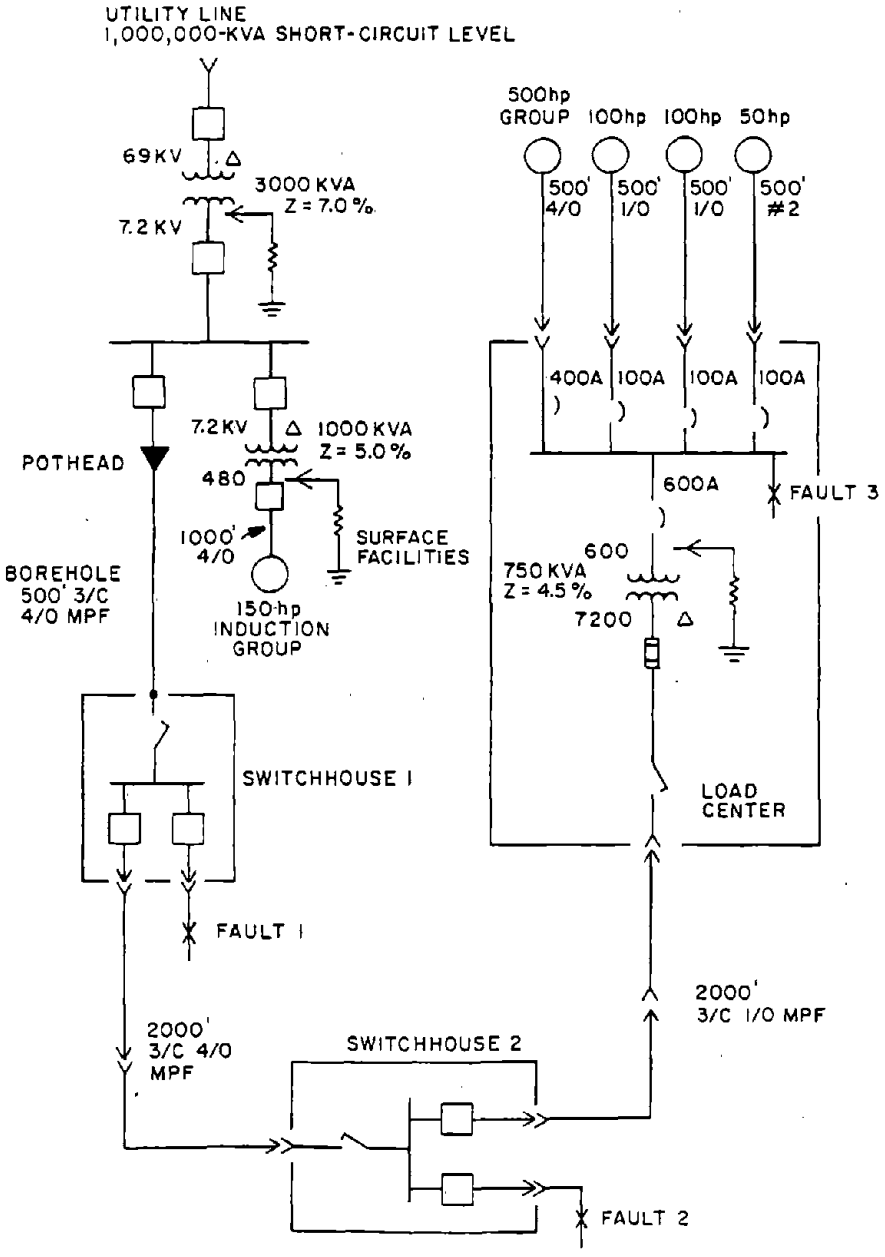


Figure 9.4. One-Line Diagram for Fault Calculations.

quantities. Accordingly, Table 9.4 provides the base-current and base-impedance calculations for each base voltage. Using these values, Table 9.5 gives the per-unit conversions for the utility-supply reactance, Table 9.6 covers power equipment, and Table 9.7 relates the per-unit values for all cables. Formulas used for these computations are available in Section 4.4.

Table 9.1 reactances can be used to approximate the variable impedance of each rotating machine. As a time saver, it is often best to determine all these reactances at this point and carry them through the subsequent reductions. However, because all the motors here are induction, subtransient reactance, X''_d, is the only value defined, with transient and synchronous reactances approaching infinity. Table 9.8 contains the per-unit conversions. Motor resistance could also be assigned but, as the X/R ratio for induction machines is about six, this is neglected.

The next process is to draw an impedance diagram, such as in Figure 9.5, showing the calculated per-unit resistance and reactance values. The diagram should be simplified as much as possible to clearly show the calculation needs. This has been done in Figure 9.6. Even though the example only concerns fault location 1, all three fault locations are shown. All rotating machines, including motors and any generators, are represented by their per-unit reactances, X''_d, X'_d, and X_d, connected to an equivalent source bus (the dashed line in Figure 9.6). Thus, the utility-supply equivalent reactance is in parallel with the rotating-machine reactances, and the combined potential, driving the fault, is 1.0 pu.

Further simplifications can now be made for each specific fault location. Figures 9.7 through 9.9 graphically show the process for Fault 1. The operations involve no more than combining parallel and series impedances to obtain a single impedance between the source bus and the fault, the Thévenin's equivalent of the faulted system (Figure 9.9).

The single equivalent impedance can now be used to calculate the first-cycle symmetrical rms current of the bolted three-phase fault, or

$$I_{sc} = \frac{Vpu}{Zpu} I_b = \frac{1.0}{0.1132} (401) = 3542 \text{ A.}$$

With the fault located in high-voltage distribution, this value can be used to compare fuse ratings based on symmetrical rms currents. (If in low-voltage, the current would also apply to circuit breakers.) It is obvious that in this case, resistance could have been omitted with negligible error.

Table 9.4. Base Quantities for Example Problem.

By selection:

Base power, kVA_b = 5000 kVA

Base voltages, 7200, 600, and 480 V line-to-line or, referenced line-to-neutral,

kV_{b69} = 39.838kV

$kV_{b7.2}$ = 4.16kV

$kV_{b.6}$ = 0.346kV

$kV_{0.48}$ = 0.277kV

Base values at 7200V:

kVA_b = 5000 kVA, $kV_{b7.2}$ = 4.16kV

$I_{b7.2}$ = 401A, $Z_{b7.2}$ = 10.37Ω

Base values at 600V:

kVA_b = 5000kVA, $kV_{b.6}$ = 0.346kV

$I_{b.7}$ = 4811A, $Z_{b.6}$ = 0.072Ω

Base values at 480V:

kVA_b = 5000kVA, $kV_{b.48}$ = 0.277kV

$I_{b.48}$ = 6014A, $Z_{b.48}$ = 0.046Ω

Note: Base impedance and current at 69 kV will not be used.

Table 9.5. Utility Supply Equivalent Per-Unit Reactance.

Utility System base values:

Short-circuit level of 1,000,000 kVA relates to 1.0 pu impedance on the utility system at 69kV.

Assume impedance is pure reactance, Xpu.

Therefore,

$$kVA_e = 1{,}000{,}000kVA$$
$$kV_e = 39.838kV$$
$$X_{pue} = 1.0\ pu$$

Calculation base values:

$$kVA_b = 5000kVA$$
$$kV_{b69} = 39.838kV$$

Reactance,

$$X_{pu} = \frac{X_{pue}kVA}{kVA_e} \left(\frac{kV_e}{kV_b}\right)^2$$

$$= \frac{(1.0)(5000)}{1{,}000{,}000} (1) = \underline{0.005pu}$$

Table 9.6. Power-Equipment Equivalent Per-Unit Reactance.

Main Substation, 3000kVA:

Percent reactance is 7% on the transformer rated kVA, referred to the high side, 69kV

$$Xpu = \frac{X_{\%}\ kVA_b}{100\ kVA_e}\left(\frac{kV_e}{kV_b}\right)^2 = \frac{7(5000)}{100(3000)}(1) = \underline{0.117\ pu}$$

1000-kVA Load Center:

Percent reactance is 5% on the transformer rated kVA, referred to the high side, 7.2kV

$$Xpu = \frac{5}{100}\left(\frac{5000}{1000}\right)(1) = \underline{0.250\ pu}$$

750-kVA Load Center:

Percent reactance is 4.5% on the transformer rated kVA, referred to the high side, 7.2kV.

$$Xpu = \frac{4.5}{100}\left(\frac{5000}{750}\right) = \underline{0.300\ pu}$$

Table 9.7. Per-Unit Impedance of Cables.

1. High Voltage, $Z_{b7.2}$ = 10.37Ω.

   a.) Borehole Cable, 500 ft, 4/0, 8kV, MP + GC:

   R = 0.032Ω, X = 0.016Ω

   R_{pu} = 0.0031pu, X_{pu} = 0.0015pu

   b.) Mine power feeder, 2000 ft, 4/0, 8kV, MPF:

   R = 0.126Ω, X = 0.064Ω

   R_{pu} = 0.0122pu, X_{pu} = 0.0062pu

   c.) Mine power feeder, 2000 ft, 1/0, 8kV, MPF:

   R = 0.254Ω, X = 0.070Ω

   R_{pu} = 0.0245pu, X_{pu} = 0.0068pu

2. 480-V System, $Z_{b.48}$ = 0.058Ω.

   1000 ft, 4/0, 2kV, G + GC:

   R = 0.068Ω, X = 0.027Ω

   R_{pu} = 1.1724pu, X_{pu} = 0.4655pu

3. 600-V System, $Z_{b.6}$ = 0.0752Ω.

   a.) 500 ft, 4/0, G + GC:

   R = 0.035, X = 0.0135Ω

   R_{pu} = 0.4514, X_{pu} = 0.1875pu

   b.) 500 ft, 1/0, G + GC:

   R = 0.064, X = 0.0145Ω

   R_{pu} = 0.889, X_{pu} = 0.201pu

   c.) 500 ft, #2 AWG, G + GC:

   R = 0.109, X = 0.0145Ω

   R_{pu} = 1.514, X_{pu} = 0.201pu

Table 9.8. Subtransient Reactances of Motors.

For 480-V System:

Load is a 150 hp group of induction motors, each less than 50 hp. Subtransient reactance is 0.25pu, based on the motors combined kVA. This base is approximately the combined horsepower rating, or 150 kVA.

Thus,

$$X''_d = \frac{(0.25)(5000)}{150} = \underline{8.33\text{pu}}$$

For 600-V System:

a.) 500-hp group. Each is about 100 hp. Hence, X''_d will be about 0.17 pu on combined kVA base, 500kVA.

$$X''_d = \frac{(0.17)(5000)}{500} = \underline{1.7\text{pu}}$$

b.) 100-hp motors. X''_d = 0.17pu on 100kVA base

X''_d = 8.5pu on 5000 kVA base.

c.) 50-hp motor. X''_d = 0.17pu on 50kVA base

X''_d = 17pu on 5000kVA base.

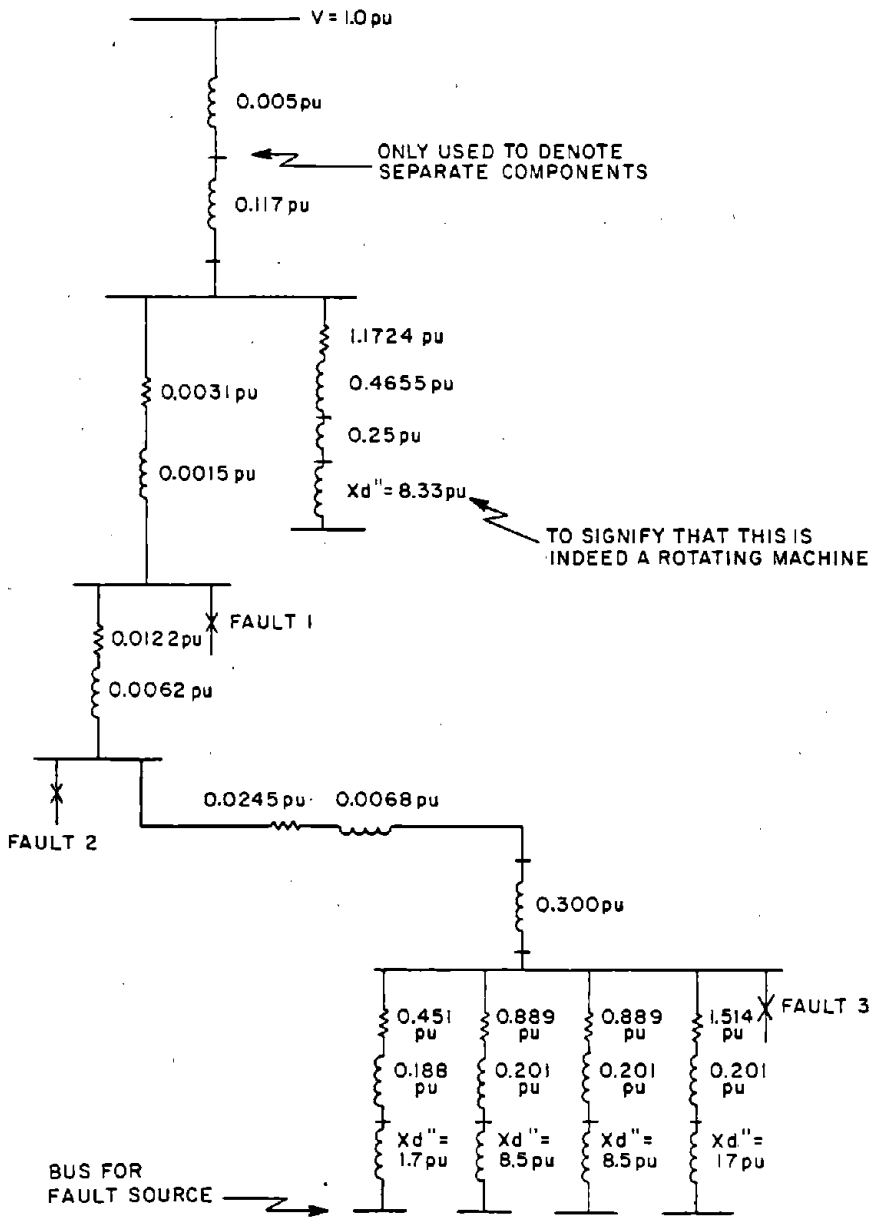


Figure 9.5. Impedance Diagram for One-Line Diagram of Figure 9.4.

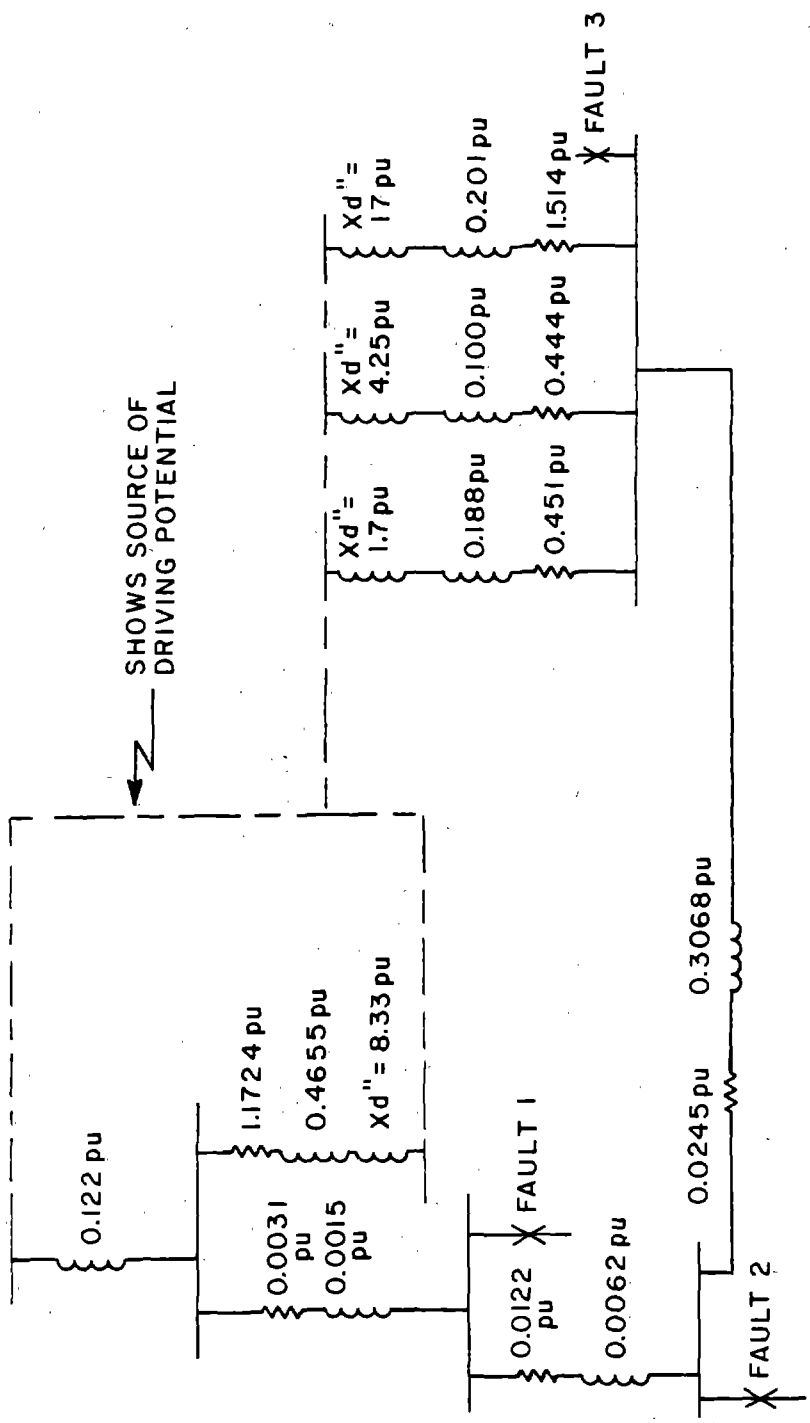


Figure 9.6. Simplification of Figure 9.5.

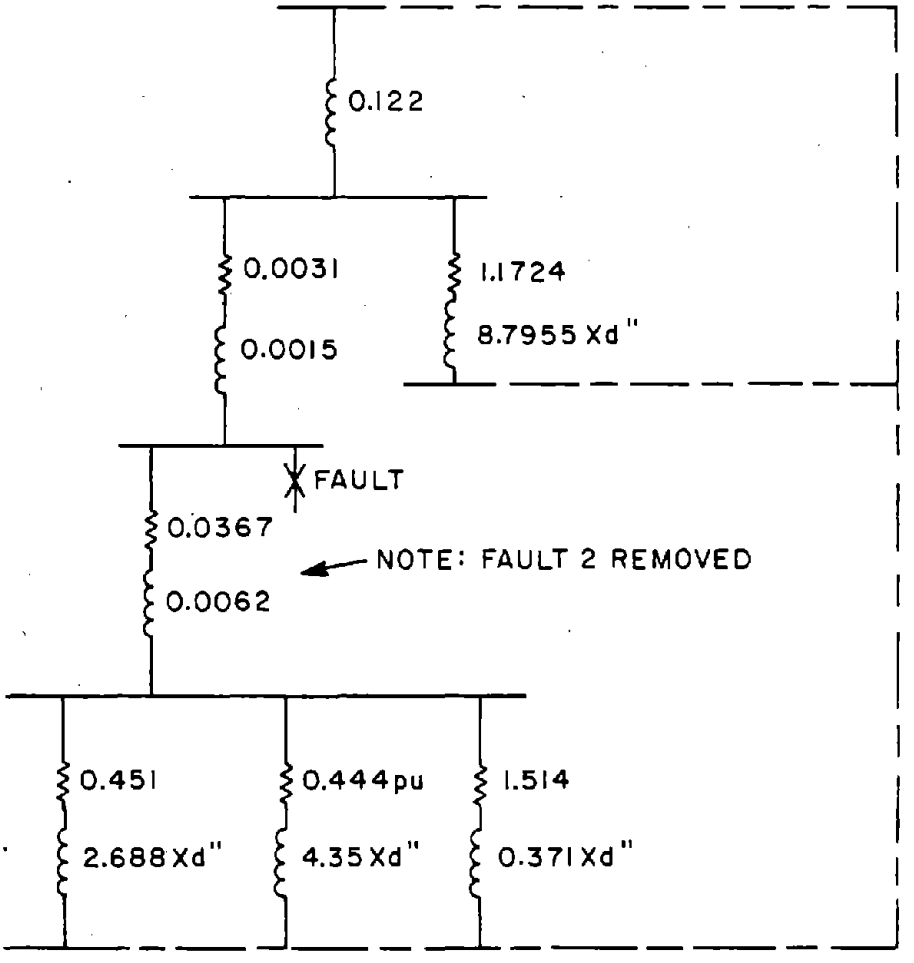


Figure 9.7. Simplification of Figure 9.6.

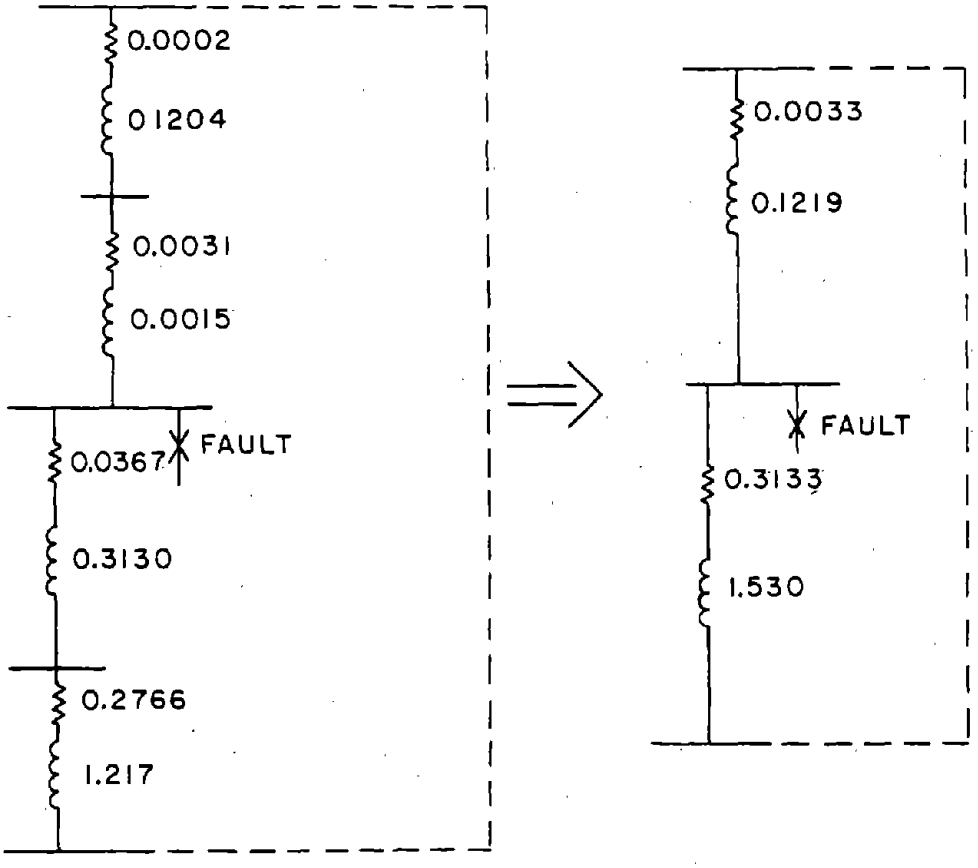


Figure 9.8. Further Reduction of Example Network.

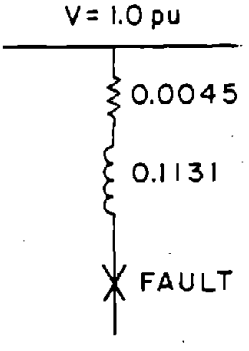


Figure 9.9. Equivalent Circuit of Figure 9.6.

On the other hand, Figure 9.10a shows a simplification of Figure 9.5 to demonstrate the possible error that would be introduced by neglecting motor fault-current contribution. As shown, the only driving source is the utility, and the equivalent circuit of Figure 9.10b is quickly found by series combination. The first-cycle symmetrical rms current in this situation is

$$I_{sc} = \frac{1.0}{0.1235} (401) = 3247 \text{ A},$$

which is 295 A less than the previous value. Thus by omitting the motors, the result is a 8.3% error and points out the earlier cautions of omission. However, this current value should be very close to the symmetrical component of fault current and can be used for time-delay comparisons (item 4 of Table 9.3).

To apply this work to high-voltage switchgear, the next calculation step is to account for fault-current asymmetry by employing multiplying factors, more specifically to adjust for the d-c component decay. Here, the subtransient reactance of all induction motors greater than 50 hp is modified by multiplying by 1.2, and the contribution of motors less than 50 hp is neglected. These adjustments actually can be compared to a "decrement factor," allowing for fault-current decay with time. Compared with Figure 9.6, Figure 9.11a reflects the change (resistance is also omitted). Figure 9.11b shows the reduced single equivalent reactance and, using the formula,

$$I_{sc(mom)} = \frac{Vpu}{Zpu} I_b(1.6) \qquad (9.5)$$

or

$$I_{sc(mom)} = \frac{1}{0.1154} (401)(1.6) = 5559 \text{ A}.$$

The current represents the maximum asymmetrical rms value in the first cycle and can be compared with momentary ratings or close-and-latch capabilities of high-voltage switching apparatus (normally circuit breakers, but devices rated on total fault current). Interestingly, if subtransient reactances are not modified in this example, the calculation would produce an asymmetrical rms current of 622 A, thus creating a small safety factor for switching-apparatus comparison.

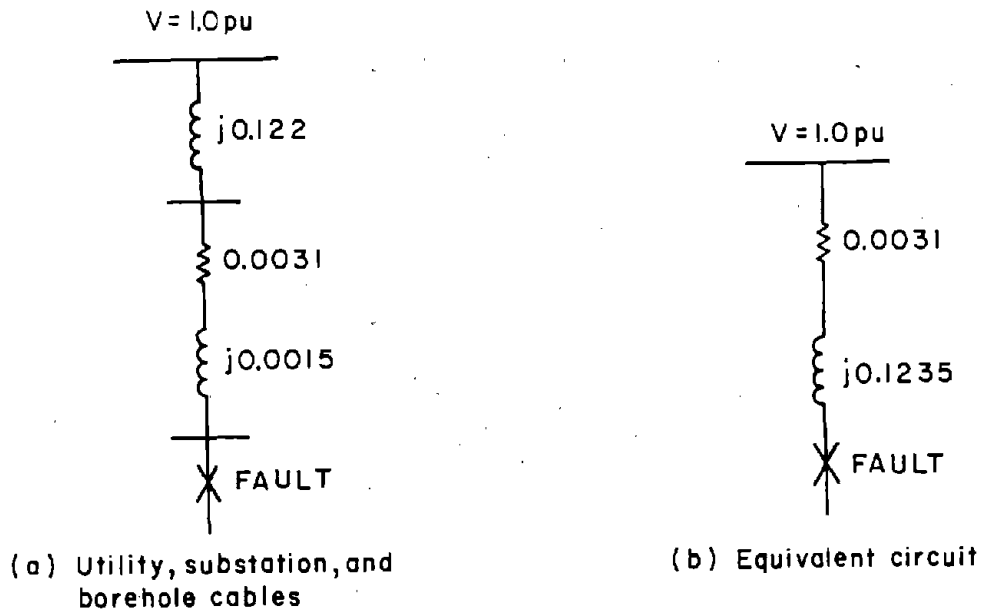


Figure 9.10. Example Problem with Motor Contribution Neglected.

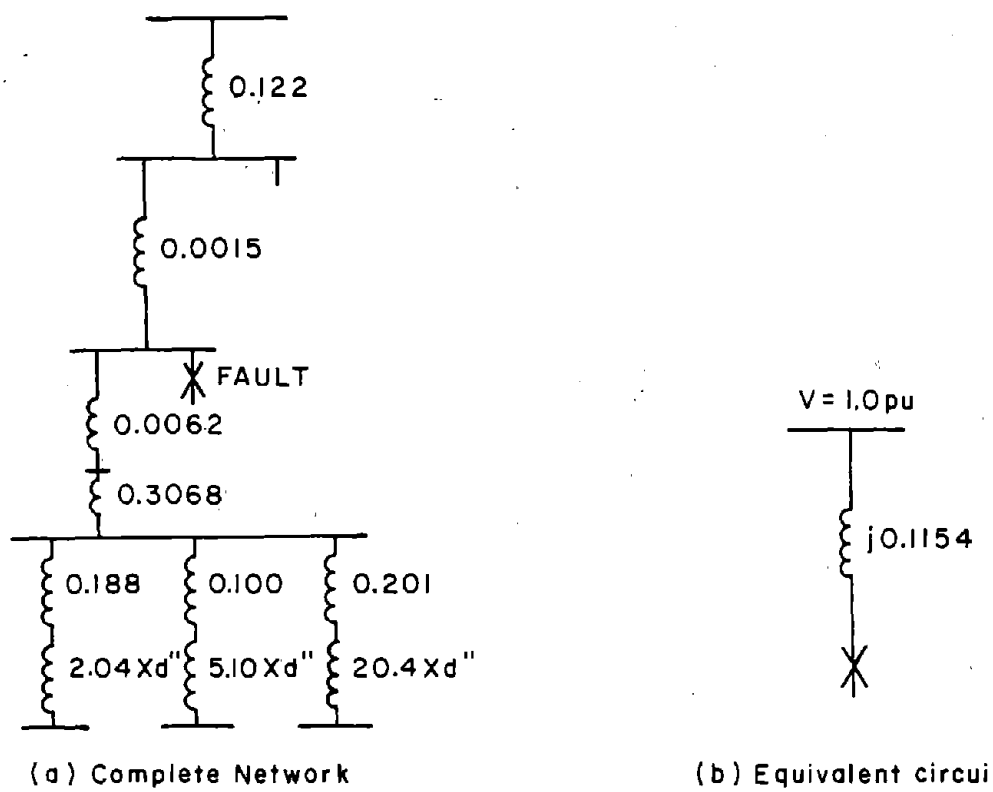


Figure 9.11. Network to Calculate Momentary or Close-and-Latch Current Duties.

Adhering to Table 9.3, the circuit of Figure 9.6 can again be adjusted to determine interrupting duties of high-voltage circuit breakers (minimum contact-parting times between 1.5 and 4.0 cycles). Again, allowing for decrement of the d-c component, subtransient reactances are multiplied by (1):

1. 1.5, for synchronous motors;
2. 1.5, for 3600-rpm induction motors over 250 hp and 1800-rpm induction motors over 1000 hp; and
3. 3.0, for induction machines of 50 hp and larger (item 2 supersedes this item where there is any overlap in coverage).

Smaller motors are considered insignificant. To obtain the necessary multiplying factor from Figure 9.2 or 9.3, the X/R ratio of the equivalent impedance or "fault-point impedance" is needed. Such can be found by reducing resistance-only and reactance-only networks, eliminating the complexity of handling complex numbers. The formula for interrupting duty, then, is:

$$I_{sc(int)} = \frac{Vpu}{Zpu} I_b \text{ (multiplying factor)} \qquad (9.6)$$

where,

$I_{sc(int)}$ = the total rms current interrupting duty (A)

(multiplying factor) = the value from Figure 9.2 or 9.3.

For comparison of circuit breakers rated in MVA, the interrupting capacity can be converted to an interrupting-current capability by:

$$I_{sc(int)} = \frac{MVA}{\sqrt{3}\, V_{oper}} \qquad (9.7)$$

in which

$I_{sc(int)}$ = the interrupting current (kA)

MVA = the system power (MVA)

V_{oper} = the system voltage (kV).

The system voltage is used when within the minimum and maximum limits of the breaker, but the minimum breaker voltage is used in the formula if the operating voltage is less.

The foregoing example is just a simple demonstration of bolted three-phase-fault calculations. The mine is small with long cables, such that the fault current found is rather small (still large in comparison with normal load current). Regardless, more fault locations should be taken, and the computations repeated until the worst-case condition is verified. As more mining sections or loads are involved, the complexity of these calculations substantially increases, oftentimes to the point where hand computing becomes too cumbersome. Computer approaches can remove much of the burden.

Computer Fault Analysis. Systematic digital-computer methods have been developed to aid the designer in specifying system protection requirements. These are usually called upon for major studies (1). A complete discussion of the theoretical bases of such techniques is beyond the scope of this chapter but is available in the literature (for instance, reference 4). However, a few thoughts about the methods follow.

Balanced-fault computations on the computer require either a generalized impedance formulation of the power-system network (referred to as ZBUS fault analysis, the network being similar to the preceding calculations) or a generalized admittance formulation (termed YBUS load-flow analysis). The impedance network has the advantage of also allowing the evaluation of unsymmetrical-fault behavior by application of symmetrical-component theory. In this manner, phase-to-neutral, phase-to-phase, and phase-to-phase-to-neutral faults may be simulated by proper connection of the power-system positive, negative, and zero-sequence network representations. On a large digital computer, computations are quite rapid, and the amount of output information is limited primarily by the user's requirements. Available information generally includes fault currents, as well as post-fault system currents and voltages, for any fault at any system location. Sequential faulting of any system bus (i.e., location) is also possible. Pre-fault load currents are normally neglected but may be included if a more exact analysis is required.

Input-output techniques vary with the program type, but may be classified as either batch or interactive. In either case, the system is generally specified to the computer in terms of impedance or even cable sizes between bus pairs. Pre-fault loading information may also be input in terms of kVA or load type. In batch-processed programs, the run is then completed and required output information displayed. Interactive techniques allow the additional capability of on-line system modifications to evaluate the effects of design changes (5,6).

Direct-Current-System Faults. The preceding chapter material almost exclusively covered a-c occurrences. Yet, knowledge about fault-current levels on the d-c portions of mine power systems is also imperative for correct application of protective equipment, as faults can occur within motors, on trolley lines, trailing cables, cable reels, and so on. Trolley lines generally pose extensive problems because of normally heavy load currents as well as their exposed nature, where for example a roof fall can cause a serious arcing fault.

In underground mines, the principal source of d-c fault current is from the d-c distribution through rectifiers, and to a lesser extent, batteries (see Chapter 13) and M-G sets. For surface mining, synchronous converters are also involved, but these fault locations are commonly confined to inside unit-designed equipment. As with a-c, the voltage drop associated with a fault can cause motors to go into a generation mode, and act as a source as long as the field and the applied inertia are maintained. Of perhaps more serious concern than with a-c, a d-c prime mover can exist for extended times, for instance, a large trolley locomotive being pushed by loaded cars. However, the variability of motor contribution from application to application is very wide, such that the assignment of series impedances, like a-c subtransient reactances, is very difficult to assess. Furthermore, simplified calculation procedures are not well established, and many authors recommend detailed techniques (for instance, reference 7)(1).

Fortunately, d-c systems in mining are almost exclusively at utilization. Often these are such that fault current, as seen by protective devices, is dependent upon location and not motor contribution. In other words, a motor might pump substantial current to the fault but not usually through a protective device (unless the fault is upstream from the device). Thus in many cases the fault network can be effectively constructed using only the principal sources and the impedance in series with the fault. Reasoning from this apparent simplicity, it is all too easy to treat d-c faulting just as an application of Ohm's law and resistance. However, importantly, system current is no longer steady state after the fault. Figure 9.12 shows an illustrative example; here, the fault current is interrupted before the maximum is reached (8). Thus, rate of rise as well as time to interruption must be considered, and circuit inductance becomes a very important factor (7). For assembling a fault network, cable inductance is a rather easy parameter to find; yet, such is not the case for trolley systems. Values between 0.2 and 2.0 mH have been found typical (8).

To illustrate the available fault-current level that can exist on rectifier-fed trolley systems, Figure 9.13 gives plots for some rectifiers versus distance of the fault from the rectifier (8).

One of the more prevalent d-c protective-relaying problems for mining is not maximum fault level but rather the possibility of having small, undetected faults occur on trolley systems. In Pennsylvania during 1978 alone, two extensive mine fires were initiated by these events. The situation here is that a trolley-wire-to-rail fault could occur, again say by a roof fall, but be of high enough resistance so the resulting fault current is less than normal load currents. Hence, the fault cannot be detected by conventional overcurrent relaying. Several methods have been proposed to detect these illegitimate loads, including discriminating relaying and rate-of-current-rise detection (9). At this writing, these are still in the demonstration stage.

9.2-3 Comments

The majority of the above paragraphs have considered the determination of the maximum available fault current in the power system. The highest value is necessary not only for sizing the interrupting and withstand capabilities of switching apparatus but also to assess the thermal-destruction and mechanical-deformation problems that might occur in any area affected by the fault (e.g., transformers, buswork, cables, etc.). However, methods have also been discussed for the calculation of minimum fault current. Further application of these will be discussed in the next section.

9.3 Device Settings and Coordination

9.3-1 Purpose

Coordination of the mine power system consists of the complete organization of the time and/or current settings for all protective devices from the loads to the sources. The prime worry is overcurrent, be it in defining an overload, short circuit, or ground overcurrent. A system fault analysis is vital input for a coordination study, not only with regard to maximum values, but also minimum values. Also involved are maximum normal operation and maximum allowable currents. Addressing the subject, this section is broken into four major parts: relay pickup settings, CT matching, low-voltage circuit-breaker settings, and coordination. The presentation will be both through discussion and example. Except for low-voltage-breaker trip settings, the majority of the content will be concerned with resistance-grounded a-c systems.

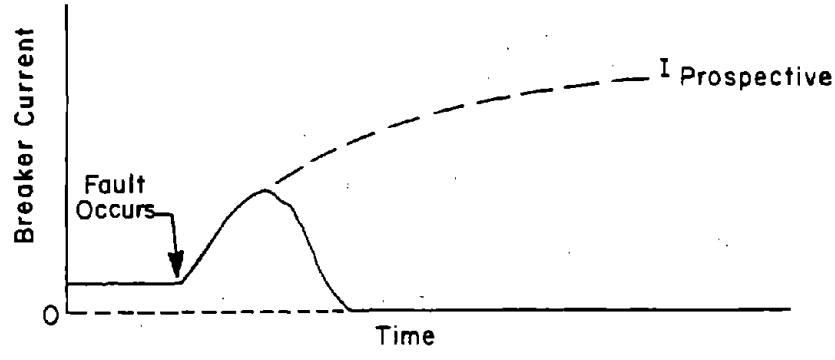


Figure 9.12. Fault Current in a Direct-Current System.

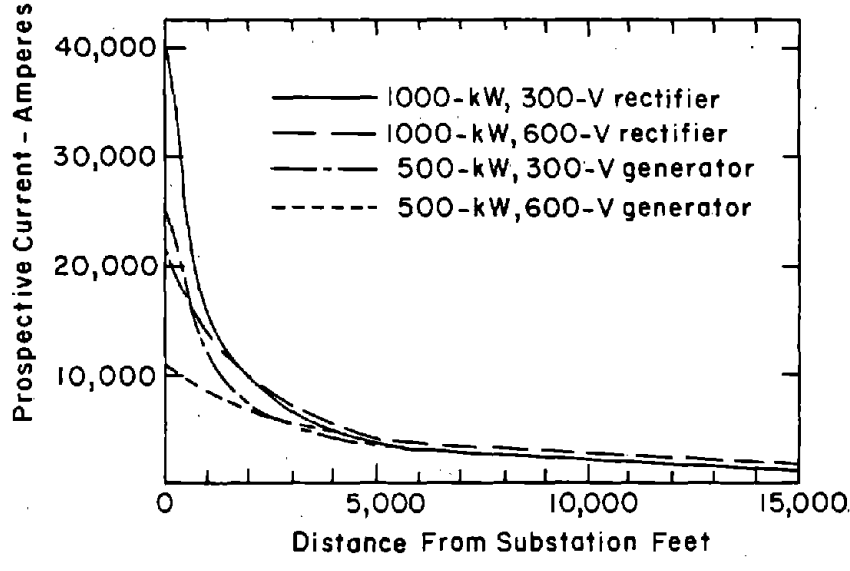


Figure 9.13. Available Fault Current Versus Distance of Fault from the Rectifier on Typical Trolley Systems.

The objective of a coordination study is to arrive at all correct instrument-transformer ratios, relay characteristics, pickup and time settings, fuse ratings, and low-voltage circuit-breaker ratings. The purpose is to make sure, through selective coordination, that a minimum of unfaulted load is disturbed when protective devices isolate a fault. Simultaneously, the circuitry must provide overload and short-circuit protection, while not creating nuisance tripping. The application of this "art" is perhaps the most perplexing problem facing many practicing engineers.

9.3-2 Relay Pickup Settings

Pickup. Pickup has already been defined as the minimum value of the actuating quantity that will cause a relay to close its contacts. Whether the application be at a trailing cable, feeder cable, or overhead conductors, the requirements[1] for overload or short-circuit protection generally translate to current pickup settings. Because of their widespread use, induction-disc relays will be implied for the following pickup applications; however, pickup techniques for other relays are basically the same. In each situation, establishing a pickup setting involves selecting a current-transformer ratio and operating-coil current for the relay. For marginal short-circuit currents, the accuracy of the combination might require verification. Although the following material will describe pickup settings at one point in the mine power system, it must be remembered that the overall goal is to obtain coordination, and settings at any location can be affected by other upstream and downstream relaying. Further, to avoid confusion, molded-case circuit-breaker trip settings will be covered later.

Short-Circuit Protection. Short-circuit or phase-fault protection can be obtained with an instantaneous element (no intentional delay) or an inverse-time overcurrent relay using the minimum time-dial setting (maximum time delay here is often restricted to no more than 0.6 s). The general requirements can be determined by the lowest value of either:

1. 115% of the maximum starting current or 115% of the peak load current, whichever is higher, for the equipment being protected; or
2. 60% of the smallest bolted three-phase symmetrical rms fault current for any point of the system protected by the relay.

---

[1] The values used in this section are generally in line with the Title 30, Code of Federal Regulations, Parts 75 and 77, in effect at this writing. The percentages defining pickup may change in the future, but the techniques presented will not.

The first value is to have pickup above normal operation current to prevent nuisance tripping. Usually, the bolted-fault-current value is the higher of the two.

To show how this requirement is obtained, consider that a production shovel in a surface mine has 2000-hp connected load rated at 4160-V phase-to-phase. As shown in Figure 9.14, the shovel is powered through 1000 ft of 4/0-AWG cable. Shovel motors, at full load, are 85% efficient and operate at 0.8 pf. The minimum value of bolted three-phase current has been found to be 6130 A. Phase-current-transformer ratios are 400/5 A, and the instantaneous element has a 10 to 50 A pickup range. The procedure is to find the minimum current according to the above criteria.

First, for the fault current, the pickup would be (60% of the bolted value divided by the CT turns ratio):

$$\text{pickup} = \frac{(0.6)(6130)}{80} = 46 \text{ A.}$$

To compare this value with maximum starting current, the full-load current of the shovel motor is found from:

$$I = \frac{746(\text{hp})}{\sqrt{3}\ V\ \eta\ (\text{pf})} \qquad (9.8)$$

or

$$I = \frac{746\ (2000)}{\sqrt{3}\ (4160)(0.85)(0.8)} = 305 \text{ A.}$$

As the machine is induction, the locked-rotor current is about six times the full-load value, and maximum motor inrush current or starting current, including d-c offset, is around 1.6 times the locked-rotor level. Thus, maximum starting current is approximately

$$I_m = (305)(6)(1.6) = 2923 \text{ A.}$$

Allowing 115% for nuisance tripping, the pickup setting is then

$$\text{pickup} = \frac{(2923)(1.15)}{80} = 42 \text{ A.}$$

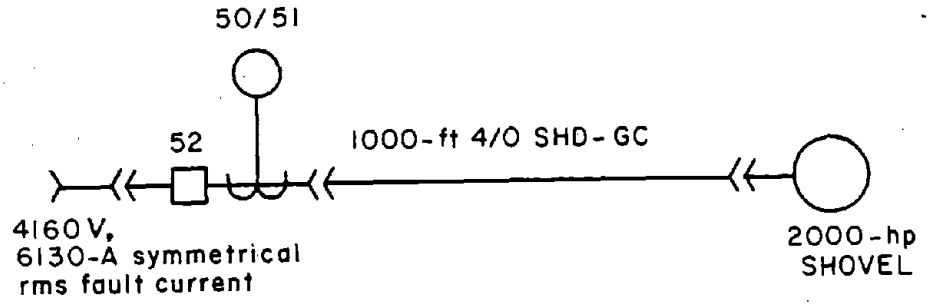


Figure 9.14. One-Line Diagram of Pickup Setting Example.

As this is less than that for the fault current, 42 A is the selected pickup setting for short-circuit protection.

Overload Protection. The prime purpose of overload (or overcurrent) pickup settings is to protect conductors and insulation from damage by excess temperature. Temperature here is a function of the ambient temperature and the I^2R power loss in the conductors; temperature rise further involves time. Therefore, time-inverse current relays are used on high-voltage systems for this protection. (Again, thermal overloads and fuses are commonly used for low- and medium-voltage systems, and these are discussed later.) The general overload requirement is that relay pickup is established whenever 125% of the ampacity of smallest power conductor in the protected system is exceeded. When directly applied to components such as transformers, the value could be 125% of the rated full-load current.[2]

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[2] The percentage for transformer overload protection is variable, depending on the protection scheme. The NEC, ANSI C1-1981, allows for transformers rated greater than 600 V, if there is no secondary protection, 300% of rated primary current with circuit breakers and 150% for fuses. For transformers rated less than 600 V, primary overload is 125% if no secondary protection and 250% if secondary protection is set at 125%. On the other hand, IEEE Std. 141-1976 recommends for transformer protection that for overload, time-relay pickup should be set 150 to 200% of primary full-load current, and for short circuit, instantaneous-relay pickup should be set at 150 to 160% of equivalent maximum secondary three-phase fault current.

Again consider Figure 9.14 as an example, where the trailing cable is 4/0 AWG, three conductor, 5 kV, 90°C-rated insulation. The relay operating coil (for the 51 contacts) has a pickup range of 4.0 to 12 A. The maximum ambient temperature in this location is 30°C.

From the data given in Chapter 7, the cable ampacity at 40°C is 321 A and at 30°C, applying the temperature correction factor,

$$\text{ampacity} = (1.1)(321) = 353 \text{ A}.$$

Allowing for 125%, the minimum primary current that defines overload is

$$I = 353\ (1.25) = 442 \text{ A}.$$

The current-transformer turns ratio is 400/5 A, so the required pickup setting is

$$\text{pickup} = \frac{442}{80} = 5.5 \text{ A}.$$

Such a tap setting would allow the time-current characteristics of the relay to determine an overload condition. However, a tap setting of 6.0 A relating to 480-A primary current as an overload is too high. Note that if an instantaneous element with a 42-A pickup is available in the relay, short-circuit protection is also provided with one CT per phase.

Ground-Fault Protection. Considering the arguments presented in Chapter 8 about ground-fault pickup, the requirement could be stated as 50% of the current rating of the grounding resistor, in other words, the ground-current limit of the system. A common application here is a zero-sequence current transformer of 50/5-A turns ratio connected to a time-overcurrent relay. If the ground-current limit is 25 A, zero-sequence flow in the three primary conductors cannot be greater than 12.5 A for relay pickup. Thus, the maximum tap setting of the operating coil is 12.5/10 or 1.25 A.

(Accordingly, when applied to solidly grounded systems, the pickup level could be defined by 50% of the minimum bolted line-to-ground fault current. The same could also apply to ungrounded systems, but a maximum ground-current, or even a ground-fault, requirement here is not easy to define. As a result, if necessary, ground-fault pickup can be related to a decrease in line-to-ground potential of any power conductor, say by 30% of the nominal system voltage. This parenthetical statement could apply to d-c as well as a-c systems.)

9.3-3 Current-Transformer Matching

Saturation. From the foregoing, the selection of CT ratios and relay pickups to afford both overload and short-circuit protection appears rather straightforward. However, current transformers are magnetic devices, which can give inaccurate results when improperly applied. The main problem is core saturation caused by excessive primary current, high secondary burden, or a combination of both these factors (2). When a CT is in saturation, accuracy is very poor, secondary current is actually less than it should be, and relays operate slower than intended. The danger is the loss of coordination for short-circuit protection. The non-linear nature of a typical CT is shown in the saturation curves of Figure 9.15 (2).

To help minimize saturation effects, the following guidelines are recommended for protective relaying (2).

1. Secondary burden should be kept as low as possible.
2. Current transformer turns ratios should be maintained as high as practical. (However, for maximum accuracy under normal loads, maximum anticipated load current should be as close to as possible, but without exceeding, the primary-current rating. Substantially under-utilizing a window CT also produces inaccuracies. See Chapters 4 and 8.)
3. The pickup setting for short-circuit protection should be below the CT current-saturation point.
4. The maximum available fault current should be not more than 20 times the CT primary rating.

Usually, saturation is only a problem on low-ratio current transformers (e.g., 50/5 versus maybe 300/5). Higher ratio CT secondaries, per application, develop higher voltage and are likely saturated under normal burden. Hence, the lower the ratio, the greater the chance that a fault will not be cleared within the intended zone; then operation of an upstream circuit breaker can cause substantial outages.

Although adhering to the above listing will usually ensure correct CT operation, accuracy calculations can verify it. In fact, when the maximum fault current is above the 20-times limit, CT performance should be checked.

Accuracy Calculations. For a CT under a specific burden, the operation accuracy or the transformer performance can be easily calculated using manufacturers' data (usually implying that the CT has a "C" accuracy class). As an example, suppose a 600/5 multiratio CT is connected through 50 ft of #12 AWG wire to an induction-disk relay and an ammeter. Both overload and short-circuit protection are intended. Figure 9.15 is a typical set of CT saturation curves, and burden data are contained in Table 9.9 (2). The primary circuit (system phase

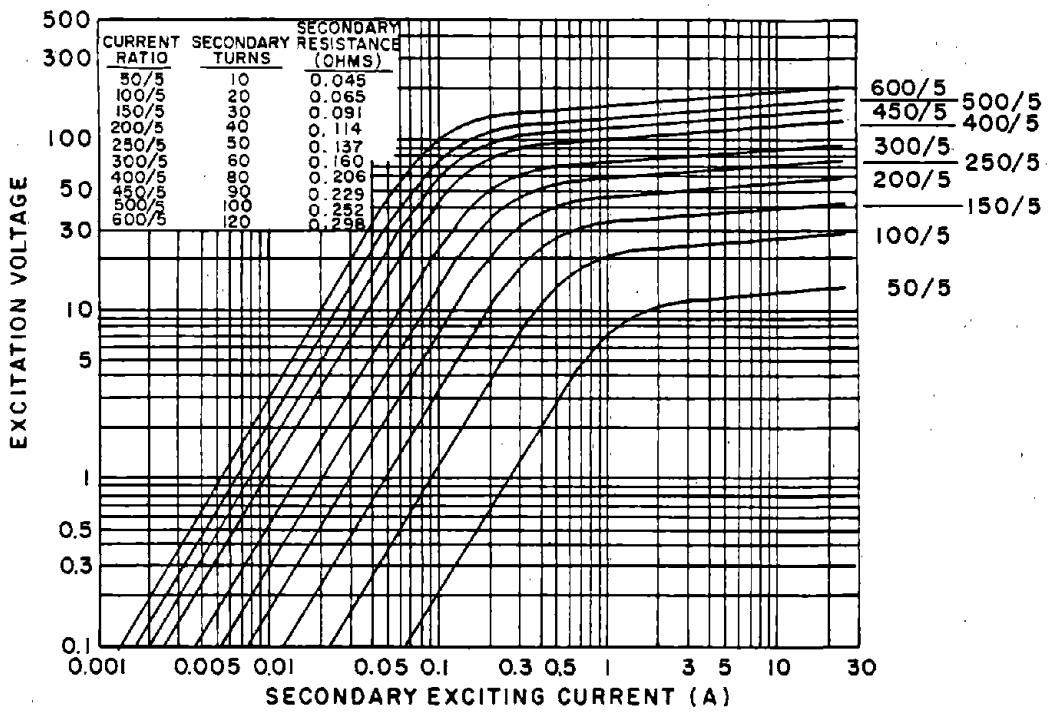

Figure 9.15. A Typical Set of Saturation Curves for a 600/5 Multiratio Bushing-Type CT.

Table 9.9. Burdens of Relay Elements and Ammeter Connected to CT.

Relay, Timed Element, 4-12 A Pickup:
2.38 VA at 4 A at 0.375 pf
146 VA at 40 A at 0.61 pf
Relay, Instantaneous Element, 10-40 A Pickup:
4.5 VA at 10 A
40 VA at 40 A at 0.20 pf
Ammeter:
1.04 VA at 5 A at 0.95 pf.
Conductor (interconnecting):
0.08Ω at 1.0 pf
Transformer Secondary Resistance:
0.298Ω at 25°C

conductor) has 24,000-A symmetrical rms of available fault current. The objective of the calculation procedure is to find the percent ratio error.

Although the error should not exceed 10% under the most extreme circumstances (20 times the secondary current (2)), satisfactory protective-relay operation often calls for smaller error, on the order of two percent or less. To compute the error, CT secondary burden and relay operating voltage must be known. Using Figure 9.14, this voltage is related to the CT secondary exciting current, which is the secondary current error.

Burden should be calculated at maximum secondary current. In most cases, this is the pickup (current) for the element providing short-circuit protection. Thus, the instantaneous element of the relay is assumed to be set at 40 A (8 times rated secondary current or 4800-A primary current). In Chapter 4, it is stated that a direct summation of the burden volt-ampere ratings will produce adequate results. While this is generally true, for precise work the impedance of each CT load should be found then summed.

The time-element burden is 146 VA at 40 A and 0.61 pf, or an impedance,

$$Z_t = \frac{S}{I^2} \angle \cos^{-1} pf = \frac{146}{(40)^2} \angle 52°$$

or

$$Z_t = 0.091 \angle 53° = 0.0557 + j0.0723 \ \Omega.$$

For the instantaneous element,

$$S = 40 \text{ VA at } 40 \text{ A at } 0.20 \text{ pf}$$

or

$$Z_i = \frac{40}{(40)^2} \angle 78° = 0.005 + j0.025 \ \Omega.$$

For the ammeter, negligible saturation will occur at 8.0 times rated current (essentially an air-core magnetic circuit), and its impedance at 5.0 A is about the same at 40 A,

$$Z_a = \frac{(1.04)}{(5)^2} \angle 18° = 0.039 + j0.012 \ \Omega.$$

The interconnecting wire (R_w) and CT (R_{ct}) resistance, 0.08 Ω and 0.298 Ω, are at unity power factor. Consequently, as all burdens are in series, the total burden impedance at 40 A is

$$Z = Z_t + Z_i + Z_a + R_u + R_{ct}$$

$$= 0.477 + j0.110 = 0.489 \angle 12.9° \ \Omega.$$

The magnitude of CT secondary voltage necessary to produce 40 A is then

$$V = I|Z| = (40)(0.489) = 19.6 \text{ V}.$$

From Figure 9.15, the secondary exciting current, I_e, is then:

$$I_e = 0.03 \text{ A}.$$

Therefore, the percent ratio error can be found by

$$\% \text{ ratio error} = \frac{I_e}{I_s} (100) \tag{9.9}$$

or at a secondary current, I_s, of 40 A,

$$\% \text{ ratio error} = \frac{0.03}{40} (100) = 0.1\%.$$

Obviously, accuracy for this application is extremely good.

Only one accuracy calculation example has been shown. As long as the data are available, the technique can be used for any CT application at any pickup current.

9.3-4 Low-Voltage Circuit-Breaker Trips

Pickup. In the preceding, overload and short-circuit pickup settings were primarily related to external relays driven by current transformers. The concepts of pickup also can be applied to low-voltage power circuit-breaker settings and the instantaneous magnetic settings of molded-case units. Pickup, in this context, would be that minimum current, within a specified tolerance (usually ±10%), which would cause the trip element to activate the operating mechanism (2). Although not entirely accurate, the term can be loosely used to describe overload current as defined by the thermal trip elements of molded-case circuit breakers. However, as element tripping is a function of stored heat, tripping times rather than pickup are often

employed (see Section 9.3-6). This section will mainly discuss overload and short-circuit trip settings with molded-case breakers. At the end, trip levels for low-voltage power circuit breakers will be briefly covered.

Overload Protection. Overload protection by thermal-magnetic molded-case breakers has already been mentioned in Chapter 8. To review, most manufacturers calibrate their breakers to carry 100% of the continuous current at 40°C; thus, maximum continuous current is the rating of the thermal-trip unit. Derating is only necessary in non-compensating devices when ambient exceeds 40°C. With these thoughts, the overload procedure given in Section 9.3-2 can be employed to match this continuous current. The thermal element itself defines overload at 125%. For instance, minimum trip time for a typical unit is around 10 s, for 500% or more of the current rating, with time increasing inversely to about 1800 s at 135% of the current rating (10).

Sections 75.900 and 77.900, Code of Federal Regulations, Title 30, define breaker use according to federal law for short-circuit and overcurrent (overload) protection of low- and medium-voltage power circuits serving three-phase a-c equipment. No further references are made to overcurrent protection except Section 75.900-2(c) which notes a circuit breaker protecting more than one branch circuit must be sized to afford overcurrent protection for the smallest conductor. Despite these references to overcurrent protection, federal regulations are interpreted and enforced so as to not require overload protection at each circuit breaker protecting a trailing cable (11).

Perhaps the lack of cable overcurrent protection requirements can be best explained in the following quote from a design engineer working with a-c load centers (12).

> "Breaker thermal trip ratings should be applied to insure complete continuity of operation through all overload current peaks rather then to give complete cable protection. Many applications are being made with no breaker overload protection. Short circuit protection only, by means of the adjustable magnetic trip units takes care of line to line cable faults. Motor control equipment on the machine takes care of motor overloads and may give some overload protection to the cable."

Some states have more stringent requirements than the federal law for overload protection. For example, Pennsylvania requires overload protection on all breakers serving trailing cables. No requirements exist, however, for sizing this overload so an operator may size a thermal-magnetic circuit breaker to whatever criteria that is deemed appropriate.

Short-Circuit Protection. The most common short-circuit protection, provided by the magnetic-trip elements of molded-case breakers, is for trailing cables. For surface mines, the pickup requirements listed in Section 9.3-2 are used. However for underground coal mines, a set of maximum instantaneous settings based on conductor size, are mandated[3]; these are listed in Table 8.3 and apply to both a-c and d-c applications. These settings are based on (13):

1. an ideal 250-Vdc source feeding a bolted fault at the extremity of a 500-ft two-conductor trailing cable, and
2. a 50% safety factor to allow for circuit breaker tolerance, system impedance, and so forth.

Presently, these values are in effect for all underground-coal-mine trailing cables.

Concerned that the d-c basis does not provide an adequate safety margin for resistance-grounded three-phase cables, Fesak and others (13) recommended a new set of maximum allowable instantaneous settings. Shown in Table 9.10, a specific setting is selected by not only conductor size, but also cable length and system voltage. The table stops with 4/0 cables, as this is the maximum practical underground-mine trailing-cable size, but their recommendations extend to 1000 MCM. The calculations behind these values assume an arcing phase-to-phase fault to find minimum short-circuit current.

Similarly, Vilcheck and others (14) recommended a refined set of maximum instantaneous settings for d-c trailing cables, based on minimum expected short-circuit current. These pickups are given in Table 9.11; in addition to conductor size, cable length, and system voltage, the method of grounding is included. Two cases of grounding are available:

1. by means other than a grounding conductor, such as diode grounding, and
2. via a grounding conductor.

With no grounding conductor, only line-to-line faults are of concern, but with grounding conductors, line-to-ground faults can also occur. Therefore, if no ground-fault protection is used, a lower circuit-breaker setting is needed (ℓ-g values in Table 9.11) for cables No. 6 AWG and larger, because of the smaller grounding conductor. Otherwise, the ℓ-ℓ table values are employed.

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[3] Section 75.601-1, Title 30, Code of Federal Regulations, Part 75. If justified, higher instantaneous trips than listed in Table 8.3 are allowed.

Table 9.10. Recommended Instantaneous Trip Settings for 480, 600, 1040 V Three-Phase Trailing-Cable Protection.

Conductor size (AWG or MCM)	Cable length (feet)	Maximum instantaneous circuit breaker setting (amps)		
		480 V	600 V	1040 V
14.....	0- 500	75	100	-
12.....	0- 500	125	150	-
10.....	0- 500	200	250	-
8.....	0- 500	300	400	-
6.....	0- 550	400	550	850
4.....	0- 500	700	850	1200
	501- 600	600	750	1050
3.....	0- 500	850	1050	1350
	501- 650	700	850	1150
2.....	0- 500	1000	1200	1450
	501- 600	900	1050	1350
	601- 700	750	950	1250
1.....	0- 500	1200	1350	1600
	501- 600	1050	1200	1450
	601- 750	850	1050	1350
1/0.....	0- 500	1400	1550	1750
	501- 600	1250	1400	1650
	601- 750	1050	1200	1500
	751- 800	1000	1150	1450
2/0.....	0- 500	1600	1700	1800
	501- 600	1400	1550	1750
	601- 750	1200	1350	1650
	751- 850	1100	1250	1550
3/0.....	0- 500	1900	1950	1900
	501- 600	1700	1800	1800
	601- 750	1450	1600	1700
	751- 900	1300	1450	1600
4/0.....	0- 500	2050	2100	1950
	501- 600	1850	1950	1900
	601- 750	1650	1750	1800
	751-1000	1350	1500	1650

Table 9.11. Recommended Instantaneous Trip Settings for 300 and 600 V Direct-Current Trailing-Cable Protection.

Cond.-size (AWG, MCM)	Cable length (feet)	300 V Max. inst. setting ℓ-ℓ(A)	300 V Max. inst. setting ℓ-g(A)	600 V Max. inst. setting ℓ-ℓ(A)	600 V Max. inst. setting ℓ-g(A)
14.....	0- 500	50	50	50	50
12.....	0- 500	75	75	100	100
10.....	0- 500	75	75	200	200
8.....	0- 500	100	100	300	300
6.....	0- 500	200	100	450	350
4.....	0- 500	400	250	650	500
	501- 600	300	150	550	450
3.....	0- 500	500	350	700	550
	501- 650	400	250	600	450
2.....	0- 500	600	400	800	650
	501- 600	500	350	750	600
	601- 700	450	300	700	550
1.....	0- 500	850	600	1350	1050
	501- 600	700	500	1200	900
	601- 750	600	400	1050	750
1/0.....	0- 500	1050	750	1550	1200
	501- 600	900	600	1400	1050
	601- 750	750	500	1200	900
	751- 800	700	450	1150	850
2/0.....	0- 500	1250	900	1750	1400
	501- 600	1100	750	1600	1250
	601- 750	900	600	1400	1100
	751- 850	800	550	1300	1000
3/0.....	0- 500	1500	1100	1950	1600
	501- 600	1300	950	1800	1450
	601- 750	1100	750	1600	1250
	751- 900	950	650	1450	1100
4/0.....	0- 500	1750	1350	2150	1800
	501- 600	1550	1150	2000	1650
	601- 750	1350	950	1800	1450
	751-1000	1050	750	1550	1200
250.....	0- 500	1950	1500	2300	1950
	501- 600	1750	1300	2150	1800
	601- 750	1500	1100	1950	1600
	751-1000	1200	850	1700	1350

Low-Voltage Power Circuit Breakers. Trip settings for low-voltage power circuit breakers can involve three direct-acting elements (2). The requirement for long-time delay elements is the same as for overload in Section 9.3-2, and the unit is usually set at 100% of the rating, regardless of tolerance. In general applications, the short-time-delay element is set at five times the overload current point, with the instantaneous element set at nine times the overload level. However for mining applications, except for trailing-cable protection, the short-circuit requirements of Section 9.3-2 apply to the instantaneous device. Trailing cables demand the same maximum short-circuit settings as were just discussed.

9.3-5 Fuses

Overload and short-circuit protection can be provided by dual-element fuses on low-voltage or (mainly) power fuses on high-voltage systems. The sizing of fuses is basically the same as for relays or tripping devices in conjunction with circuit breakers. In cable overload protection, the continuous-current rating of a fuse cannot exceed the lowest ampacity of any conductor in the protected system. Beyond this, as a general guide, fuses should always be sized to the very smallest continuous-current rating that will safely carry any load that should be maintained (2).

Transformer inrush currents, if not heeded, can be a problem with high-voltage fuses (and for relay pickup as well). For instance, upon energizing, a power transformer can draw 8.0 to 12 times its full-load current rating for a duration up to 0.1 s (2). Expulsion and boric-acid fuses can be obtained with inverse-time characteristics to withstand this, thereby affording both overload and short-circuit protection of the transformer. Yet high-voltage current-limiting fuses, because of their fast response, often must have a continuous-current rating to account for inrush. In these instances, current limiting fuses can provide only short-circuit protection.

9.3-6 Coordination

General. The basic principles of coordination have already been discussed in Section 8.6 and earlier in this chapter. The following paragraphs are projected at specific procedures used in coordination studies. To elaborate on this subsection, references 1 and 2 are highly recommended.

A coordination study is basically a comparison of the time involved for individual protection devices to operate when normal or abnormal current flows through them (1). A preliminary study should always be made in the early stages of designing a mine power system. This could indicate that transformer sizes or impedances require modification or cable sizes need to be changed.

After devices and components are determined, a final study must be made to confirm the tentative study. Furthermore, a new coordination investigation is required when the original system is changed, for instance, by adding new loads or replacing existing equipment with higher-rated components. Regardless, an additional study should always be made whenever a fault causes a major shutdown of an existing system.

Coordination has two conflicting objectives: protection and selectivity (1). In other words, each relay, tripping unit, or device is bound to a protective requirement and, for maximum safety, each faulted circuit must be isolated as fast as possible. At the same time, continuity of service requires selectivity, which demands successively larger fault clearing times for each protection site from the loads to the source. Optimizing the requirements of these objectives, without compromising personnel safety, is the purpose of a coordination study. A coordination-curve plot is one of the best methods to obtain the desired results. For resistance-grounded systems, two plots can be made: one for phase protection, the other for ground faults. The protection described next refers mainly to phase-protection plots, but also applies to grounding.

Coordination Plots. Before a curve plot is constructed, a coordination study always begins with a good one-line diagram of the system. In addition to normal entries (see Section 4.3-3), this should also include the following information (1,2):

1. maximum and minimum levels of short-circuit current that are expected to flow through each protective device (obtained from a system fault analysis);
2. normal and maximum load currents for each system portion (from a load-flow analysis);
3. current-transformer ratios; and
4. relay, circuit-breaker, and fuse ratings and adjustment ranges (time-current characteristics must also be known).

With these data available, the study can proceed to plotting.

Coordination curve plots are normally drawn on standard log-log graph paper, using the vertical scale for time and the horizontal axis for a common current scale (1). For good results, this scale usually corresponds to currents in the lowest voltage level, and currents in higher voltage levels are plotted on the same scale as equivalents. For instance, if utilization is at 600 V with distribution at 7200 V, the current scale is calibrated for 600 V, currents in those system portions are plotted directly, but distribution currents are multiplied by 7200/600 or 12, then plotted. (Note: this is not a firm rule, as any conventional scale can be used.)

Important current levels can be placed on the graph as points, such as transformer inrush, motor starting, fault current, and so on.

A critical protection path is now selected from the one line by selecting, for example, a critical load or safety hazard and following the protection path back to the source. Fortunately, because of radial distribution, this selection is often an easy matter for most mine power systems. Time-current characteristics of all protective devices, along that path or sometimes affecting that path, are then plotted on the graph.

First of all, such a plot is invaluable as it allows visualization of protective-device action throughout the system on the same current basis (an advantage similar to that of per-unit analysis). Further, it provides the normalization of the characteristics for each protection device, because they rarely have the same shape (and sometimes scale). After construction, the plot allows the selection of current and time settings to provide the best possible protection and safety while also giving selectivity. An approach could be by first specifying the characteristics of the most downstream protection then sequentually positioning each protection step towards the source (or vice versa). An example of a one-line diagram and a corresponding coordination curve plot is shown in Figures 9.16 and 9.17, respectively (2).

Time Intervals. As evident in Figure 9.17, operating time intervals must be maintained between protective devices in order to have correct sequential operation. When applied to relay activated circuit breakers, this time margin must allow for circuit-breaker interrupting time, overtravel time, and a safety factor (2). All these times are additive.

The time required by a circuit breaker to interrupt current, once it receives the trip signal, is equal to its speed in cycles divided by 60. A typical power circuit breaker has an operative speed of five cycles corresponding to an 0.08 s operating time. Overtravel is important in electromechanical time relays, especially inverse-time induction-disk types. Owing to moving-part inertia, these relays will continue to close their contacts even after the fault is removed. Overtravel can thus create a relay operation delay, and typical overtravel time for inverse-time induction-disk relays is 0.01 s. The safety factor mainly allows for variations in relay characteristics due, for instance, to manufacturing, tolerance, aging and dust; the commonly-assigned range is 0.12 to 0.22 s. Summing these factors results in a necessary time-margin range of 0.3 to 0.4 s (2). The typical case is considered 0.4 s, but the margin can be reduced to 0.3 s for carefully tested systems. (Note: static relays eliminate overtravel and allow using the minimum safety factor; thus, the typical time margin can be reduced to 0.2 s. See Chapter 12.)

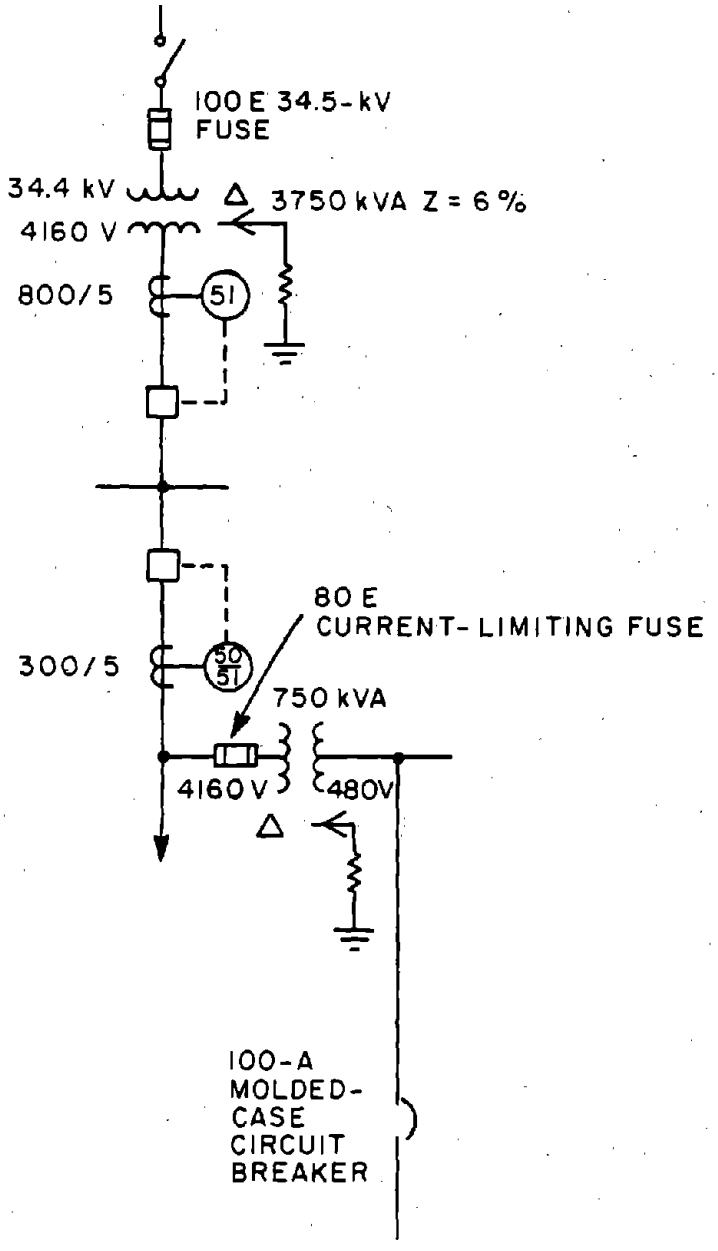

Figure 9.16. One-Line Diagram for the Coordination-Curve Plot in Figure 9.17.

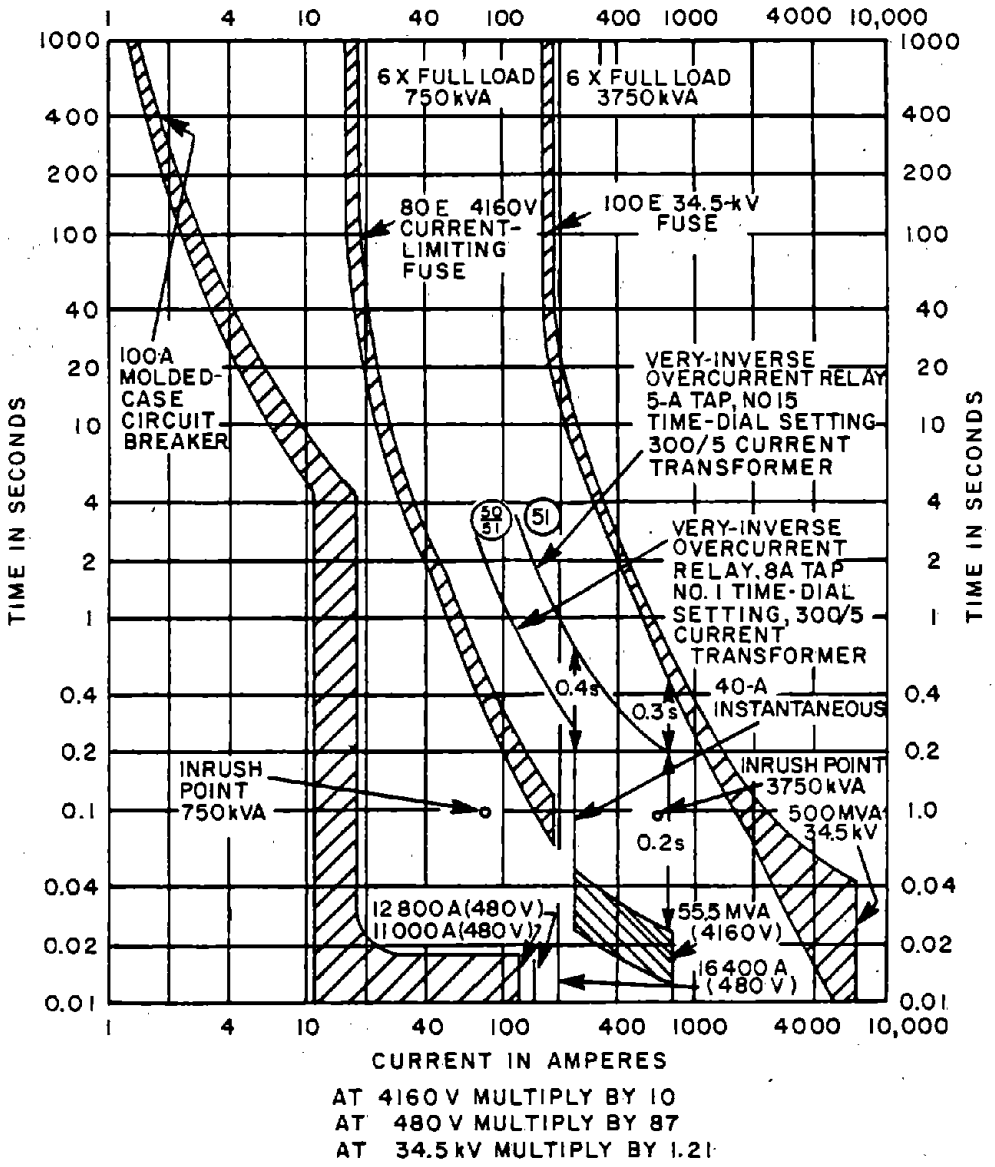

Figure 9.17. Coordination-Curve Plot Showing Various Protective-Device Characteristics.

The above selective time interval is used for relay-to-relay coordination, and instances of phase-relay time selections are shown in Figure 9.17. For an additional example, consider ground-fault protection in a resistance-grounded distribution system. If the most inby switchhouse zero-sequence relay is set to pick up with minimum time-dial setting, the time dial on the ground-fault relay in the next outby switchhouse would be set 0.4 s higher (the time difference can be as low as 0.2 s, allowing for the foregoing constraints). Further, each upstream switchhouse ground-relay time would be set progressively higher until the neutral-bushing of the source transformer is reached. This allowance involves the current equivalent of potential relaying about the grounding resistor. Because of the necessity of maintaining time intervals, many engineers have found that coordination of more than four relays in one ground-fault-current path borders on being impossible for resistance grounding. Regardless, to arrive at each relay operating time, a coordination-curve plot of ground-fault conditions alone can be consulted. Yet, as available ground-fault current in a resistance-grounded mine distribution system remains fairly constant, the same very-inverse relays could be used for all ground-fault protection (perhaps, excluding resistor potential relays), and the manufacturer's characteristic curves might be employed instead of plotting.

The above time interval only considered external relay tripping of circuit breakers. However, even when direct-acting low-voltage circuit breakers are coordinated together or with relayed interrupters, the typical 0.4 s time margin is often utilized. The same is true in coordinating a circuit breaker with a downstream fuse, or a low-voltage circuit breaker with an upstream fuse, when total fuse clearing time is greater than 1.0 s. With less than 1.0 s, fuse-to-circuit-breaker time margins can be reduced to as low as 0.1 s (2).

9.4 Summary

This chapter has served to introduce the important parameters used in protective-device selection and adjustment. Coupled with Chapter 8, the information serves as one basis for Chapter 11, "Mine Power Equipment." There, the components and techniques described in these two chapters will be applied. The next chapter actually contains an additional discussion of another kind of protection, this being for the sometimes hidden dangers of transients and overvoltages.

The material presented in Chapters 8 and 9 might lead an individual to believe that, in terms of safety, overload, short-circuit, and ground-fault protection must be applied to all circuits. Although this is true for almost all portions of the mine power system, most exceptions involve the following fact: equipment protection can never be applied in instances

where personnel safety can be compromised. Examples of this protection exclusion, for the most part, almost always involve unit-designed equipment, such as elevator motors or the swing, hoist, and travel motors of surface excavators. The only other exceptions to mandatory protection are cases where there is no question of personnel safety when protection is not present.

9.5 References

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Chapter 10

TRANSIENTS AND OVERVOLTAGES

10.1 General

The term, "electrical transient," can mean different things to people of different interests. However, there are some common ideas. As defined by Greenwood (1), ". . .an electrical transient is the outward manifestation of a sudden change in circuit conditions, as when a switch opens or closes, or a fault occurs on a system." The circuit parameters of inductance and capacitance are, to some extent, found in any power system. When the system is changed, the quantities of current, voltage, magnetic flux, and so on, do not instantly assume new values. Rather, they go through a transition to reach the new steady-state condition (2). It is this transition period which gives rise to the transient voltages and currents.

Transients are of short duration, and the time in which they occur is an extremely small percentage of the total operating time. However, it is during these short periods that some of the greatest electrical stresses can result, mainly due to excessive currents or voltages. The latter is often critical in mine-power-system design. In extreme cases, system parts are damaged, and equipment failure follows. Safety can be further compromised because anomalous voltages can exist at machine frames.

Transients are a fact of life on every power system, yet careful design, within the technical and economic constraints of a system, will result in a reduction of transient-related component failures. However, mine power systems are particularly vulnerable to transient-induced failures because their operation and arrangements are extremely dynamic. As a mining activity advances, the electrical system is expanded, often on a weekly basis. Although this expansion is normally designed into the system, circumstances in the mine can call for modifications. In some cases, these on-the-spot modifications are not pursuant to sound engineering principles.

A lack of knowledge about transients has resulted in power-system requirements which are considered vague by many mine power engineers. Furthermore, in the process of maintaining the system, faulty components can be replaced with devices of different specifications or even total incompatibility. These two factors also increase the vulnerability of the mine power systems.

10.2 Transient Sources

There are several discrete sources of transient overvoltages. Although there are slight differences in classifying these events,

IEEE standards catalog seven types (3):

1. lightning
2. switching surges,
3. static,
4. contact with a high-voltage system,
5. line-to-ground faults,
6. resonant conditions, and
7. restriking ground faults.

The following paragraphs will briefly introduce these sources in light of mining applications. It should be noted that references 1, 2, and 31 are invaluable sources of transient information, and these should be consulted for detailed coverage of transient phenomena and problems.

10.2-1 Lightning Phenomena

On a global scale, the earth and the lower part of the ionosphere may be considered as conductive bodies separated by a rather poor conductor, the atmosphere. The entire system is analogous to an enormous capacitor with a leaky dielectric. Any charge unbalances which accumulate are dissipated by sudden breakdowns in the dielectric (atmosphere), and the resulting current (i.e., lightning) is of short duration but high amplitude. At any given time, electrical storms are taking place somewhere on earth, and the average current flow between air and earth is more or less constant at a level of 1500 A. During fair weather, the normal voltage gradient in the air near the earth's surface is about 3.0 V/cm, but this rises to around 500 V/cm beneath a thundercloud. The potential difference needed to initiate a lightning stroke is on the order of 50,000,000 V (4). In the continental United States, a typical stroke lasts for only a fraction of a second, yet releases a tremendous amount of energy, approximately 200,000,000 J. The total quantity of charge involved in the average stroke is about 20 C, and the peak current value is around 20 kA (5).

As shown in Figure 10.1, the shape of the discharge starts with an extremely short-duration voltage pulse, whose crest may reach five megavolts or more (6). This is closely followed by the current waveform which rises more slowly to its peak value and lasts longer. About 82% of the strokes occurring in the United States are negative in polarity; that is, they transfer electrons from the clouds to earth. Figure 10.2 illustrates the wide distribution of current magnitudes which may be expected in various lightning strokes (7).

The probability that a particular object will be hit by lightning depends upon the cloud charge intensity, the geographical locale, and the height of the object in relation to its surroundings. Figure 10.3 shows the expected number of thunderstorm

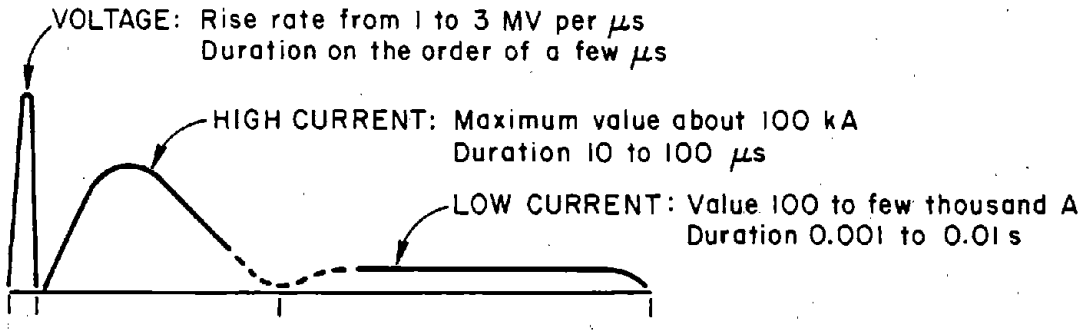


Figure 10.1. Schematic Representation of a Lightning Stroke Discharge.

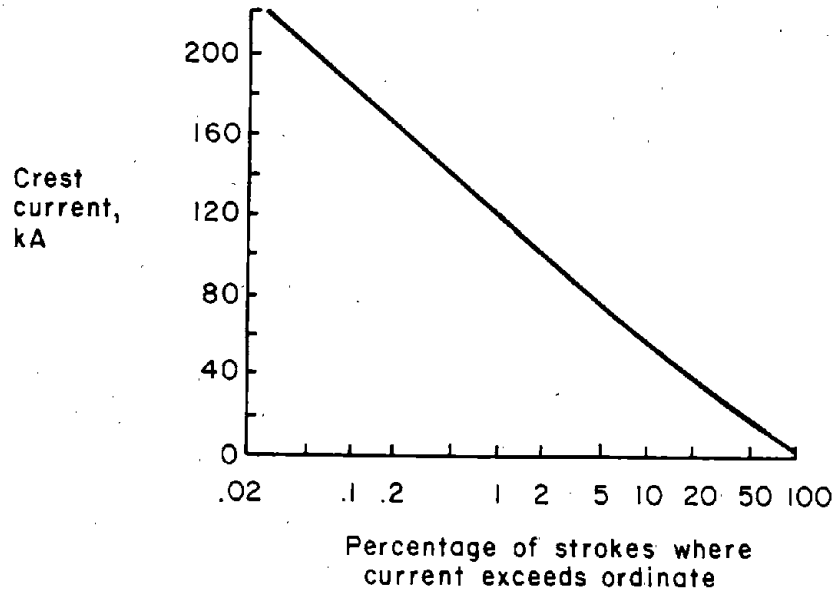


Figure 10.2. Distribution of Crest Currents in Lightning Strokes.

days per year for any of the 48 contiguous states (7). Charge intensity is a parameter because an increased charge in the tip of the stroke generates a proportionally higher electric-field gradient. This determines the "attractive range" of the stroke, in other words the horizontal distance from the tip of a down-coming leader and an object receiving the stroke. As shown in Figure 10.4, the striking distance for a typical 20-kA stroke is about 30 m or 100 ft (7).

The exposed surface portions of a mine's electrical distribution system are particularly vulnerable to lightning. For instance, overhead lines on wood poles are often used to carry three-phase power from substations to surface facilities of underground mines. In surface mines, the overhead lines can extend to the proximity of the shovels and other electrically-operated equipment in the pit. Since these poles, many times, also carry the safety grounding conductor, it is doubly important that they be adequately protected from lightning.

Three separate failure modes are recognized whereby an electrical distribution system may be damaged by lightning. If the impedance to ground of a supporting structure is high and it is struck by lightning, it may become elevated above ground to the point that a flash-over occurs from tower to phase conductor. This is known as "backflashover." If a high-intensity stroke to earth happens nearby, the resultant electric field may be great enough to induce excessive potentials on conductors; a phase conductor can then arc over to the tower. In a "shielding failure," lightning hits a phase conductor directly, raising its potential to the point where arcing takes place between the conductor and the support structure (7). Induced potentials on grounding conductors, including equipment frames, can elevate the ground system above earth and cause damage to protective devices or a personnel hazard. With nearby strokes to earth, the magnitude of the induced voltage depends upon stroke current, distance, and height of the conductor, as illustrated in Figure 10.5 (8).

10.2-2 Switching Transients

Switching operations account for the majority of all transient phenomena. Furthermore, except for direct strikes by lightning, the most destructive power-system transients can occur from this source. Everytime a switch is operated, a transient can occur, but these transients can be classified into two types: normal and abnormal (2). "Normal" voltage and current transients are considered a characteristic of proper operation. The maximum outcome can be a transient voltage or current no greater (but usually less) than two times the system's peak steady-state voltage or current. Transients exceeding this level are termed "abnormal." These are not the result of correct component operation or design. There are several ways that

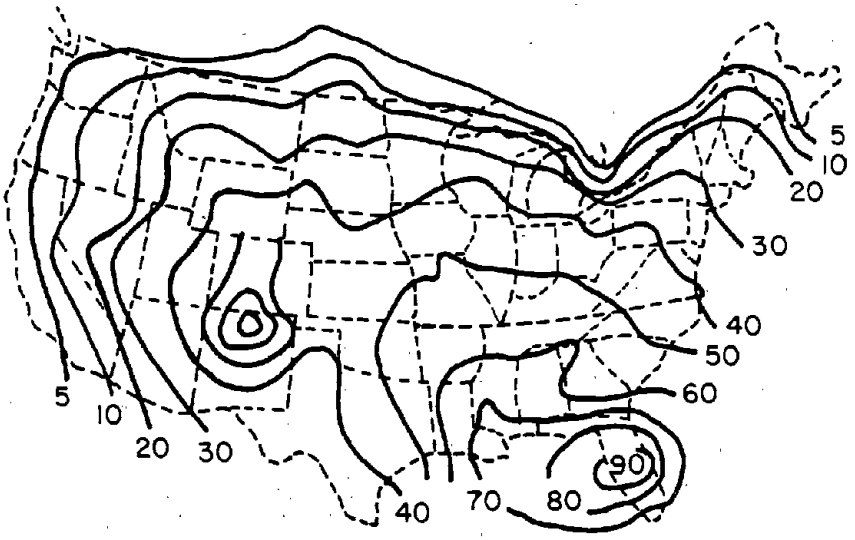


Figure 10.3. Map Showing the Average Number of Thunderstorm Days per Year in the United States.

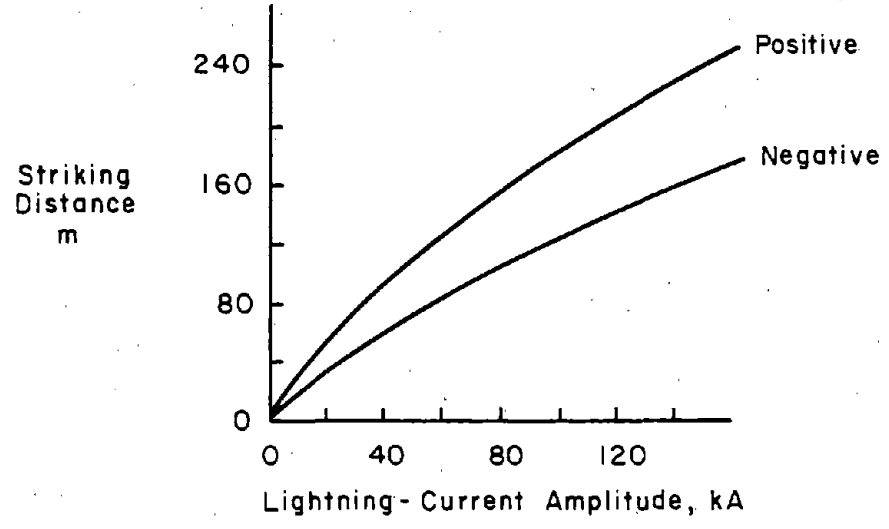


Figure 10.4. Striking Distances for Negative and Positive Strokes.

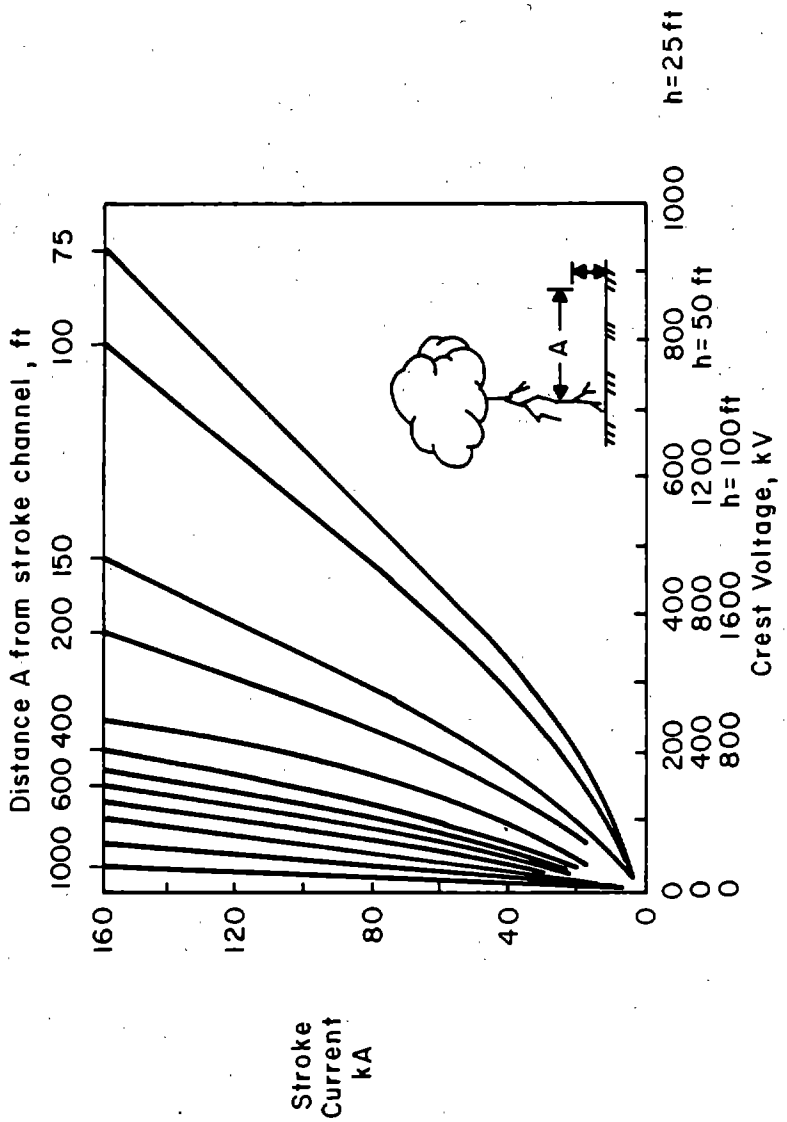


Figure 10.5. Crest Voltages Induced on Transmission Lines by Nearby Strokes.

abnormal transients can occur, but all involve the release or exchange of trapped energy in the power-system inductance or capacitance (1,2). Interestingly, a normal transient can be generated on a quiet power system but, if this transient energy is stored and afterwards a second transient is created, the latter will be abnormal.

Capacitance Switching. Because of the extensive use of cables and power-factor-correction capacitors, capacitance plays a major role in most mine electrical systems. Abnormal transients can occur when a-c current to capacitance is interrupted (1,9,10). The problem is that current leads voltage by nearly 90°. Capacitive currents are usually rather small so there is a good chance that current flow is stopped at a very early current zero. Thus, the load-side capacitance would be charged to the peak voltage of the system, and this energy becomes trapped.

A simple circuit to demonstrate capacitance switching is shown in Figure 10.6, where an a-c source is feeding lumped capacitance through a circuit breaker. Source voltage and current waveforms are given in Figure 10.7a; the point of current interruption is signified by the dashed vertical line. Figure 10.7b shows the voltage across the capacitance, and Figure 10.6c relates the potential, or "recovery voltage," across the circuit-breaker contacts, which is the difference between the source and load sides. System inductance and stray capacitance are neglected in these waveforms to exemplify the effects of the trapped charge (1).

Because early interruption is possible, the voltage across the circuit breaker contacts (the "recovery voltage") may be two times the system peak when the contact gap is quite small. Hence, the arc may reignite or "restrike." With restrike, a LC circuit is formed with a resonant frequency

$$f_o = \frac{\omega_o}{2\pi} = \frac{1}{2\pi(LC)^{1/2}} \qquad (10.1)$$

where

L = the system inductance (H)

C = the system capacitance (F)

f_o = the resonant or "natural" frequency of the system (Hz).

The basic equation for the per-phase voltage after restrike is

$$v = L\frac{di}{dt} + v_c \qquad (10.2a)$$

where

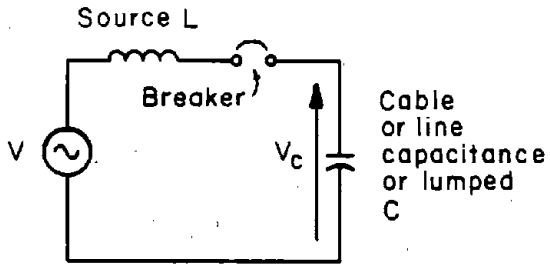


Figure 10.6. Simple Circuit to Illustrate Capacitance-Switching Voltage Transients.

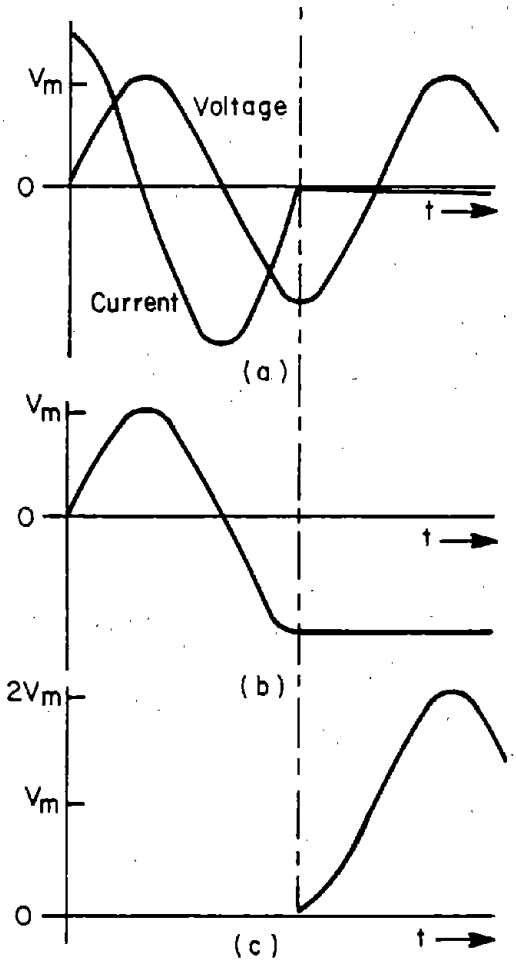


Figure 10.7. Voltage and Current Waveforms Before and After Current Interruption.

v = the source voltage = $V_m \cos\omega t$,

V_m = the peak source voltage (V)

v_c = the capacitance voltage = $V_{c(o)} + \frac{1}{C}\int i\,dt$

$V_{c(o)}$ = the voltage across the capacitance at restrike

i = the current through the circuit breaker (A)

or

$$L\frac{di}{dt} + \frac{1}{C}\int i\,dt = V_m \cos\omega t - V_{c(o)}. \qquad (10.2b)$$

To investigate the current transient in the short time interval after restrike,

$$\cos \omega t \approx 1$$

and thus

$$L\frac{di}{dt} + \frac{1}{C}\int i\,dt = V_m - V_{c(o)}. \qquad (10.2c)$$

Solving this equation for the time-domain current, it is found that

$$i(t) = (V_m - V_{c(o)})\left(\frac{C}{L}\right)^{1/2} \sin \omega_o t. \qquad (10.3)$$

Accordingly, the voltage across the capacitance would be

$$v_c = V_{c(o)} + \frac{1}{C}\int_o^t (V_m - V_{c(o)})\left(\frac{C}{L}\right)^{1/2} \sin \omega_o t\,dt$$

or

$$v_c = V_{c(o)} = \frac{V_m - V_{c(o)}}{(LC)^{1/2}} \int_o^t \sin \omega_o t\,dt$$

or

$$v_c = V_{c(o)} + \frac{V_m - V_{c(o)}}{(LC)^{1/2}} (1 - \cos \omega_o t). \qquad (10.4)$$

For the worst case,

$$V_{c(o)} = -V_m$$

$$V_m - V_{c(o)} = 2V_m,$$

the transient current is

$$i(t) = 2V_m\left(\frac{C}{L}\right)^{1/2} \sin \omega_o t \qquad (10.5a)$$

and transient voltage per phase for the load-side capacitance is

$$v_c = V_m - 2V_m \cos \omega_o t. \qquad (10.5b)$$

Both these sinusoidal waveforms are illustrated in Figure 10.8; the oscillations are at the system natural frequency (1). Equation 10.5b is of special interest as the transient voltage can obtain three times the peak system voltage. The decay shown in the waveforms is due to damping by system resistance. (Obviously, system resistance is neglected in the foregoing derivation, but its effect is considered small as compared to capacitance and inductance for this type of switching.)

To show the significance of the current transient, consider Figure 10.9, which is a per-phase diagram of three-phase motor circuit. Here, three-phase 4160-V power is being fed through a circuit breaker (used as a motor starter) through 25 ft of SHD cable to a 1500-hp wound-rotor motor. A 300-kVAR capacitor bank is used for power-factor correction, placed at the load side of the breaker. Assume that the motor is drawing very little current, the breaker is opened, and interruption occurs at the first current zero. If motor current is very small as compared to what the capacitor draws, the stage is set for restrike. Peak restrike current would be approximately:

$$I_p = 2V_p\left(\frac{C}{L}\right)^{1/2}$$

or

$$I_p = 2(3396)\left(\frac{5 \times 10^{-5}}{10^{-3}}\right)^{1/2} = 1520 \text{ A}.$$

Since the steady-state current through the capacitor is around 45 A, this transient-current peak is about 34 times normal capacitance-current flow, approaching a level expected for motor-starting inrush.

Even though this is significant, the real problem is not the current transient but the possible overvoltage produced. After one restrike, the per-phase voltage can approach 3 V_m, 3(3396) V, or about 10 kV. This is substantial, but within the capabilities of most 4160-V system insulation. However, if the capacitor voltage is still around 3 V_m when current becomes zero again, a current interruption will trap 3 V_m across the capacitor. Now, 4 V_m may

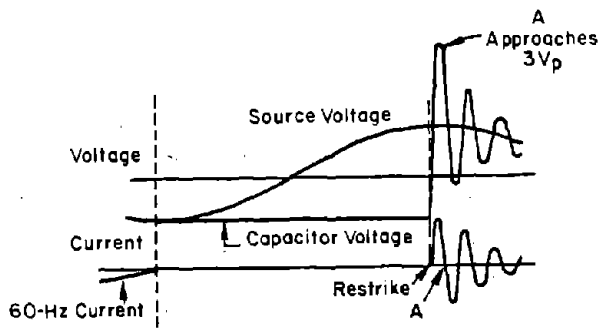


Figure 10.8. Voltage and Current Transient Waveforms Occurring with Capacitance Switching and a Restrike.

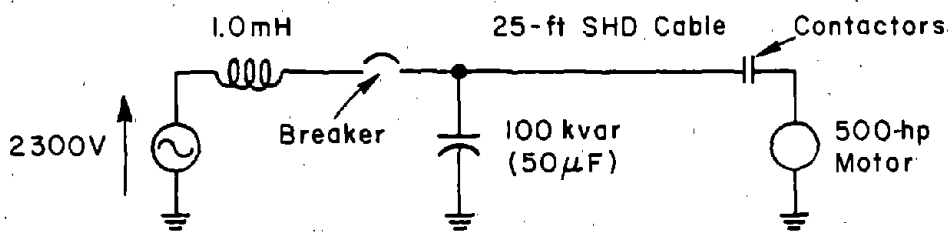


Figure 10.9. Per-Phase Diagram of a 4160-V Pump-Motor Circuit.

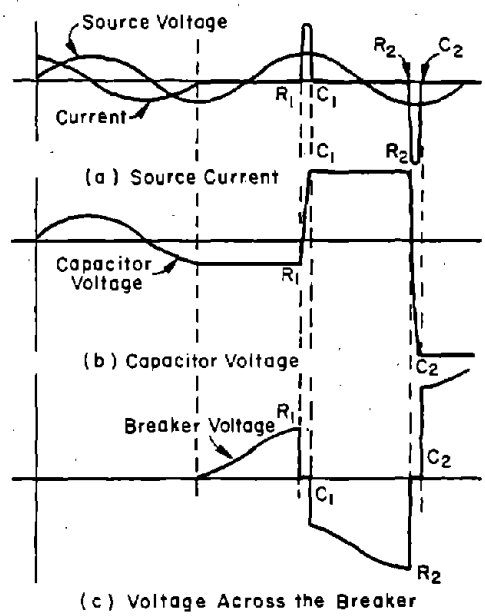


Figure 10.10. Voltage and Current Waveforms Resulting from Multiple Restrikes after Capacitance Switching.

appear across the circuit-breaker contacts, causing a second restrike and a capacitor voltage of -5 V_m. The situation can continue developing higher voltages. Such a "multiple-restrike" process is shown graphically in Figure 10.10 (2). The voltages created can cause insulators to flashover.

The problem here is large capacitance as seen by the switching apparatus, with a very small impedance between the load-side contact and that capacitance. Situation examples could include the charging current to an unloaded cable or distribution line. Yet perhaps the most drastic instance would be interrupting current to a load-side capacitor bank, involving one phase of a grounded bank or two phases of an ungrounded bank.

Current Chopping. The high efficiency of vacuum circuit breakers, which has in part led to their wide application, is ironically the characteristic which can cause severe transients. Such can occur when small currents (for example, transformer magnetizing current) are interrupted. In this case, the small current is forced to zero before the natural current zero, thereby trapping magnetic energy in the power system (1). "Current chopping" is the name of this effect and is graphically illustrated in Figure 10.11. The current waveform before chopping is distorted from the third-harmonic content of the transformer magnetizing current.

The level of current drop (di/dt) at the instant of chopping, is greatly influenced by the contact material, primarily the cathode (11). Most VCB contacts are of a copper-bismuth material and it appears that copper is the large contributor to chopping. Bismuth, in minor amounts, is employed to make the copper brittle, hence reduce its weld strength. Therefore any welding of the contacts during operation, can be easily broken by the breaker mechanism. The copper, however, does not generate enough vapor in the vacuum bottle on small currents to sustain arcing until the natural current zero. Thus this high efficiency can cause current chopping. However, it should be noted that all circuit breakers can chop current to a greater or lesser extent, regardless of the arc environment. Further, as current-limiting fuses are extremely fast, they can cause chopping when interrupting fault currents.

To perceive the magnitude of the created overvoltages, consider the simple mine-power-system segment shown in Figure 10.12, where a switchhouse is connected to a load center by a short cable. A typical switching procedure in mining is to interrupt (or switch out) an unloaded load center, say during a maintenance shift. Even though there are no connected loads on the secondary, the transformer still draws a small amount of magnetizing current (about 0.03 to 0.05 pu of rated current for most mining applications).

A simplified equivalent circuit for Figure 10.12 is shown in Figure 10.13. The components can be considered per phase for the three-phase system. If the VCB chops the magnetizing current at

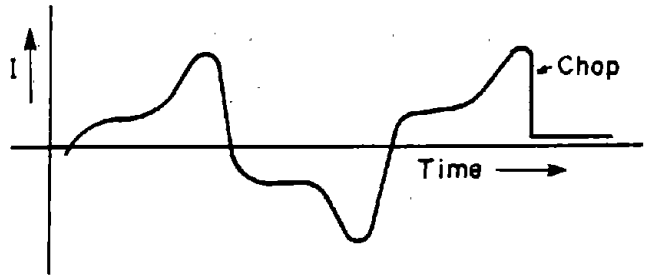


Figure 10.11. Graphic Example of Current Chopping by Breaker Interruption.

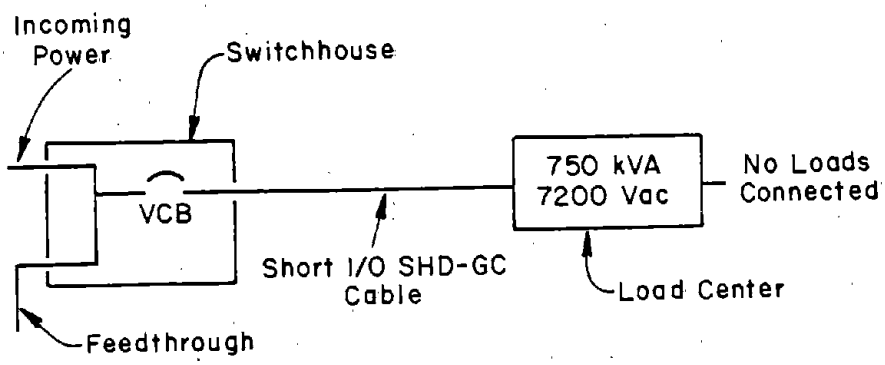


Figure 10.12. A Segment of a Mine Power System.

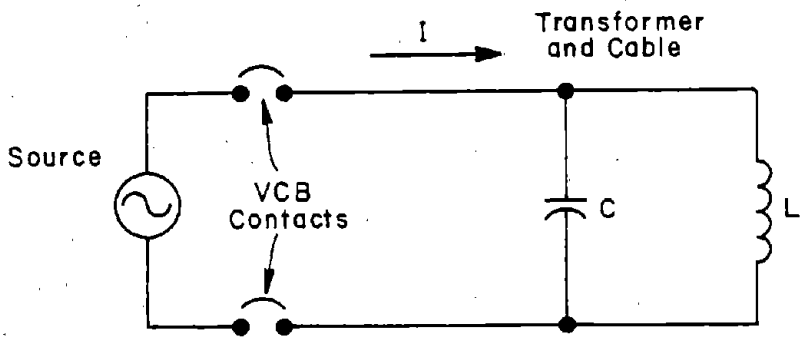


Figure 10.13. Equivalent Circuit of Figure 10.12 with Lumped Components per Phase, Neglecting Resistance.

magnitude I, magnetic energy is stored at that instant in the system inductance (mainly the transformer) at a level (2):

$$W_L = \frac{LI^2}{2} \tag{10.6}$$

where

W_L = the energy stored (J)

L = the transformer magnetizing and cable inductance (H)

C = the lumped capacitance of the cable and transformer (F)

I = the magnitude of chopped current (A).

This energy is then transferred to the capacitance and charges the capacitance to:

$$W_c = \frac{CV^2}{2} \tag{10.7}$$

where

V = the voltage produced across the capacitance (V).

Neglecting losses, both energies are equal, producing a voltage

$$V_p = I\left(\frac{L}{C}\right)^{1/2} = IZ_o \tag{10.8}$$

in which

V_p = the peak transient voltage (V)

Z_o = the system surge (or characteristic) impedance (Ω).

Following the capacitance charging, the energy is transferred back to the system inductance. The effect of transferral (back and forth) will cause oscillations with a frequency equal to:

$$f_o = \frac{1}{2\pi}\left(\frac{1}{LC} - \left(\frac{R}{2L}\right)^2\right)^{1/2} \tag{10.9}$$

where

f_o = the oscillation frequency (Hz)

R = the system resistance (Ω).

Equation 10.9 shows the damping effect of system resistance but, for very small resistances (as are usually the case in power systems), the equation reduces to approximately:

$$f_o = \frac{1}{2\pi (LC)^{1/2}}. \qquad (10.10)$$

This is again the natural frequency of the power system.

The preceding has considered the theoretical pure world and, of course, actual systems exhibit losses. Present day dry-transformer iron limits energy storage to about 40%, mainly through hysteresis losses (12). Therefore, the peak transient voltage is restricted to about 63% of equation 10.8 or:

$$V_p = 0.63\ I(\frac{L}{C})^{1/2} = 0.63IZ_o. \qquad (10.11)$$

An illustration of a resulting voltage transient from chopping (by trapping energy) is given in Figure 10.14.

Again, consider the power system shown in Figure 10.12, but assume that the cable is very short so it has negligible capacitance and inductance in comparison to the transformer. A typical load center in underground coal mining is 750 kVA, and common unloaded transformer values for a 7200 Vac system are C = 3000 pF and L = 15 H. If 1.0 A is chopped by the VCB, the per-phase crest voltage that can be produced on the system is

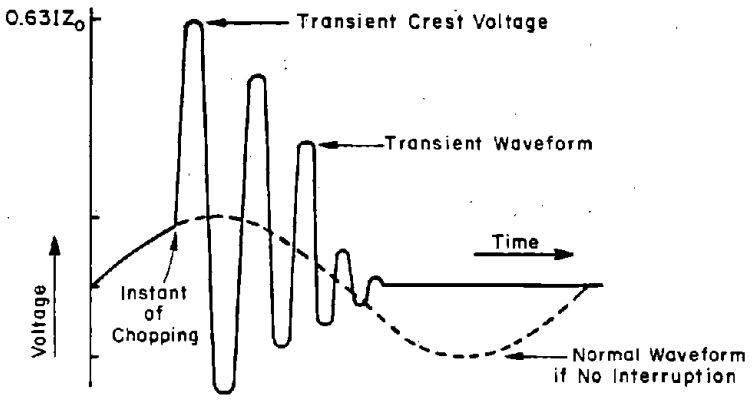


Figure 10.14. Graphic Example of Chopping Voltage Transient.

$$V_p = (0.63)\ (1.0)\ \left(\frac{15}{3 \times 10^{-9}}\right)^{1/2} = 44.5\ \text{kV}.$$

The level is indeed high, being directly proportional to the product of the system surge impedance and the chopped current. Hence, if 2.0 A is chopped (say, the peak due to distortion), V_p would equal 89.1 kV. Importantly, the level is independent of rated system voltage. Common mine-power distribution systems employ 4160, 7200, or 12,470 V, and transformers of the same capacity (kVA) have similar cores, surge impedances, and magnetizing currents. Therefore, similar energy levels can be stored by chopping, and similar peak transient voltages produced, regardless of system voltage.

The magnitude of chopping obviously depends upon the instant of switching. For example, if switching occurred at the natural current zero, no chopping could result, and the transient would be normal. Yet the probability of this happening is extremely small. Consequently if the surge impedance is high, there is a likelihood that serious transients can be created.

Similar configurations to that described above can result in large chopping transients, for example, a cable-connected motor. However, surge impedance and magnetizing current are smaller than for a transformer, thereby reducing the danger of large chopping transients.

In addition to system losses, there are other phenomena that can reduce the transient voltage. After chopping, with only a small VCB contact separation, the dielectric in the bottle is often unable to support the transient voltage, and an arc restrikes (1). Sometimes the circuit breaker will make successive attempts to clear the circuit in this manner, reaching progressively higher voltages as the contact gap increases, until isolation is finally established. However, the maximum voltage attained may not be as great as when switching is clean; the stored energy is not allowed to accumulate. The effect can reduce V_p as much as one-half (12). Nevertheless, the sequential restriking and clearing of a VCB can create dangerous overvoltages, and the voltage escalation can be much more rapid (1).

If the cable length between the switchhouse and load center is increased, the cable capacitance will be proportionally increased. This will reduce the surge impedance and, therefore, the possible severity of the chopping transient. Yet, too large a capacitance can result in other transient phenomena, not only from restrikes, as previously covered, but also from the type which follows.

Prestrike. During initial energization of system capacitance, an arc ignition or "prestriking" may occur across the contacts of

a circuit breaker, prior to (final) mechanical closure (13). The phenomena appears to be enhanced when the load-side capacitance is "considerably" in excess of the source-side capacitance. However these events seem dependent upon the capacitive inrush current, and the magnitude of inrush current is mainly controlled by the amount of load-side capacitance. Prestrike transients have usually been associated with vacuum interrupters, and overvoltages have been found to reach substantial levels if the initial inrush current caused by the prestrike is momentarily stopped then followed by a subsequent prestrike or contact closure. Situations can involve energizing one phase of grounded capacitance or two phases of ungrounded capacitance.

Hypotheses accounting for prestriking include the following (14).

1. Contact "whiskers." When exposed to a high electrostatic stress in a vacuum, extremely fine filaments can grow from the surface of metals. Such filaments could cause an arc ignition.

2. High electric-field strength. Stress created by a high electric-field strength could cause breakdown of the dielectric.

3. Contact bounce. "Contact bounce" is deflection of the moving contact after impact with the fixed (of the interrupter). Considered as caused primarily by a "weak" operating mechanism, the resulting separation could allow arc extinction.

Whatever the source, if the load-side capacitance is uncharged and a prestrike occurs, the voltage on the immediate load side of the breaker will collapse to zero. This can cause voltage and current traveling waves (see Section 10.2-4) to radiate on cable and lines. The waves can reflect and refract at discontinuities of the system characteristic impedance, and the typical frequencies of the resultant waveforms can be 60, 600, 6000, 60,000 and 600,000 Hz, all superimposed. The combination of the harmonics obviously has many current zeros and, when these zeros occur between the prestrike and the mechanical contact closing, the circuit breaker can easily interrupt the inrush-current flow. In the same manner as capacitance switching, energy can be trapped on the capacitance being energized. Subsequent arc reignitions then interruptions can create an unusually rapid escalation of high overvoltage. Pflantz (13) has found that prestrike transients can have crest voltages up to 7.0 pu of system peak, with an oscillating frequency band that spans from 60 Hz into the megahertz region.

The combination of capacitance switching, chopping, and prestrike is very perplexing for high-voltage distribution design. If capacitance on the downstream side of an interrupter is small,

destructive voltage transients can occur from current chopping. However, when this load-side capacitance is large, overvoltages may result from capacitance-switching or prestrike event. Consequently, the placement of capacitance within a mine power system is critical, and this will be discussed in Section 10.4.

It is interesting to note from the foregoing discussion of a-c switching transients, that the resulting overvoltage in each case can crest in the neighborhood of 7.0 pu of the system peak voltage or more. However, a way to distinguish among the three types is the oscillation frequency:

1. the system natural frequency for capacitance switching or chopping (generally less than 10 kHz), and
2. much higher for prestrike (often these have frequency components greater than 100 kHz.

Direct-Current Interruption. Direct-current systems are also subject to abnormal voltage transients from circuit openings. Opposed to a-c, where interruption generally occurs at a current zero, d-c must be forced to zero. Large amounts of energy can be stored in the system inductance and any sudden current decrease can result in an overvoltage. The magnetic energy is transferred to capacitance in a-c circuits, but in d-c the energy is dissipated in the arc (9). The arc voltage tends to drive current in the opposite direction of that from the source, forcing the circuit current to zero.

Figure 10.15 shows a simple d-c circuit to illustrate the overvoltage phenomenon and could represent a switching operation to clear a short circuit. The relationship for voltage and current is

$$L \frac{di}{dt} = V_s - v_A \qquad (10.12)$$

where,

L = the system inductance (H)
i = the system current (A)
di/dt = the rate of current change (A/s)
V_s = the source voltage (V)
v_A = the arc voltage (V).

To stop current flow, the arc voltage must be greater than the source potential (see Figure 10.16). As the source is constant, the peak transient voltage is proportional to the rate of current decrease (i.e., the faster the decrease, the higher the voltage produced).

The same thoughts can also be applied to interrupting d-c motor operation (as well as other current flows). For instance,

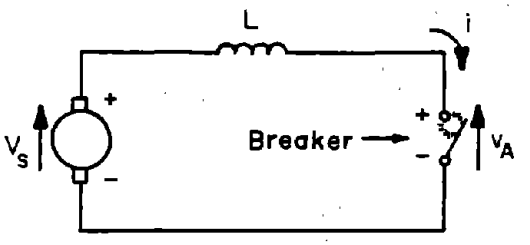


Figure 10.15. A Circuit to Demonstrate Voltage Transients in Direct-Current Systems.

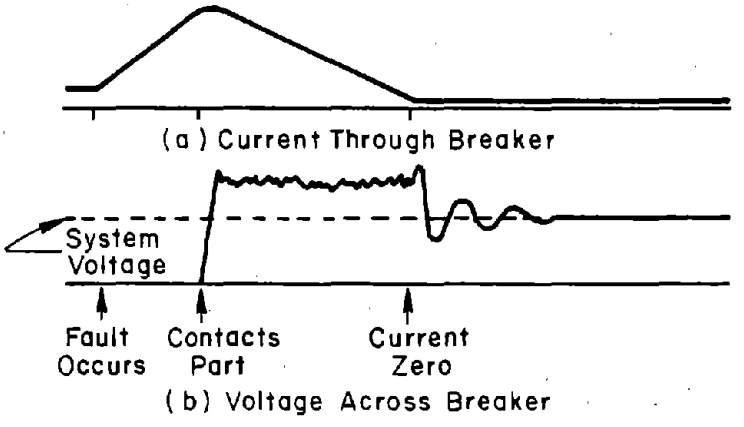


Figure 10.16. Transient Overvoltage Resulting from Current Interruption on a Direct-Current System.

if a d-c motor current is terminated, there exists a high rate of current charge. Such can develop a voltage, across the system inductance between the source and the motor contactors, equal to Ldi/dt. A dramatic example of this would be dropping the contactors on a large trolly locomotive while drawing full-load current.

Other Switching Transients. Transient problems are not restricted to main power components. Considering a-c or d-c systems, small tripping and relay coils when coupled with a very small capacitance can exhibit high voltages even though they operate in low-voltage circuits (2). Silicon diodes and silicon-controlled rectifiers can create considerable overvoltages by current chopping, sufficient to destroy themselves (1). In fact, solid-state conversion equipment is constantly in a transient state.

10.2-3 Other Transient Phenomena

Due to existing protection methods in mine power systems, transients resulting from line-to-ground faults or contact with higher voltage lines are minor, although destruction from localized heating may be severe. However, if the protective circuitry malfunctions, as sometimes occurs in the harsh mining environment, the problem can become critical. Local heating at the fault site will cause the conductors to melt. As this happens, the potential gradient across the conductors is sometimes sufficient to strike an arc. The arc will extinguish and reignite, all things remaining equal, at each zero crossing of the voltage wave. The random fluctuation of arc resistance, as well as phenomena related to arc reignition, results in large transient overvoltages (2).

Resonant conditions can result in transients exceeding ten times the nominal line voltage (2). Since the power-system contains inductance and capacitance which are normally much greater than system resistance, resonance can occur at the natural frequency of the system. Resonance may result from the presence of line-frequency harmonics (harmonic overvoltage) or from the frequency components of other transients (dynamic overvoltage). Although this is probably not the most frequent form of transient voltages, the number of failures resulting from this mode are believed by some engineers to be significant. When transformers are involved, transient resonant conditions creating dynamic overvoltages have historically been given the term, "ferroresonance." Considering circuit component values, the occurrence of these transients in mine power systems should be rare. However, a possible problem area could be a pole-mounted transformer powered through a cable feeder, but the series-resonant condition can be easily corrected by simply changing the cable length (15).

Restriking ground faults, which are found primarily on ungrounded systems, can cause transients several times greater than the nominal line voltages. Some systems are operated ungrounded

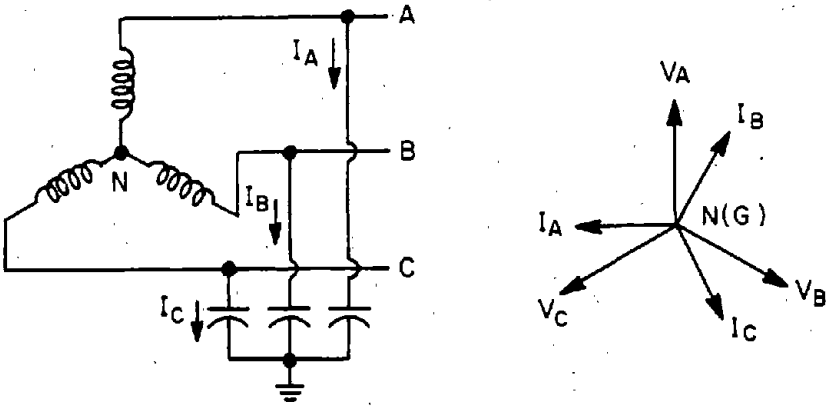


Figure 10.17. An Ungrounded System, Showing Capacitive-Current Flow.

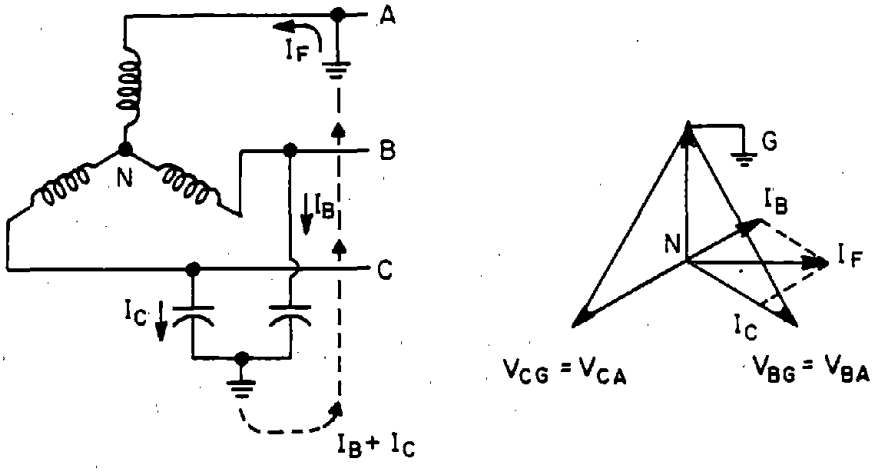


Figure 10.18. An Ungrounded System, with Fault on Phase A.

because, when a phase-to-neutral fault occurs, little or no fault current flows, and the system remains operational. Yet, some current will exist due to system capacitance. To illustrate the effect of this capacitive current during faulting, Figure 10.17 shows a normal ungrounded system, with Figure 10.17a providing the voltage and current phasors. As shown in Figure 10.18, consider that a phase-A-to-ground fault occurs; I_f is a small fault current but sufficient to support an arc. The arc may extinguish itself at a current zero but, when this happens, phase-to-phase voltages are trapped on phases B and C. The system voltage will thus be offset on these phases (see Figure 10.18b). In the oscillatory return to steady state, it is possible to get restrikes of the fault and further self interruption. In other words, a large voltage can build up. Consequently, this is a major reason why systems should not be operated ungrounded unless stern overvoltage precautions are heeded.

Since coal-mine power systems for portable and mobile equipment are required to use a resistance ground, restriking-ground-fault transient generation is also rare, except when the protective-circuitry malfunctions. A specific case would be an open grounding resistor. Then, uncleared faults may cause transients.

10.2-4 Traveling Waves

The transient discussion, except for prestrike, has considered circuits which have lumped resistance, capacitance, and inductance. In many circuits, even though these parameters are distributed, transient behavior can be accurately predicted (1). However, there are many power-system portions where concentration will result in too large an approximation. An outstanding example is a transmission or distribution line, be it overhead or cable (16). Fortunately, these exhibit a certain resistance, inductance, and capacitance per unit length of line, respectively R, L, and C. For analysis, the line can be divided into small but finite elements as shown in Figure 10.19 (resistance and leakage are neglected) (16).

The voltages created by transient can have a "rise-time" in microseconds; in other words, they rise from zero to peak in that time. When very fast voltage changes occur, it is often best to analyze the system in terms of traveling waves, rather than by conventional methods (16). To show why, consider Figure 10.19 given that the switch has just closed. Conditions that exist at the source end are not immediately observed at the load end; it takes time to pass the voltage-current conditions through each LC segment. A feature of a circuit with distributed impedance is its ability to support traveling waves of voltage and current (1).

From analysis of this circuit, with Δx made very short, it can be shown that the voltage-current relationship for each incremental section is (1):

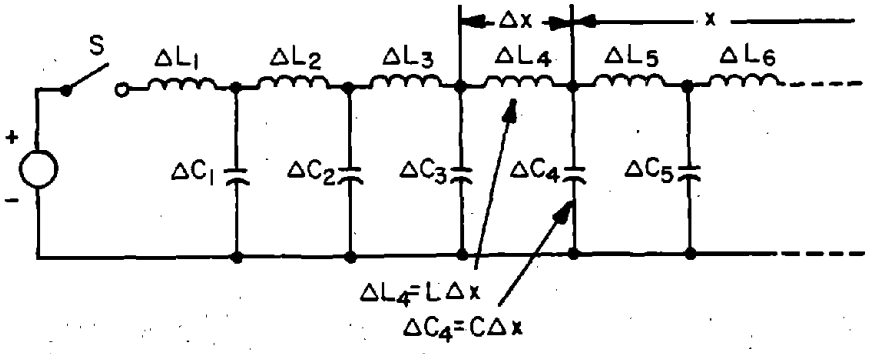


Figure 10.19. The Distributed Inductance and Capacitance of a Two-Wire Line Shown as Incremental Sections.

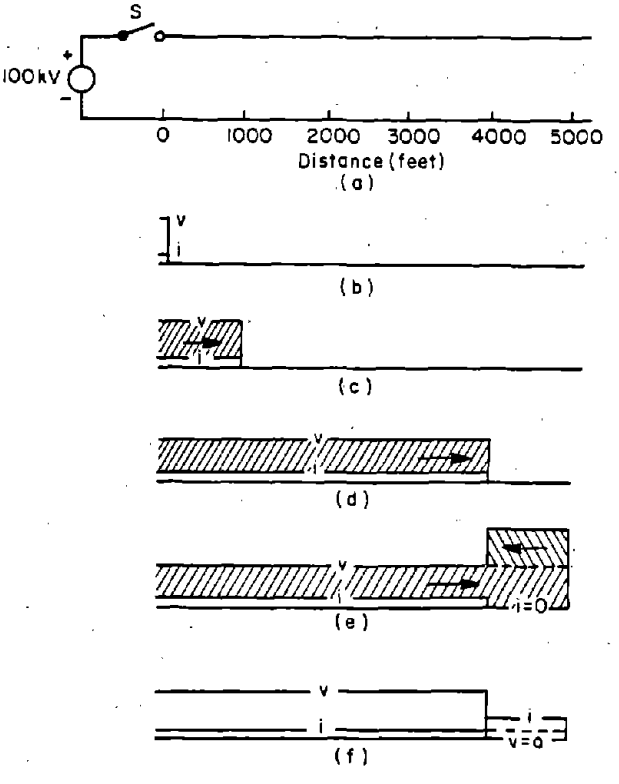


Figure 10.20. Demonstration of a Traveling Wave on an Overhead Line.

$$dv = \sqrt{\frac{L}{C}}\, di$$

$$v = \sqrt{\frac{L}{C}}\, i = Z_o i \qquad (10.13)$$

where

v = the voltage existing in the incremental element (V)
i = the current existing in that element, (A)
L = the total inductance of the line, (H)
C = the total capacitance of the line (F)
Z_o = the surge impedance or "characteristic impedance" of the line (Ω).

The propagation velocity, U, of voltage and current is (1):

$$U = \frac{dx}{dt} = \frac{1}{\sqrt{LC}}. \qquad (10.14)$$

For open lines, the propagation velocity is approximately the speed of light, 1000 ft/μs; with solid-insulation cable, the speed is about 500 ft/μs (17).

To illustrate the time behavior, suppose an overhead line with 400-Ω surge impedance, depicted in Figure 10.20a, is hit with an 100-kV step function at time, t = 0 (16). At this instant, voltage and current exist only at the source end and nowhere else on the line (see Figure 10.20b). At t = 1.0 μs, the voltage-current conditions have propagated down the line 1000 ft and, between zero and 1000 ft, the voltage is 100 kV with the current

$$i = \frac{v}{Z_o} = \frac{100000}{400} = 250 \text{ A}.$$

Beyond 1000 ft, voltage and current are zero (Figure 10.20c). At t = 4.0 μs, the surge has moved 4000 ft, voltage and current being 100 kV and 250 A to the left of that point, zero to the right (Figure 10.20d).

Reflection and Refraction. If the line shown in Figure 10.20a was of infinite length, the bundle of energy would theoretically travel forever. Because conductors have finite length, problems occur at the line end or at a "discontinuity," which is a point where the surge impedance changes (1,16). At either place, the strict proportionality between the voltage wave and the associated

current wave must be satisfied by adjustment. Reflected and refracted waves are the result. The "reflected wave" propagates back down the line superimposed on the original or "incident" wave, whereas the refracted wave travels beyond the discontinuity. The reflected and refracted amplitudes are such that the voltage-to-current proportionalities are preserved, as dictated by equation 10.13 and the surge impedances for the lines on which they travel (1). Expressed mathematically,

$$v_1 + v_2 = v_3 \tag{10.15a}$$

$$i_1 + i_2 = i_3 \tag{10.15b}$$

where

$$v_1 = Z_1 \, i_1 \tag{10.15c}$$

$$v_2 = -Z_1 \, i_2 \tag{10.15d}$$

$$v_3 = Z_3 \, i_3 \tag{10.15e}$$

and

v_1, i_1, Z_1 = the condition for the incident wave
v_2, i_2, Z_2 = the condition for the reflected wave
v_3, i_3, Z_3 = the condition for the refracted wave.

The assumption is that energy is conserved. The minus sign expressed for equation 10.15d is because i_2 is traveling in a minus-x direction and thus has a sign opposite of v_2. By combining the above equations, expressions for the reflected and refracted voltage-wave magnitudes in terms of the incident wave can be obtained:

$$v_2 = \frac{Z_2 - Z_1}{Z_2 + Z_1} \, v_1 \tag{10.16a}$$

$$v_3 = \frac{2Z_2}{Z_2 + Z_1} \, v_1 . \tag{10.16b}$$

Traveling-wave behavior under reflection and refraction can be demonstrated using the preceding example and terminating the overhead line by either an open circuit, short circuit, or a line with a different surge impedance.

Figure 10.20e illustrates the conditions if the line end is open circuited. At the instant the incident waves reach the end, the current at that point must be zero, as equation 10.15b relates,

$$i_1 + i_2 = 0$$

or

$$i_2 = -i_1$$

but, by equation 10.15d,

$$v_2 = -Z_1 i_2 = Z_1 i_1 = v_1.$$

In other words, the reflected current wave will have a magnitude of $-i_1$, the reflected voltage wave having v_1. Moving to the left, both will superimpose on the incident waves. Therefore, at t = 6.0 μs, as shown in the figure, the voltage from 4000 to 5000 ft is 200 kV, and the current is zero.

Instead of an open circuit, consider that the line end is short circuited. When the incident waves reach the short circuit, the voltage at that point must be zero, or from equation 10.15a,

$$v_2 = -v_1$$

yet, by equation 10.15d,

$$i_2 = -\frac{v_2}{Z_1} = \frac{v_1}{Z_1} = i_1.$$

In this case, the reflected waves superimposed on the incident waves will result in zero voltage, but two times the incident current magnitude. Figure 10.20f shows the conditions at t = 6.0 μs, with current to the right of 4000 ft as 500 A.

Now, suppose that the overhead line is terminated by a cable with 50-Ω surge impedance. The situations before and after the incident waves reach the junction are shown in Figure 10.21 (1). For the reflected wave (equation 10.16a),

$$v_2 = \left(\frac{50 - 400}{450}\right) 100 \text{ kV} = -78 \text{ kV}$$

and (equation 10.15d),

$$i_2 = \frac{(-78,000)}{400} = 195 \text{ A},$$

for the refracted wave (equation 10.16b),

$$v_3 = \left(\frac{2\ (50)}{450}\right) 100 \text{ kV} = 22 \text{ kV}$$

and (equation 10.15e)

$$i_3 = \frac{22,000}{50} = 445 \text{ A}.$$

Therefore, the surge that penetrates the cable has a marked reduction of voltage magnitude. The benefit is employed in power systems to protect equipment from surges coming down connected lines (1). Instances include machine trailing cables in surface mines and feeder cables for underground mines. It should be noted that for this case, the refracted waves propagate at 500 ft/μs, whereas the reflected waves are traveling at 1000 ft/μs.

The foregoing thoughts can be expanded to any line termination, including those which have more than two connections. Within a specific line, reflections can occur at both ends, causing the traveling waves to move back and forth. Resistance and leakage has been neglected so the energy of the traveling wave is conserved. In practical circuits, the presence of these means losses are incurred when current flows, and the loss serves to attenuate the waves magnitudes as they propagate (1). Even though the preceding demonstrations have used only a step function and disregarded losses, the concepts can be applied to any waveform with very fast voltage rise time.

A couple of important points can be extracted from this brief discussion of traveling waves (16). First, if a line is open ended, terminal equipment of that line may experience a potential higher (up to two times) than that for the traveling wave which produced it. Next, a common practice to protect

personnel working on exposed power lines is to place protective grounds on each power conductor. Consider that a traveling wave is on the line, such as that produced by a lightning stroke, and a person is touching that line between the surge source and the protective ground. The person will be exposed to the incident voltage for the time the wave travels from that location to the protective ground and back. Accordingly, such protective grounds should always be installed right at the work site, or at least between probable surge locations and the workers.

10.2-5 Electromagnetic Phenomena

As might be obvious now, electrical transients are in essence electromagnetic phenomena. According to Faraday's law, transients existing on a specific circuit can thus produce electrostatic and electromagnetic induced voltages on nearby or associated circuits.

It was shown in Chapter 3 that whenever two charged conductors are separated, an electric field and a potential difference exists between them. The charge is related to the potential difference by the proportionality constant capacitance. The physical arrangement between the conductors is shown in Figure 10.22a (1). As shown by Figure 10.22b, when another conductor is placed in the same space, it distorts the original electric field. There will exist a charge separation on the third conductor surface, and the conductor will assume a potential somewhere between the original two conductors. The relationship will also establish capacitances among the three conductors (1).

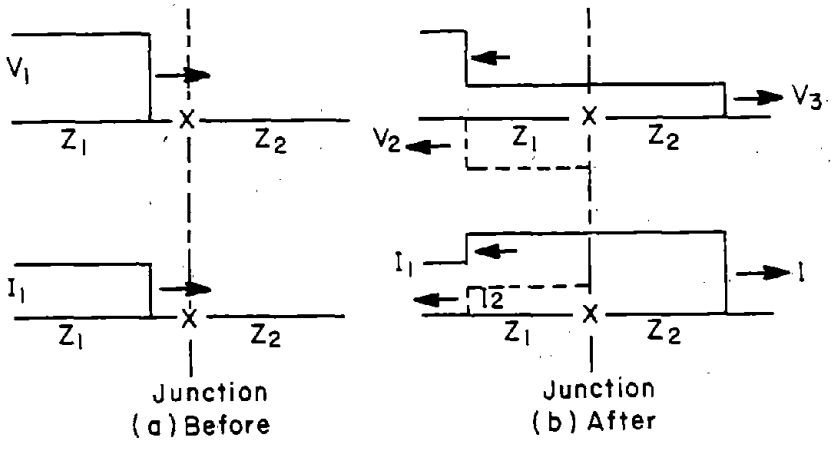
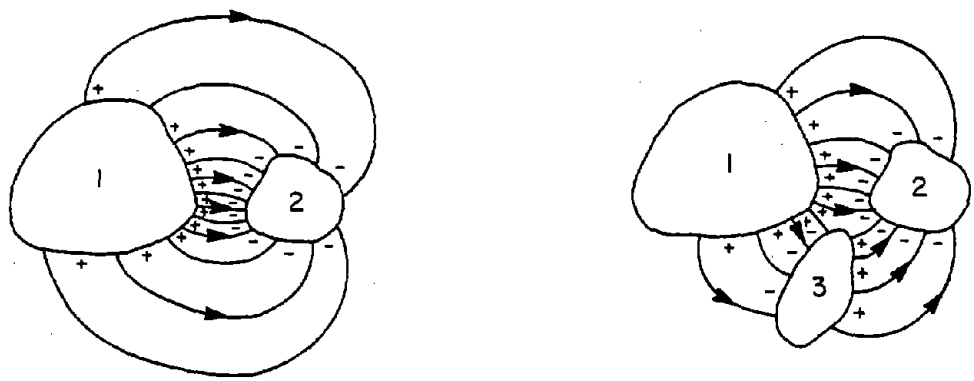


Figure 10.21. Incident Waves Being Reflected and Refracted at a Discontinuity.



(a) Two Charged Conductors (b) Third-Conductor Presence

Figure 10.22. Electric Field Between Conductors.

Suppose that conductors 1, 2, and 3 are, respectively, high-voltage power, grounding, and ground-check conductors. If the potential on the power or grounding conductor suddenly changes, an emf is induced in the ground-check conductor, causing current flow. This redistribution of charge could operate a relay, thereby nuisance tripping a circuit breaker. The third conductor could be for some other control, monitoring, communication, or grounding circuit. Beyond false relay operation, the result in these cases might be incorrect machine operation, erroneous meter readings, communications noise, or injury to personnel.

10.3 Transient-Induced Failures

General. Deteriorating electrical insulation affects the entire mine power system and may jeopardize its safe operation. Whether the dielectric is in a transformer winding, motor winding, portable cable, or rectifier, it is a critical factor in the safe, economical, and reliable operation of any mine power system. Disturbances which threaten to compromise the integrity of the power system must be eliminated at the source. This is why attention must be paid to the causes of electrical transients and their elimination. Consequently, it may be helpful to examine the effect of abnormal voltages on dielectrics.

Each type of insulation or dielectric is designed for a safe maximum applied voltage and a transient overvoltage. The transient overvoltage rating is given in terms of "BIL," the Basic Impulse Insulation Level. The most common BIL measurement is the 1.2 x 50 wave test (see Figure 10.23), where the voltage impressed across the dielectric reaches its peak in 1.2 μs (17). Thus, a dielectric with a 95-kV BIL rating can safely withstand a 1.2 x 50 pulse of 95 kV. This wave test is considered more severe than the transients found in mine power systems.

The event of dielectric deterioration is determined in large part by the rise time of the transient, as well as the crest magnitude. Furthermore, the greater the overvoltage pulse width (duration), the greater the probability for failure, as more energy is involved. These voltage anomalies break molecular bonds in the dielectric, which reduces its effectiveness. If the overvoltage contains sufficient energy, the dielectric can fail immediately; however, this is usually not the case. Rather, the insulation is progressively weakened until it finally fails. The result is a line-to-ground or line-to-line fault.

If the weakened insulation is in a portable cable or splice, a considerable personnel safety hazard exists, since the insulation "appears" to be functional when in reality a lethal potential may exist on the cable surface. Although the deteriorating dielectric may not present a direct safety hazard, complete failure may do so from an explosion or arcing. In any case, a serious hazard exists for the equipment in terms of repair, replacement costs, and downtime.

Winding Response. The physical construction of equipment may increase its susceptibility to transient failure. For instance, motor and transformer windings often fail at the end of a coil due to increased electrical gradient. Figure 10.24 can be used to show why this can happen (1). Illustrated is the distributed nature of the winding inductance and capacitance. The capacitance is assumed to be uniformly divided among the windings, consisting of capacitance to ground and to adjacent turns; resistance is neglected. The winding neutral may be grounded depending upon the position of the switch.

From an analysis of the circuit, the following general equation can be obtained (15):

$$C \frac{\partial^2 V}{\partial t^2} = K \frac{\partial^4 V}{\partial X^2 \partial t^2} + \frac{1}{L} \frac{\partial^2 V}{\partial X^2} \qquad (10.17)$$

where

C = the winding capacitance to ground (F/m)
K = the winding series capacitance (F/m)
L = the winding inductance (H/m)
V = the voltage applied across the winding (V).

By simplification, this can be used to solve for the response of the winding to a surge. Consider that surge waveform is a step function with amplitude, V. If the neutral is grounded, at the instant the step function hits the winding, the initial voltage distribution across the winding is

$$V_x = V \frac{\sinh \alpha x}{\sinh \alpha l} \qquad (10.18)$$

and for the ungrounded neutral

$$V_x = V \frac{\cosh \alpha x}{\cosh \alpha l} \qquad (10.19)$$

where

$$\alpha = \left(\frac{C}{K}\right)^{1/2}$$

l = the winding length (m)
x = the distance between the neutral and a point on the winding (m)
V_x = the voltage at that distance x (m).

For a specific α, the initial voltage distribution across the winding in response to the surge can be plotted, as shown in Figure 10.25 (1).

This figure relates that as α increases, the distribution becomes nonuniform. When $\alpha = 10$, 60% of the voltage is initially impressed across the first 10% of the winding, with 75% across the first 20%. Therefore, under surge conditions, very high stresses can occur on the first few turns and, if precautions are not taken, transformers and motors can fail by breakdown of turn-to-turn insulation in this region.

Coupling Through Transformers. When a fast rise-time voltage surge hits a transformer, as just shown, the parameter of concern is winding capacitance. Series capacitance and capacitance-to-ground exist not only for the primary, but the secondary winding as well. Figure 10.26a approximates the situation for a two-winding transformer, and the equivalent circuit, shown in Figure 10.26b, forms a crude capacitive voltage divider (1). When a change of voltage is applied to the primary, the voltage divides inversely with capacitance (18, 19):

$$V_s = \left(\frac{C_1}{C_1 + C_2}\right) V_p \qquad (10.20)$$

in which

V_p = the magnitude of transient voltage impressed on the primary (V)
V_s = the magnitude of transient voltage transmitted to the secondary (V)
C_1 = the primary-to-secondary winding capacitance (F)

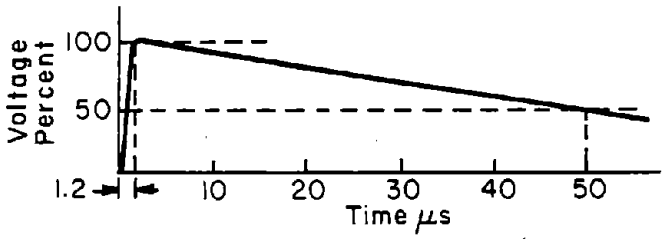


Figure 10.23. A 1.2 x 50 Test Wave Used for BIL Measurement.

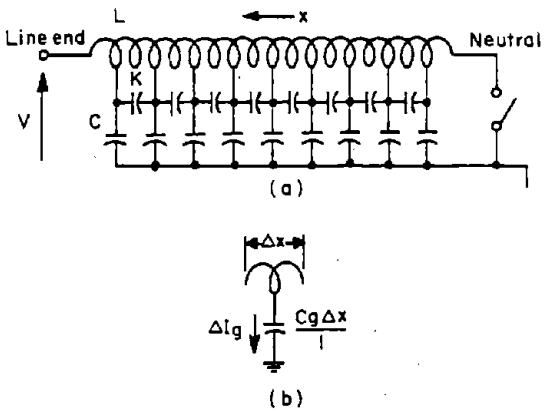


Figure 10.24. An Equivalent Circuit of a Multiturn Winding Showing Distribution Inductance and Capacitance.

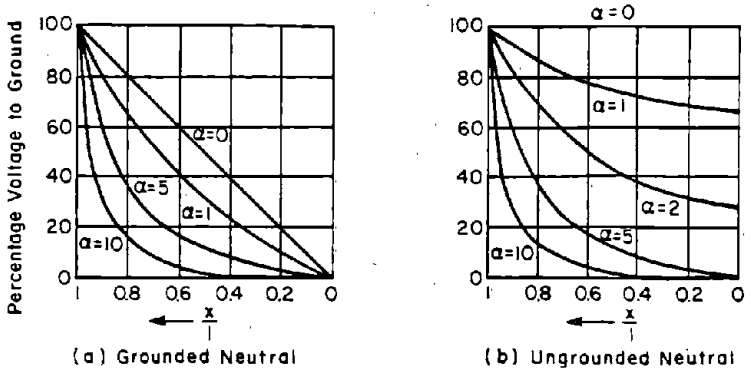


Figure 10.25. Initial Voltage Distribution Across a Uniform Winding from a Step Function.

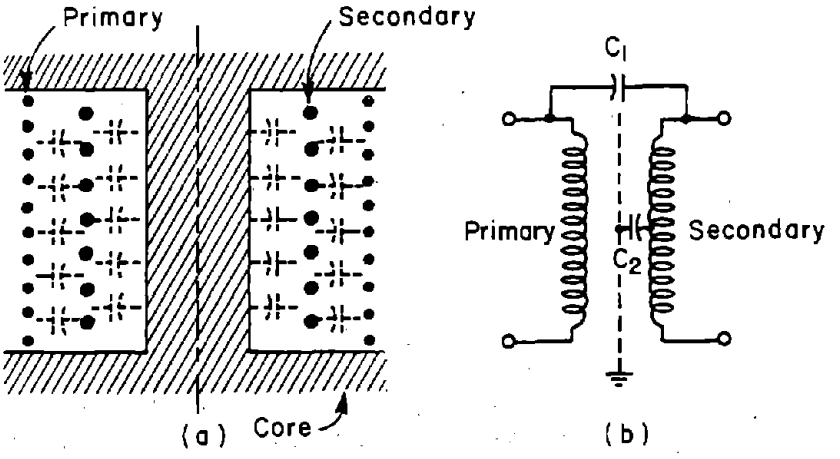


Figure 10.26. Capacitive Coupling of a Transient Voltage Through a Two-Winding Transformer.

C_2 = the secondary-to-ground winding capacitance (F).

Obviously, the voltage transmitted from the primary to the secondary is not tied to the transformer turns ratio. Typical values are 35 to 40% of the impressed voltage (15,18). If the transformer is a step down, say from distribution to utilization, the result can be low-side per-unit voltage levels much higher than existed on the high side.

10.4 General Protection

Elimination of transient-voltage problems is best started with an excellent power-system design applying time-tested principles. The basic intent is to avoid the situations covered thus far in this chapter. However, such an effort often can only address normal conditions, and the unpredictable abnormal conditions can still arise, producing destructive transient overvoltages (1). Accordingly, additional overvoltage control must be placed in the mine power system. This control is afforded by protective devices or techniques, including surge arresters, surge capacitors, shielding, and circuit arrangements.

The role of these protective schemes is to ensure that equipment dielectric strengths are not exceeded. In other words, if a transient attempts to raise the voltage above an insulation withstand level, the protective device must exert a "clamp" or restraint to maintain the voltage within acceptable limits (1). Effective transient voltage suppression is, thus, basically the dissipation of transient energy.

10.4-1 Surge Arresters

Spark Gap. The most simple form of overvoltage device is the "spark gap," essentially two conductors separated by air (e.g., the tips of two rods). One side is connected to a power line, the other to the neutral or earth. The spacing between the conductors establishes a specific dielectric strength, and voltage, above that level, will cause the gap to "spark over." The spark gap has no effect on normal system operation, but the main disadvantage is that once an arc occurs, it creates a fault on the system, which remains until the gap is deionized. The attendant current flow, or "follow current," often can only be interrupted by a circuit breaker or a fuse. "Surge arresters," formerly called "lightning arresters," use this spark-gap principle to clip the peak of a voltage and divert the excess current to ground, but also contain a device to interrupt the follow current (20,21). There are two common surge-arrester types, expulsion and valve; they differ by the interrupting scheme.

Types. The "expulsion surge arrester" extinguishes the arc in a similar manner as an expulsion fuse does (see Chapter 8). That is, an overvoltage establishes an arc across the spark gap and also a gas-evolving material (usually organic), then the expulsion of gas blows out the arc (15). The operation sets three disadvantages. First, some gas-producing material is destroyed during each operation, and only a limited number of interruptions are available. Second, because of the gaseous discharge, care must be taken in placement, and installations are restricted to outdoors. Lastly, the arrester has an assigned curent-interrupting rating and cannot be used on circuits having a greater available fault current.

In "valve surge arresters," the spark gap is in series with a nonlinear resistor or "valve block," as shown in Figure 10.27. The block, commonly made of silicon carbide, has the property that the resistance diminishes sharply as the voltage across it increases. To increase gap efficiency, a number of short gaps are used; these spark over more consistently and in less time than one long gap. Therefore, on an overvoltage, the gaps spark over, and the valve block operates in its highest conductance to safely pass the surge current to ground. After the surge voltage diminishes, the block then changes to a low-conductance mode to limit the follow current, such that the gaps can provide an interruption. The valve surge arrester has none of the disadvantages of expulsion types, and it is used extensively for equipment protection, especially on distribution systems. The balance of this section, thus, will cover only valve-type units.

Four important parameters are connected with the proper application of surge arresters (20, 21).

1. "Voltage Rating." The "power frequency sparkover voltage" is the lowest rms 60-Hz a-c voltage across the arrester at which it will perform the operating cycle. This level is 1.5 times the arrester voltage rating (for arresters rated at 60 kV and below).

2. "Sparkover Voltage." The highest crest voltage at which arcs will form across the gap electrodes, initiating the operating cycle.

3. "Discharge Current." This is the current through the arrester created by the overvoltage immediately after spark over.

4. "IR-Discharge Voltage." This is the voltage formed across the arrester during the discharge of surge current.

Ideally, gap sparkover should occur on any dangerous system overvoltage, ignoring all minor and harmless transients. Proper sparkover requires high-speed response to fast rise-time wave fronts (e.g., lightning surges) and consistent response to slower rates of voltage rise (e.g., system generated surges). Both are satisfied through electrical grading of the gap structure, consisting of shunting each gap with a high resistance. Figure 10.28 shows the technique in simplified form (21). After sparkover, the IR-discharge voltage occurs, being equal to the product of the discharge current and the arrester-discharge-path resistance. As discharge current may be very large, the discharge voltage may equal or exceed the sparkover voltage. Thus, protected equipment are exposed to both the sparkover and IR-discharge voltages, and the system insulation withstand ability must be safely above both.

To establish an IR-discharge voltage, it is important to realize the possible discharge currents. A surge arrester is likely to be exposed to a wide discharge range, but experience from field measurements has shown that discharge currents (21):

1. typically range from 1000 to 2000 A,
2. that 5.0% exceed 9000 A, and
3. that only 1.0% exceed 20,000 A.

Even though 20,000 A is rare, it is often used to estimate the discharge voltage, justifying a worst case.

There are three classes of valve-type arresters available (20).

1. "Distribution class" has the lowest cost and is satisfactory for general equipment-protection purposes. Typical voltage ratings range from 1000 V to 18 kV, and they can withstand a 65-kA current surge. (Surge arresters are generally used on high-voltage systems

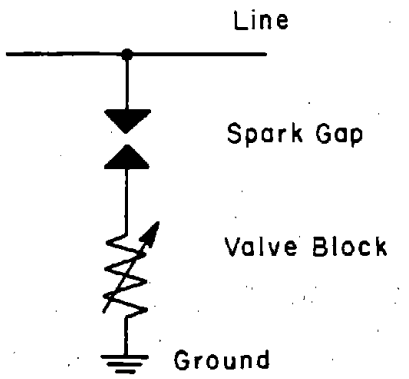


Figure 10.27. A Basic Valve Surge Arrester.

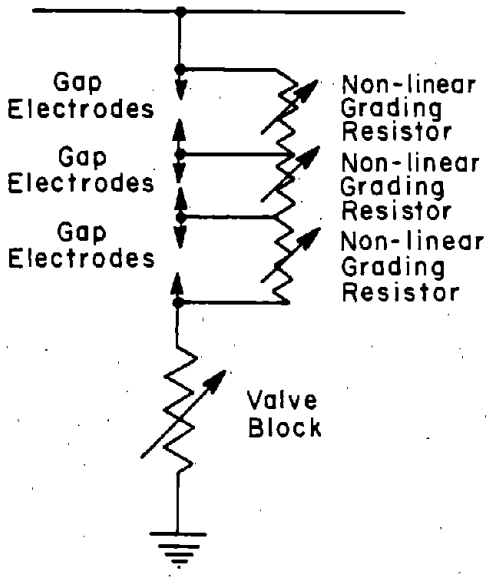


Figure 10.28. A Surge Arrester with Nonlinear Resistance Grading to Equalize Each Gap Structure.

in mining, but these devices are actually available as low as 50 V.) When protecting rotating machinery and dry-type transformers, because of low BIL's, they must be the low-sparkover rotating-machinery (RM) type.

2. "Intermediate class" has lower sparkover and IR-discharge voltages than distribution-class arresters. Available voltage ratings are from 3000 V to 73 kV, and they also can typically withstand a 65-kA surge current. The cost is about five times that for a distribution arrester.
3. "Station-class" arresters can handle discharge currents up to 100,000 A and are available for almost any distribution or transmission voltage applications. They are considered to provide the best possible protection, but cost about twice as much as intermediate-class arresters.

Both station- and intermediate-class arresters have pressure-relief systems; if stressed by a surge beyond their capability, the internal pressure is vented to prevent housing rupture.

10.4-2 Surge-Arrester Applications

Class. The factors to consider when selecting an arrester class are the degree of transient exposure and the importance of the equipment being protected. This is basically an economic question but, in general, intermediate or station arresters are justified for surface substations, with distribution-class arresters being suitable for distribution and utilization equipment protection.

Voltage Rating. An arrester voltage rating of a certain class has associated sparkover and IR-discharge voltages. System voltage, as well as the method of system grounding, affects the voltage that the arrester is exposed to and, therefore, the selection of the arrester voltage rating. Consequently, once an arrester voltage rating is set, the system insulation withstand ability, most often related as a BIL for the equipment being protected, must be coordinated.

Arrester application versus system grounding refers to two techniques: effectively grounded and noneffectively grounded. The "coefficient of grounding" can be employed to find which category is being used, and is defined as the percent ratio of the highest rms line-to-ground voltage existing during a line-to-ground fault to the nominal line-to-line voltage (21). If the ratio does not exceed 80%, the system is termed "effectively grounded." Solidly grounded and typical low-resistance-grounded systems are in this class (the neutral potential remains rather constant during phase-to-neutral faults). However, for high-resistance and ungrounded systems, the occurrence of a phase-to-

neutral fault can shift the neutral to near the faulted phase, with the potential to ground of the other two phases approaching phase-to-phase system voltage. The coefficient of grounding here can be from 80 to 100%. These systems are termed "noneffectively grounded," and resistance-grounded mine power systems for portable and mobile equipment are included. In either grounding case, the arrester voltage rating should be above the possible exposed crest voltage. If not, a disruptive discharge might occur.

Therefore, on effectively grounded systems, the arrester is sized to maximum expected line-to-ground voltage, whereas maximum line-to-line voltage is used for noneffectively grounded systems (22). To allow for the expected increase due to voltage-regulation compensation, the arrester voltage rating should be 5 to 10% above these values. Tables 10.1 and 10.2 provide recommended sizing for resistance-grounded mine power systems (20). The first table refers to station and intermediate arresters, the second being for the low-sparkover distribution class. (Note: The transformer BIL is specified according to ANSI C57.12.00-1973 (reference 23) and may be too low for some mining applications, see Chapter 11.)

With a selected arrester, equipment protection from voltage surges can be verified. Full coordination requires checking arrester performance over a full time range for an expected surge (23). However, the following quick guidelines will ensure safe protection (20).

1. The insulation BIL ratings of equipment should be at least 20% greater than the arrester sparkover voltage.
2. The BIL rating should be above the IR-discharge voltage of the arrester.

As mentioned earlier, a discharge current of 20,000 A to establish IR-discharge voltage is a good approximation of worst-case conditions. Tables 10.1 and 10.2 also provide typical sparkover and IR-discharge voltages for arresters used in mining service (20). However, manufacturer catalog values should be consulted for actual applications as differences among manufacturers' products exist. Additional details of surge-arrester equipment protection are provided in Chapter 11.

Another important point about maximum exposed surge voltage concerns the arrester connections to line and ground. These conductors extend from each ungrounded power conductor to an arrester and from the arrester to ground (in resistance-grounded three-phase systems, a minimum of three-arresters is needed). For stationary equipment on the surface, an arrester ground bed, such as a substation system ground bed, serves as the grounding medium (it must be low resistance); on portable equipment, the frame would be the ground. As the connections exhibit inductance,

Table 10.1. Recommended Station and Intermediate Surge Arresters for Resistance-Grounded Mine Power Systems to Protect Oil-Immersed Transformers (Surge Voltage Levels are Station Class/Intermediate Class).

INSULATION CLASS	SYSTEM VOLTAGE[1]		TRANSFORMER BIL[2]		ARRESTER RATING	FRONT-OF-WAVE SPARKOVER[3]	IR DISCHARGE VOLTAGE[3] 20,000 A.	MAX. 3 PHASE LINE-TO-LINE VOLTAGE
			POWER	DISTRIBUTION				
kV	Nominal	Max.	kV	kV	kV	kV	kV	
2.4	2400	2540	60	45	3	13 / 12	7.8 / 12	3000
5.0	4160	4400	75	60	6	19 / 21	15.5 / 20	6000
5.0	4800	5080	75	60	6	19 / 21	15.5 / 20	6000
8.7	7200	7620	95	75	9	30 / 31	23 / 27	9000
15	12470	13200	110	95	15	51 / 51	39 / 45	15000
15	13200	13970	110	95	15	51 / 51	39 / 45	15000
15	13800	14520	110	95	15	51 / 51	39 / 45	15000
15	14400	15240	110	95	18	- / 61	- / 54	18000
15	14400	15240	110	95	21	70 / -	54 / -	21000

[1]Maximum system voltages are from ANSI C84.1-1970.

[2]BIL ratings are from ANSI C57.12.00-1973 for oil-immersed transformers.

[3]Values given are (station class)/(intermediate class).

Table 10.2. Recommended Distribution-Class, RM Type, Surge Arresters for Resistance-Grounded Mine Power System to Protect Rotating Machinery and Dry-Type Transformers.

INSULATION CLASS	SYSTEM[1] VOLTAGE		TRANSFORMER BIL[2]	ARRESTER RATING	FRONT-OF-WAVE SPARKOVER	IR VOLTAGE 5000 A.	MAX. 3 PHASE LINE-TO-LINE VOLTAGE
kV	Nominal	Max.	kV	kV	kV	kV	
2.4	2400	2540	20	3	13	10	3000
5.0	4160	4400	25	4.5	17	15	4500
5.0	4800	5080	25	6	22	20	6000
8.7	7200	7620	35	7.5*	24	25	7500
15	12470	13200	50	15	44	50	15000
15	13200	13970	50	15	44	50	15000
15	13800	14520	50	15	44	50	15000
15	14400	15240	50	15*	44	50	15000

[1]Maximum system voltage are from ANSI C84.1-1970.

[2]BIL ratings are from ANSI C57.12.00-1973 for oil immersed transformers.

*Arresters may occasionally be exposed to voltage above their rating.

they should be as short as possible and of No. 6 AWG solid-copper conductor or larger. Otherwise, the inductance of too long a conductor can render an arrester ineffective (1). Sharp bends should also be avoided, because a bend substantially increases effective inductance. The inductance of arrester connections, which adhere to these requirements, is estimated at 0.4 μH/ft, with the voltage drop produced during a surge as 1.6 kV/ft, using a current wavefront of 4000 A/μs (21). This voltage can be added to sparkover and IR-discharge voltages to assess protective margins.

Location. As a general rule, all arresters should be located as close as possible to the equipment they are to protect. Ideally, they should be across the protected equipment terminals, the connections for three-phase systems being a wye configuration with the common arrester connection grounded. First of all, this location minimizes the possibility of a destructive surge entering the circuit between the protecting and protected devices (1). Secondly, close proximity also reduces the chance of surge-voltage amplification through refraction and reflection of a traveling wave. For instance, consider Figure 10.29 where a transient voltage surge is traveling along a power conductor towards surge-arrester protected equipment (17). The arrester is located a distance, d, from the line end. As the wave passes the arrester location, the arrester sparks over at its protective level, but lets a traveling wave with a crest equal to its sparkover value through. The voltage wave reaching the equipment terminals is amplified by the addition of the incident and reflected wave, the resultant magnitude depending upon the line-end surge impedance. Consequently, surge-arrester locations, other than directly across the equipment terminals, can lead to higher surge voltages at the protected apparatus than the arrester sparkover voltage. The terminal-voltage rise will be aggravated by a greater separation distance, d. (Note: with a wavefront rise-time no greater than 0.5 μs, a maximum distance of 25 ft is perhaps allowable, but shorter distances always afford greater protection (5).)

10.4-3 Capacitors and System Capacitance

Rate-of-rise. "Surge capacitors," also termed "rotating machinery (RM) capacitors," are special units with low internal inductance that are used extensively to protect rotating machinery and dry-insulated transformers (5). This equipment is very susceptible to line-end turn-to-turn failures caused by fast rise-time wavefronts. The faster the rise time, the greater is the probability for damage. Connected across equipment terminals in grounded wye, as shown in Figure 10.30, the capacitors serve to limit the rate-of-rise of the transient voltage. Simply, the capacitor has to be charged before the overvoltage can be impressed on the system dielectric. Transient rise time is then largely determined by the capacitor charging rate.

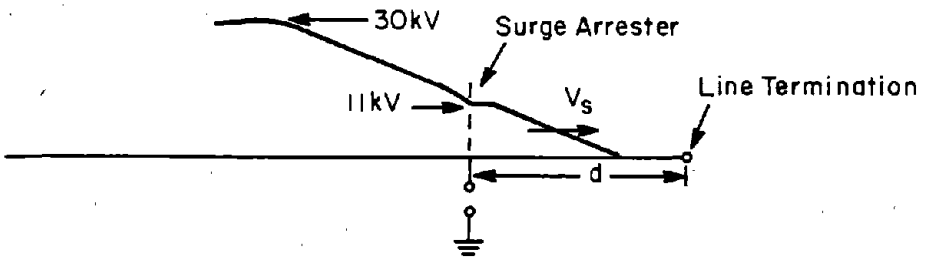


Figure 10.29. A Surge Approaching Surge-Arrester Protected Equipment.

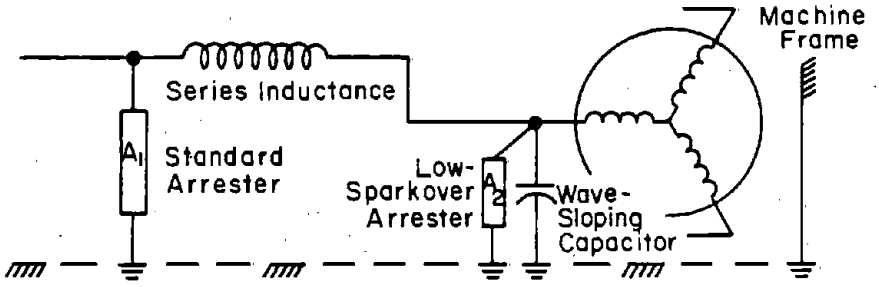


Figure 10.30. Typical Surge Protection of Rotating Machinery and Dry-Insulated Transformers.

Table 10.3. Commonly Used Surge Capacitors for Limiting Voltage Rate-of-Rise on Rotating Machinery and Dry-Insulated Transformers.

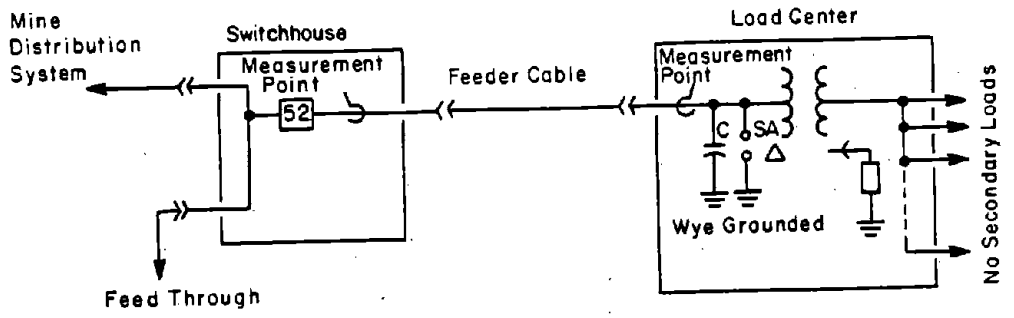
	Rated Equipment Voltage		
	650 V or less	2400 to 6900 V	11,500 V or higher
Capacitance, μF	1.0	0.5	0.25

Coupled with the system inductance, the limiting criterion is that at least 10 μs is needed before the crest value of the protected-equipment nameplate voltage is reached (17). Low internal inductance of the capacitor is important, because the presence of series inductance in the capacitor circuit deteriorates the wave-sloping action. Accordingly, the capacitors shown in Table 10.3 have been standardized for this kind of protection (17). In combination with the recommended low-sparkover distribution-class surge arresters (Table 10.2), the crest voltage of transients is considered restricted to harmless values for the utilization equipment (21).

Surge-Impedance Reduction. Surge capacitors are also used to control transient overvoltages by reducing the system surge impedance. An increase of system capacitance, as exhibited by equation 10.8, can lower the surge impedance, and therefore the possible peak transient voltage resulting from current chopping. A fine line exists here, because too much capacitance on the load side of switching apparatus can cause capacitive-switching or prestrike transients. For instance, prestrike events are dependent upon the capacitive inrush current during contact closure, and the magnitude of inrush current is controlled by the amount of load-side capacitance (25). With capacitive-switching, the transient overvoltage is created by the ability of the load-side capacitance to hold a charge, thus causing a recovery voltage across the breaker so restriking occurs. System capacitance is therefore a critical factor in transient protection.

Hence, the problem of surge-impedance reduction is mainly pointed at how much capacitance is necessary to safely limit transient overvoltages caused by current chopping. Actually, any magnitude below the minimum insulation withstand level or, if used, surge-arrester sparkover, can be considered safe, yet perhaps the most conservative approach would be to limit any chopping event to two times the peak system voltage. The most critical portion of the mine power system would be where capacitance is minimum, such as the case with a switchhouse connected to a distribution transformer, as illustrated in Figure 10.31, or rotating machinery. It can be inferred here that the current chopping is the result of vacuum-circuit-breaker operation, but other switching-apparatus types, including current-limiting fuses, could be a chopping source.

Equation 10.8 can be used to select a value of capacitance, which will include that inherent to the distribution system (i.e., the equivalent phase-to-neutral capacitance of all devices on the load side of the switching apparatus). Considering a three-phase transformer as the load, the procedure can be as follows (9):



C = Surge Capacitor = usually 0.25 μF
SA = Low-sparkover Distribution-class Surge Arrester
* = Most Load-center transformers were delta-wye; some were wye-delta or delta-delta. Common capacity was 750 kVA; other capacities included 650 and 1000 kVA

Figure 10.31. Simplified Sketch of a Mine-Power-System Segment.

1. determine the allowable peak voltage, V_p;
2. find the exciting current and assume interruption is at peak level, I_m;
3. determine the transformer exciting inductance, L_m;
4. assume all transient energy is absorbed by the capacitance, C; then
5. the necessary per-phase capacitance is farads, referred to the transformer primary circuit, is

$$C = \frac{I_m^2 L_m}{V_p^2} . \qquad (10.21)$$

However, a more useful form of this equation can be found if (26):

1. the allowable peak voltage is limited to two times the peak system voltage;
2. the inductance of the transformer and the power system is no greater than 20%; and
3. the peak exciting current is expressed in terms of the rated capacity and rms voltage of the transformer.

With these,

$$C = \frac{10\ S\ (60)}{V_s^2\ f} \qquad (10.22)$$

where,

C = the necessary capacitance (μF)
S = the per-phase transformer capacity (VA)
V_s = the phase-to-phase voltage rating of the transformer primary, (V) (if it is desired to connect the capacitance across the secondary, secondary phase-to-phase voltage is used)
f = the power-system frequency (Hz).

The value resulting from equation 10.21 or 10.22 is total system capacitance per phase. If the level is above that supplied by the system, additional capacitance might need to be added.

For three-phase systems, the common surge-capacitor connection here is in a wye configuration with the center being connected to ground. The typical location is directly across the protected equipment terminals as in wave-sloping applications. Another popular location has been at the switching-apparatus load terminals. The philosophy here is that the interrupter directly "sees" the increased capacitance, and thus chopping transients are limited more effectively. (In other words, transients are best eliminated at their source.) Furthermore, it is a belief that the entire system downstream from the capacitor location would receive protection. However surge capacitors have an extremely low internal series impedance. Therefore, at the interrupter load terminals, they can be a significant source of capacitive inrush current, as well as having the ability to effectively exchange transient energy to and from the system. Consequently, the best location for applying surge capacitors, when they are needed, is at the protected-equipment terminals.

Two advantages are gained through the ground connection: transient energy is shunted to ground and, compared with delta connections, a lesser voltage rating is necessary. The capacitor working-voltage rating (WVDC) should be at least three times the exposed rms system voltage, usually phase-to-neutral for wye grounded, phase-to-phase for delta connections (9). However, for the same reasons given for surge arrestors, it is perhaps better to rate surge capacitors in resistance-grounded systems to phase-to-phase voltages.

Buss and others (27) and Morley and others (25) have performed extensive tests on actual underground-coal-mining equipment to clarify the severity of transients existing on these distribution systems. For the most part, these involved recording staged transients on unloaded and loaded systems by chopping (tripping the interrupter) and prestrike (engaging the interrupter). In every instance, the system segment was similar to Figure 10.31 and consisted of a VCB-equipped switchhouse with various lengths of cable supplying a load center. Various switchhouses and load centers were used, all typical of actual mine installations. Beyond the principal goal of uncovering the

nature of any transients, the overall objective was to see if surge capacitors were necessary to limit chopping voltage transients and what effect they have on prestrike events. Buss and others (27) backed up their actual equipment testing with computer simulations but primarily addressed chopping events. Morley and others (25) extended their research to cover prestrike activity.

In terms of transient protection by surge capacitors, the results of both research programs are practically identical and apply directly to underground mine power systems or similar surface arrangements. Specifically, be they in grounded wye or ungrounded wye, surge capacitors, applied as given in Table 10.3, did significantly reduce chopping transients. With capacitors removed and minimum practical cable length present, chopping transient voltages reached substantial levels (about 4.5 pu system voltage for a common event) but were below the sparkover level of correctly-applied low-sparkover distribution-class surge arresters (thus, within the BIL withstand of system equipment). However, with surge capacitors installed and a 1000-ft cable length, some prestrike transient activity was present with peak voltages similar to the maximum observed for chopping, but again not exceeding the surge-arrester sparkover. The worst-case prestrike activity was associated with switchhouse-located surge capacitors.

The conclusion was that surge arresters alone were sufficient transient protection for underground-coal-mine distribution systems. Surge capacitors were at least unnecessary redundant protection, and their general use could result in more severe transients than those they are installed to correct. Furthermore, as long as surge arresters protect each distribution load, it was found that vacuum circuit breakers can be employed on any mine distribution system without a need to add surge capacitors (27).

However, without surge capacitors, a significant length of cable should be installed between switchhouses and loads to limit chopping events to safe levels. For general mining applications, 500 ft of SHD cable was recommended, although 100 ft would probably be satisfactory (25,27). The capacitance calculated from equation 10.22, when compared with cable values (see Table 10.4), supplies comparable results. Beyond overall surge-impedance reduction (if lumped circuit elements are considered), the normally lower surge impedance of the cable, as compared to that of the switchhouse circuits, provides a reduction to the crest of voltage traveling waves through refraction.

Even with these findings for common system arrangements in mining, some installations could benefit from the wave-sloping action of surge capacitors. One instance would be in surface mines, where there is a high incidence of lightning and the

distribution loads are rotating machines (e.g., excavators) or dry-insulated transformers.

Capacitive-Charging Current. Wye-grounded surge-capacitor combinations have been recommended for several years as a preventative for severe VCB chopping transients. Mines, therefore, often employ them at the high side of every distribution transformer. Such extensive use can pose problems in the mine's high-resistance grounding system.

As stated in Chapter 6, the ground-fault current, limited by the grounding resistor, should not be less than the system capacitive-charging current. This requirement restricts the amount of capacitance that can be placed on a specific sized system. In other words, the size of the mine's distribution system is limited by the total connected capacitance (27). Some relief is gained through power-transformer configurations, because the zero-sequence system is isolated in each voltage level. Regardless, with excessive capacitance, say in distribution, the capacitance can discharge during a phase-to-neutral fault, feeding the fault with capacitive ground current in excess of current limit.

Table 10.4 provides a listing of typical system capacitance to assist in estimating a per-phase system capacitance (28). The following can be used to compute system charging current per phase:

$$I_{co} = \frac{V_{ln}}{X_{co}} \qquad (10.23)$$

in which

I_{co} = the per-phase system charging current (A)
V_{ln} = the phase-to-neutral system voltage (V)
X_{co} = the per-phase capacitive reactance (Ω) = $1/(wC_o)$
C_o = the lumped charging capacitance per phase (F).

This current, compared with ground-current limits, can be used to assess the effect of adding surge capacitors. Further, the table values alone are valuable, for example in comparing the results from equation 10.22 for chopping events.

10.4-4 Other Suppression Devices

The discussion thus far has been concerned mainly with surge suppression on high-voltage distribution. Transient-related failures can also be severe on mine systems below 1000 V. An outstanding example is the destruction of solid-state elements

Table 10.4. Typical Capacitances Per Phase of Power-System Components.

1. Overhead open-wire lines: Negligible for line lengths used in typical mine distribution.
2. Shielded power cable, SHD, SHD-GC, or SHD + GC:

Size, AWG or mcm	capacitance, µF/1000 ft			
	5 kV	8 kV	15 kV	23 kV
8	0.0607	--	--	--
6	0.0709	--	--	--
4	0.0836	--	--	--
2	0.0993	0.0850	0.0401	--
1	0.1096	0.0938	0.0456	0.0345
1/0	0.1202	0.1029	0.0524	0.0388
2/0	0.1321	0.1131	0.0507	0.0441
3/0	0.1452	0.1243	0.0661	0.0504
4/0	0.1600	0.1369	0.0715	0.0546
250	0.1598	0.1368	0.0776	0.0588
350	0.1846	0.1580	0.0844	0.0634
500	0.2150	0.1840	0.0920	0.0685
750	0.2410	0.2062	0.0981	0.0743
1000	0.2740	0.2345	0.1118	0.0789

3. Non-shielded cable: 0.02-0.05µF/1000 ft, typically 0.03µF/1000 ft.
4. Non-shielded cable in conduit: 0.02-0.06µF/1000 ft, typically 0.04µF/1000 ft.
5. Surge capacitors:

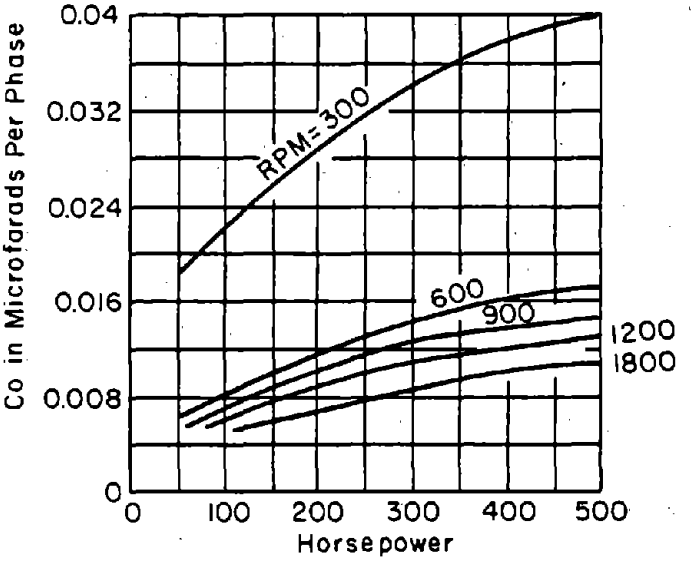
Voltage	Capacitance, µF
480 V, 600 V	1.0
2400 V, 4160 V	0.5
7200 V and above	0.25

6. Synchronous and induction motors:

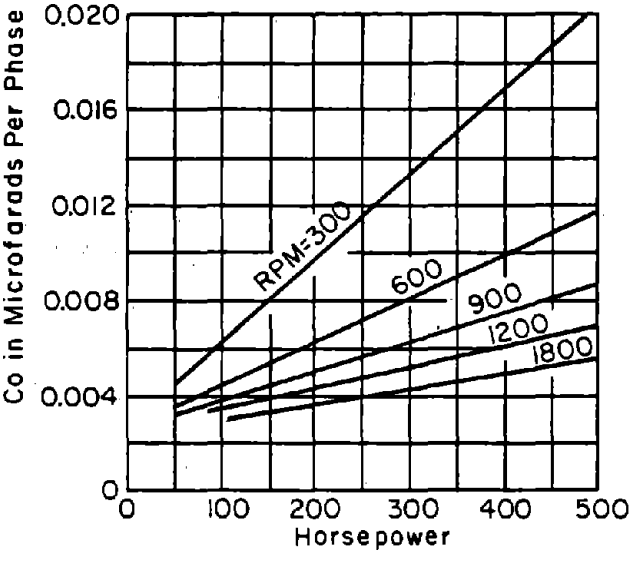
Voltage	Capacitance, µF/1000 hp
650 V and below	0.032
2300 to 7200 V	Use graphs below

Table 10.4. Typical Capacitances Per Phase of Power-System Components. (Continued)

6. Synchronous and induction motors: (Continued)



Capacitance for 2300-V induction motors; for motors up to 7200 V, value will not vary more than ±15% of above.



Capacitance for 2300-V synchronous motors; for motors up to 7200 V, value will not vary more than ±15% of above.

Table 10.4. Typical Capacitances Per Phase of Power-System Components. (Continued)

7. Power transformers: Typically 4000 pf per phase.

8. CT's and PT's:

Voltage	Device	Range	Typical Value
4160 V	L-L PT	150-250 pf	200 pf
7200 V	L-L PT	175-275 pf	225 pf
12.47 kV	L-L PT	200-300 pf	260 pf
23 kV	L-L PT	250-440 pf	300 pf
4160 V	CT	220-280	260 pf
7200 V	CT	210-280	250 pf
12.47 kV	CT	200-270	240 pf
23 kV	CT	180-260	220 pf

9. Bushings and Couplers (below 15 kV maybe negligible):

Voltage	Range	Typical Value
5000 V	140-180	160 pf
8700 V	150-200 pf	175 pf
15 kV	160-220 pf	200 pf
23 kV	190-450 pf	300 pf

in equipment, including ground-check monitors, communications apparatus, power supplies, and so forth. Frankly, the transistors, integrated circuits, and thyristors are the most sensitive devices to transient overvoltages. Problems can occur even through induction from transients occurring on power conductors to neutral or communications circuits. Two suppressor types already presented also offer effective protection for low-voltage systems: valve-type surge arresters and surge capacitors (also termed "snubbers"). This section's purpose is to cover other common protection devices designed principally for (though not necessarily restricted to) low-voltage applications. Generally, these can be divided into two classes: transient suppressors and circuit-shorting devices.

Transient Suppressors. "Transient suppressors," also called "constant-voltage devices," are basically non-linear resistances placed across the circuit to be protected (29,30). They directly act to clamp or limit voltage rise much like the valve block of a surge arrester (no series spark gap is used). Typical transient suppressors are power zeners and metal-oxide varisters.

Power zeners are primarily for d-c protection, working on the zener-regulator principle covered in Chapter 3. They can be used in a-c circuits when two devices are placed back to back (anode to anode, giving bidirectional operations). Zeners have the capability to clamp transient voltage rise to a level largely independent of the impedance, or voltage-current characteristic, of the transient. The response is extremely fast, and the clamping action is very firm. Although effective for low-energy transients, events common to industrial power systems easily destroy all but the most expensive high-energy zeners or "avalanche diodes" (29).

"Metal-oxide varisters" ("MOV's") are ceramic suppressors, using zinc-oxide-based materials (e.g., a zinc-oxide/bismuth-oxide ceramic body is very popular) (29). The construction results in a voltage-dependent very non-linear resistance with symmetrical conducting properties. The bidirectional breakdown allows use on either a-c or d-c circuits. The response is similar to back-to-back zeners, but the clamping action is "softer" than for zeners yet "faster" than valve-type surge arresters (30). As with the silicon-carbide valve block in surge arresters, transient energy is dissipated throughout the entire volume of material, making the MOV a very rugged suppressor.

Metal-oxide varisters can be used for a wide range of applications from power-supply voltage regulation to power-system transient suppression, including high-voltage systems. Rated voltages extend from 22 V to the thousands (29). A very popular use in mining is to suppress transients across thyristors in solid-state motor starters, where a MOV is mounted across

each SCR. A projected employment at this writing is for direct replacement of valve surge arresters in a-c distribution and d-c trolley-line applications.

Circuit-Shorting Devices. "Circuit-shorting devices" or "crowbars" can be described as a device which senses a high voltage and throws a short circuit or low resistance across the line (29). Types include spark gaps, gas-discharge tubes and thyristors. However, the low resistance is not removed until the current through the crowbar is brought to a low level; hence, these devices need to have the power removed momentarily for resetting to occur (30). To facilitate this requirement, crowbars are often used in conjunction with circuit breakers, for instance, having the device connected in series with a shunt-tripping element, and the combination across the line on the breaker's load side. Sensing an overvoltage, current through the crowbar trips the circuit breaker, but normal circuit operation is not resumed automatically. These quick-acting devices are available for a-c or d-c systems, typically 250 V and below.

10.4-5 Faraday Shields

Faraday shields have application for protecting the low side of a transformer against surge voltages. The shield is a turn of non-magnetic metal sheet placed between the primary and secondary windings, insulated from all windings and connected solidly to ground (18). The location effectively destroys interwinding capacitance and thereby substantially reduces the transfer of surge conditions. The shield has the further advantage of practically eliminating interwinding faults.

However, such shields have been responsible for many transformer breakdowns, as their presence produces a dielectric-stress concentration at the edge of the shield. This tends to strain insulation locally and can result in destruction of the high-voltage winding. Even with the reported failures, several manufacturers appear to have solved the Faraday-shield problem through improved construction practices.

An alternative to a Faraday shield has been erroneously believed to be available with sheet-aluminum secondary windings by connecting the secondary turn closest to the high-voltage winding to ground (usually via the grounding resistor). From analysis of the configuration, the interwinding capacitance can only be reduced by a separate grounded shield.

Other advantages of these shields will be covered in Chapters 11 and 13.

10.4-6 Circuit Arrangements

As induced voltages caused by transients on high-voltage or other power-system conductors can be a serious problem, there are four recommendations to reduce the induction possibility (9).

1. Separate low-voltage circuits from high-voltage systems by a large distance.
2. Use shielded conductors on the low-voltage circuit or maintain shielding between circuits serving different purposes.
3. Twist low-voltage conductors (this effectively cancels many induced voltages).
4. Place conductors on the high-voltage circuit close together.

10.5 Static Wires and Overhead Lines

Static Protection. Exposed overhead lines are susceptible to direct contact from a lightning stroke, which obviously produces severe transient overvoltages. An excellent means of protecing distribution lines from such occurrences involves the use of overhead ground wires or "static wires" (8,31). In practice, one or two ground wires are strategically situated above and between the phase conductors to provide a "shielding" effect, as illustrated in Figure 10.32 (7). Line "a" bisects a line drawn from the ground wire to the outer phase conductor, and lightning strokes in sector 1 are intercepted by the static wire. Line "b" is equidistant from the outer phase conductor and earth's surface; lightning streamers in region 2 discharge to the earth. The position of line "b" in Figure 10.32 varies with the relative height of the supporting structure. Line "c" is described by an arc whose radius depends upon the size and construction of the supporting structure. A stroke in area 4 will be borne by the supporting structure (if metallic). Area 3 is the danger region (and may include area 4); lightning flashes in this region will strike the phase conductor (7).

Extensive tests and observations have been conducted to determine the optimum angle θ, which is measured from the vertical up to the line joining the phase conductor and the static wire. Theta is dependent upon the height of the supporting structure, as shown in Table 10.5 (7). However, field results have shown that a good average for this angle is 30° (31). (Actually, 45° provides satisfactory performance if the line is situated on a level surface, but on a hillside, theta should be decreased from 45° by the slope angle of the hill.) Importantly, the design of static protection is practically independent of the system voltage. Figure 10.33 illustrates two approaches for shielding overhead lines by static wires when the support structure is wooden (31).

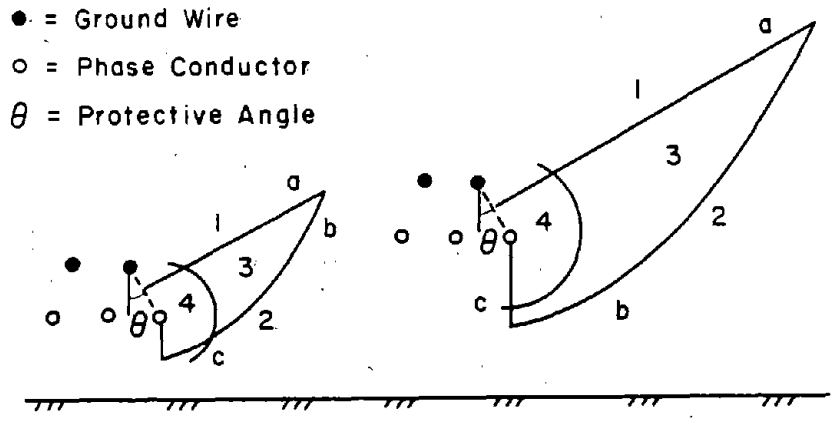


Figure 10.32. Overhead-Ground-Wire Shielding for Low and High Distribution Towers.

Table 10.5. Protective Angle versus Structure Height.

Tower height, ft	Angle theta, degrees
50	45
100	25 - 30
150	10 - 12

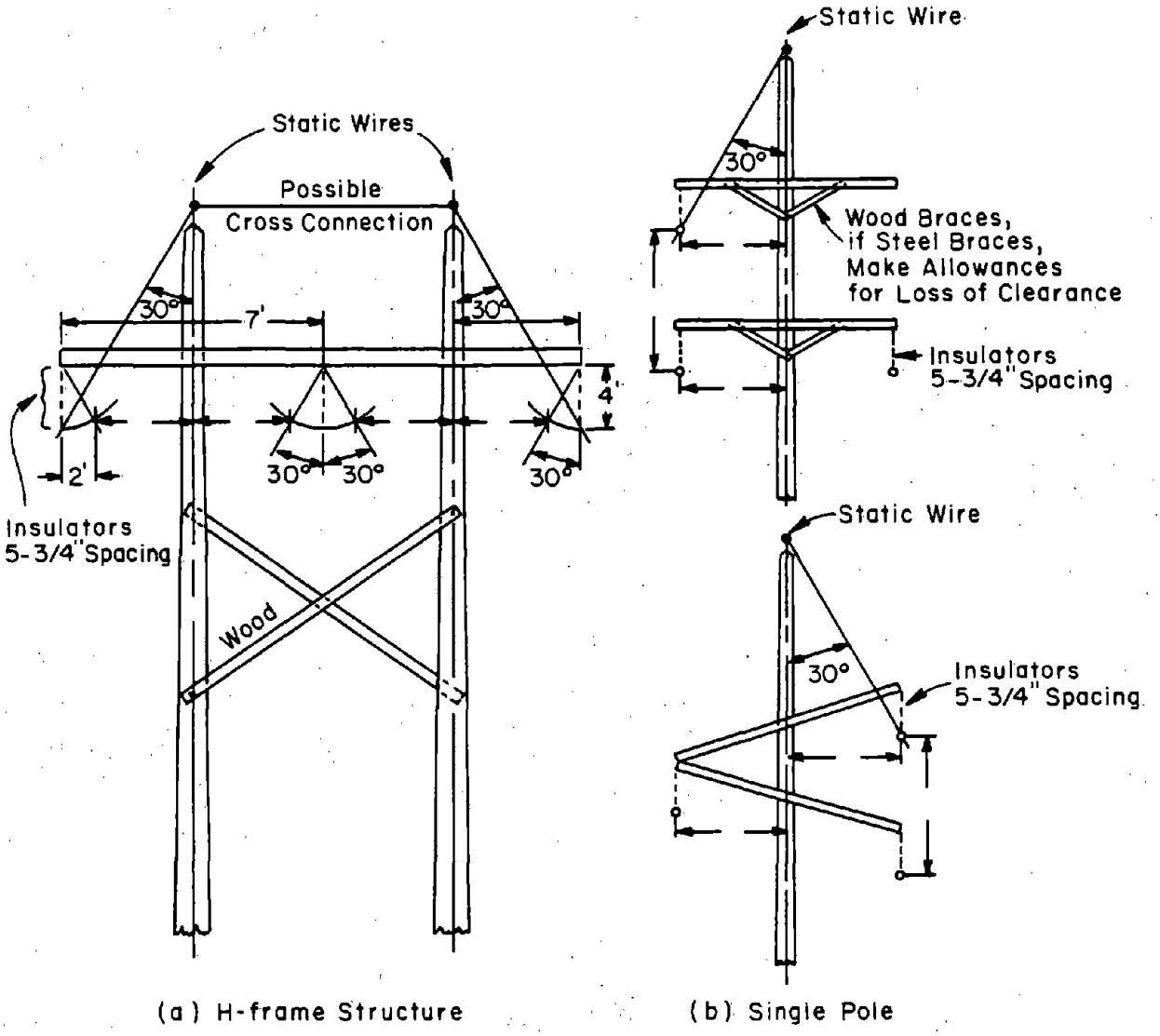


Figure 10.33. Static-Wire-Protection Designs of Wooden Support Structures Using 30° Protective Angle.

In addition to intercepting direct strokes, the static wires perform another function. When struck by lightning, the resulting surge current is immediately halved since the impulse travels in both directions from the point of contact. The magnitude of the induced voltage on the static wire is thereby also halved, leading to a similar reduction in the induced potentials seen by the phase conductors.

Adequate grounding must be used in conjunction with the overhead static wires. The system generally consists of down-leads extending from the static wire to grounding electrodes. Induced voltages are minimized by conducting stroke currents to earth as quickly as possible. This also helps to reduce the surge impedance of the overhead static-wire system. The grounding electrode may be provided by driving several ground rods at the base of each supporting structure and connecting them to the static wires via the down-lead (3). An alternate method is based upon the use of a "counterpoise," which comprises one or more buried horizontal wires located at the base of each tower (32). The counterpoise may be a single continuous conductor buried directly beneath the phase conductors and running from tower to tower, or it may consist of several short wires radiating outward from each tower base (33). Often in mining, the best that can be done is a "butt wrap," wrapping heavy wire around the base of each wooden pole before it is placed in the hole. Which technique is selected depends upon the criterion that the grounding electrode must have as low a surge impedance as practical. Accordingly, the down-leads must adhere to the same guidelines as set forth for surge-arrester connections stated earlier. As a general rule-of-thumb, down-leads and grounding electrodes should not be spaced greater than 500 ft. Considering normal spans in mining, this translates to grounding the static wire nor more than every other supporting structure.

Mining Practice. The following are some important considerations about the application of static wires. At the voltage levels used on conjunction with overhead lines to distribute power in mining, the normal separation distance between phase conductor and static wire for insulation is perhaps insufficient to prevent a lightning stroke which hits the static wire from jumping directly to the phase conductors (31). Often, the static wire is connected to earth only at the system-ground bed at substation; however, this probably leads to a high-impusle impedance for the static-wire system, thereby reducing its effectiveness. An alternative may be the use of protector tubes or surge arresters on the phase conductors on conjunction with pole grounds (31). Additional points about static-wire applications in mining are presented in Chapter 11.

Impulse Performance of Ground Beds. The impedance of a ground bed is directly connected with ability to help dissipate a transient. The general consensus about the performance of

ground beds when subjected to impulse currents is that the surge resistance of an electrode (R_s) is almost invariably less than the normal resistance value (R_n) as measured by an earth tester (33,34,35). Examinations of oscillograph records show that under surge conditions, the ground system exhibits a resistance equal to or slightly higher than its normal value for the first one or two microseconds. The surge resistance then quickly decreases to a level usually from 20 to 80% of the normal value (36). Figure 10.34 illustrates that, as the value of peak surge current increases, the ratio of impulse to 60-Hz resistance (R_s/R_n) decreases (37). Furthermore, ground beds which exhibit a rather high normal resistance show a proportionally larger resistance decrease when subjected to an impulse (36). Thus two ground beds which have dissimilar values of R_n may exhibit R_s values which are very close to each other (38).

Experiments have shown that soil in many respects behaves as a dielectric material (39). When a certain critical potential gradient is reached, the soil breaks down or arcs internally. Thus, the ground-bed-resistance decrease under surge conditions is due to electric discharges within the soil which spark across areas of high electric-field intensity. As shown in Figure 10.35, the presence of moisture in the soil acts to increase its dielectric strength (39). Accordingly, very dry soil breaks down much more readily than soil which contains a minor amount of water. Grounding systems may be designed in such a way that their performance under surge conditions is optimized. Figure 10.36 shows how increasing the pointedness of electrodes results in lower values of surge resistance (35). Thus in lightning-prone areas, driven ground rods may be superior to meshes, since the pointed electrodes are conducive to high stress concentration build-up and will therefore cause the soil to break down more readily under surge conditions.

10.6 Summary

This chapter has attempted to define the electrical transient and its ramifications on mine-power-system safety and integrity. An electrical transient has been defined as the outward manifestation of a sudden change in circuit conditions. The magnitude and fast rise time of the overvoltage can cause damage to electrical components, particularly insulating materials. In addition to sound design practices, techniques and devices are available to reduce the damage done by surge voltages. The application of these in the design of mine power equipment is covered in the next chapter.

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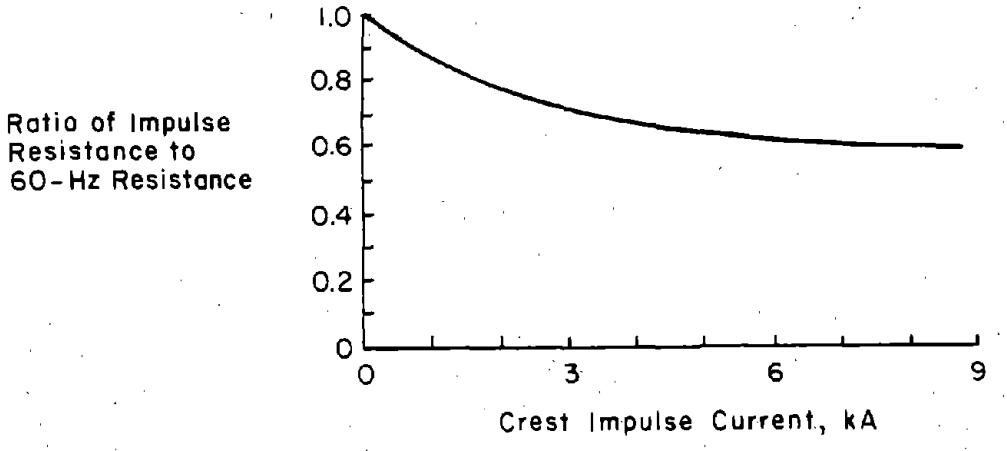

Figure 10.34. The Ratio of Impulse to 60-Hz Resistance as a Function of Peak Impulse Current, for Driven Rods.

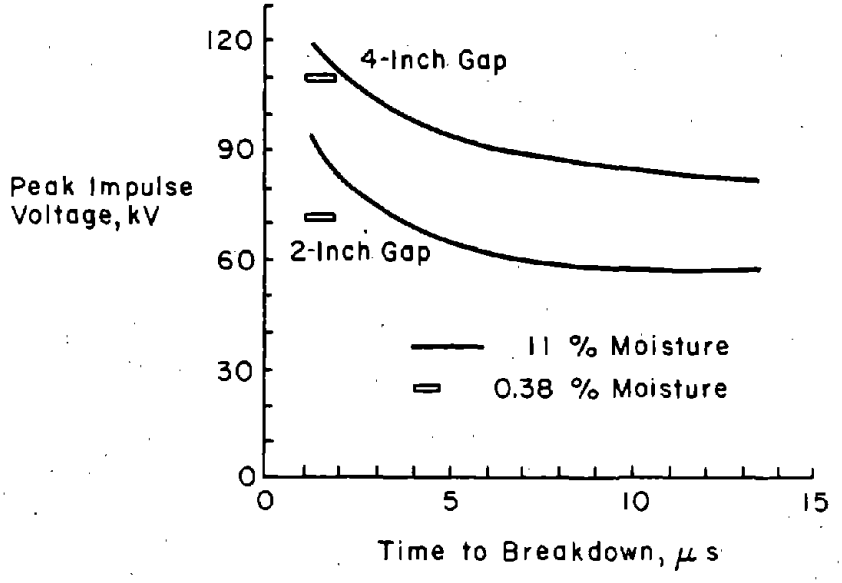

Figure 10.35. Impulse Breakdown of Sand for Two Moisture Conditions Using Spherical Electrodes.

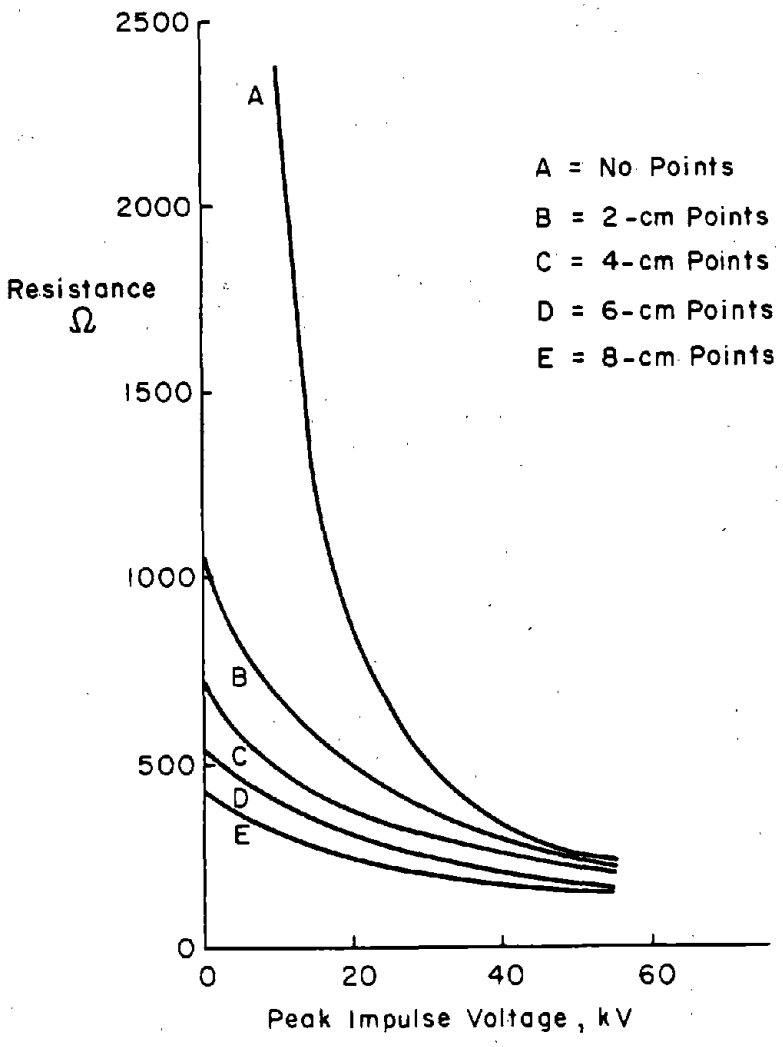

Figure 10.36. Impulse Characteristics of a Spherical Electrode, with Seven Attached Pointed Protrusions of Various Lengths.

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Chapter 11

MINE POWER EQUIPMENT[1]

11.1 General

Chapter 2 introduced the major power equipment used in mine power systems: power or load centers, switchhouses, and substations. An elementary look at the contents of each was given at the end of Chapter 8. The other chapters, preceding Chapter 11, covered numerous basic concepts and techniques; the thrust has actually provided the background for this chapter. Here, the internal components and construction of typical mine power equipment will be detailed. As no standards yet exist for these, the discussion and descriptions relate the authors' opinions as well as extensive information that has been supplied from major manufacturers serving the industry and several mine operators.

Many circuit diagrams in this chapter apply directly to underground coal mining. With a few notable exceptions, underground power equipment is the most complex electrical equipment found in mining. An understanding of this equipment should therefore lead to comprehension of any other mine power apparatus. For instance, the internal components of switchhouses and substations are practically identical in both surface and underground mines, but the difference lies in the constraints imposed on underground equipment by the space limitations. Other peculiarities may arise when underground mines are fed by surface substations. The isolation of the mine grounding system can necessitate more elaborate grounding systems and ground-fault relaying.

In the paragraphs that follow, some material contained in preceding chapters is reviewed, but usually the content is either changed or expanded. The main reason is to enhance many section presentations without making the reader refer to other information. However, references will be made to major chapter sections where extensive material has direct input to the discussion at hand.

11.2 Equipment Specifications

An important objective of this chapter is to provide sufficient information for an individual to draw up the detailed specifications required in procuring a piece of power equipment that will fit a mining need. It is often stated that a manufacturer

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[1] This chapter was originally written for the report by Thomas Novak, Instructor of Mining Engineering, The Pennsylvania State University. The author edited and included additional material.

supplies what the customer requests. Since there are no official standards or recommended practices at present and given the variability of most equipment, every piece of mine power apparatus must be specified individually. If these specifications are not drawn up in complete detail, down to each nut and bolt, the purchaser might not receive what he intended.

Making detailed equipment specifications does not imply criticism of equipment manufacturers. It is a fact that many companies employ very capable applications-oriented engineers who have the total respect of the mining industry. Some can deliver precisely-matched power systems just by knowing the mining equipment being used and the seam in which it is operating. Even in these cases, however, a complete specification from the buyer is still wise in terms of the protection it affords both the manufacturer and the customer. If a situation arises where a manufacturer receives a specification he believes is faulty, or he feels money can be saved by another approach, most manufacturers will contact the buyer for clarification rather than following the specification rigidly and without question.

A listing of the minimum number of items which are recommended for a specification is provided in Table 11.1. A document prepared to this format could be used as part of a purchase order directly to one manufacturer or as a solicitation for bids from several companies. Usually, such information is preceded by a general title, a phrase expressing what the specification covers and the number of units desired. The next paragraphs will present suggestions for the content within each item of the table. The individual making the specification is referred to as the buyer or purchaser.

The time schedule alerts the manufacturer as to when the buyer expects work on the equipment to begin. Furthermore, it serves notice that the manufacturer must have enough personnel, equipment, and material to complete work within the delivery time stated. (Obviously, if the number of sources for the equipment is restricted, and sometimes that could be only one, the buyer must accept the seller's delivery dates.) Item 2.0 should contain a statement that the purchaser will only accept equipment that meets the specifications. In other words, the units may be rejected if they do not comply, and the purchaser has no obligation to pay.

A detailed account of the intended use for the equipment should be given under Item 3.1 so the manufacturer knows exactly what the specification covers and what the buyer expects to do with the unit after he receives it. Item 3.2 primarily applies (but is not restricted) to unit-designed equipment. Content examples include:

Table 11.1. Minimum Recommended Content for an Equipment Specification.

1.0. Time Schedule.

2.0. Work by Purchaser.

3.0. General.

- 3.1. Intended Use of Equipment.
- 3.2. Enclosure Specifications.
- 3.3. Special Needs.

4.0. Internal Components.

- 4.1. One-line Diagram.
- 4.2. Description of Each Component.

5.0. Drawing and Manual Requirements.

- 5.1. With Manufacturer's Bid.
- 5.2. Before Construction Starts.
- 5.3. With Equipment Delivery.

6.0. Inspections.

- 6.1. During Construction and Prior to Delivery by Purchaser.
- 6.2. Manufacturer Compliance with Local, State, and Federal Regulations Applicable to his Company.
- 6.3. Equipment (being built) Compliance with Applicable Local, State, and Federal Regulations.

7.0. Guarantee.

- 7.1. Minimum Guarantees or Warrantees Demanded by Buyer.
- 7.2. Request for Proper Storage Requirements Before Service.

8.0. Delivery Dates.

1. minimum material requirements;
2. physical protection of internal parts;
3. desired mounting (tire, skid, or rail);
4. prevention of water from the inside of the enclosures; and
5. maximum length, width, and height.

An instance of listing minimum materials would be where the specification is going out for bid, and ruggedness for the mining environment is imperative. To discourage any inadequate bids, it would be good to provide minimum acceptable steel thickness for the base plate, frame, end plate, and covers. The last entry above is vitally important for underground operations. It may be absurd, but there are many instances where equipment has been purchased and is too large to fit down a shaft or slope. Item 3.3 suggests special desires such as engraved nameplates for all major components and labeling of internal wiring and terminal blocks.

The Internal-Component portion is commonly the major part of a specification. A one-line diagram is the best communication about how the components are to be interconnected. Afterwards, a complete listing of all components must be presented. However, in addition to just stating what the component is, information on why it's there and what purpose it is serving must also be provided. Special needs, such as transformer ratios, trip settings, and minimum insulation levels should be given when applicable.

As noted in Table 11.1, Item 5.0 consists of three areas. If the specification is for receiving bids, it is good to request one-line and general physical-arrangement diagrams from prospective manufacturers. For unit-designed equipment, details for the physical layout would include, for instance, the basic frame, mounting arrangement, and major-component locations. Next, prior to starting construction, the manufacturer should be requested to submit all applicable outlines, arrangements, and schematics for approval. After construction and with delivery, the number of necessary parts manuals and instruction manuals as well as drawings (usually some should be reproducible) to be supplied must be stated.

Item 6.0 is to protect the customer. The first entry here must relate that the buyer has the right to physically inspect the equipment during manufacture and prior to delivery. Any discrepancies from the specification (which are noticed) must be corrected. Orders, at times, can be construed as contracts. Accordingly, the buyer might be held (in part) legally responsible if the manufacturer violates any local, state, or federal ordinances, codes, acts, regulations, or laws. Thus, the specification must demand compliance with all applicable statutes;

this should be extended to any subcontractors or suppliers that the manufacturer may use. The last necessary entry for Item 6.0 is a demand that the specified equipment shall comply with all federal and state regulations and requirements that apply to the intended use in the state in which it will operate.

On some mine power equipment, guarantees or warranties (Item 7.0) cannot be obtained. Regardless, a request for a minimum is wise, for example, a one-year guarantee that begins after the equipment is placed in operation. The manufacturer should also be asked to supply any special instructions or precautions which are necessary for proper equipment storage prior to its being placed in service.

Finally, the specification must relate the dates that the equipment shall be delivered to the mining operation.

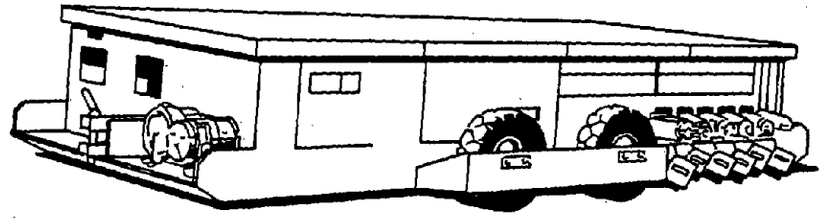
Establishing an adequate specification is not always an easy process. As will be seen, certain types of mine power equipment could result in a document of numerous pages. However, a good specification might be the difference between having a unit that performs superbly throughout the life of the mine or one that is a headache from the day it is placed in service.

11.3 Mine Power Centers

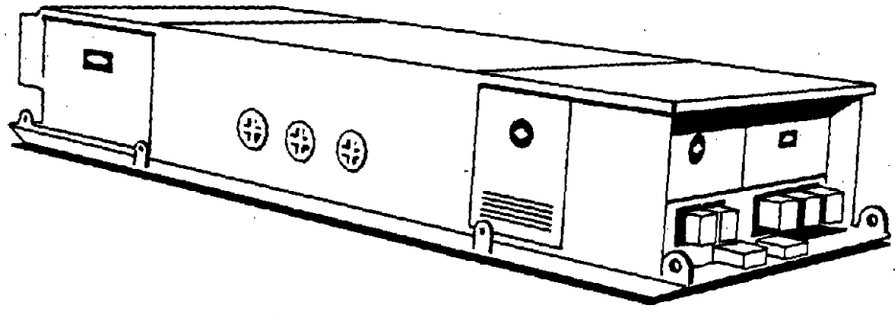
11.3-1 General

One of the most essential power-system units for underground mines, and also for surface mines in a simpler form, is the power or load center. Its primary function is to convert the distribution voltage to utilization for operating various equipment throughout the mine. It must also provide protective circuitry to ensure safe, efficient, and reliable operation. In effect, the power center could be considered a portable substation. Because of application, however, the main component and perhaps the entire unit might be termed a distribution transformer.

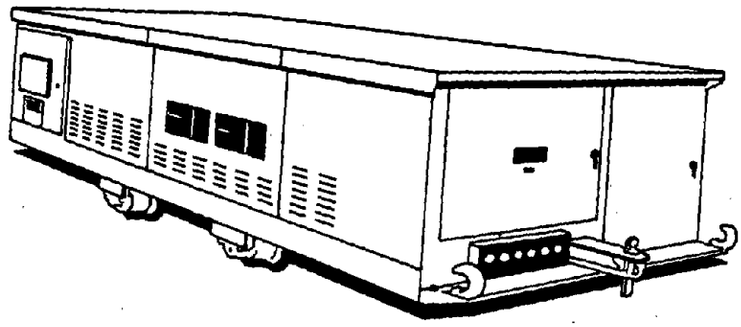
The electrical components of the power center usually are housed in a heavy-duty steel enclosure (or "metal clad" as it is sometimes referred to), which may be tire mounted, skid mounted, or track mounted. Illustrations of typical underground coal-mining units are given in Figure 11.1 (1,2). Towing lugs or pin-and-link couplers are commonly provided on each end of these enclosures to permit towing as the mining section advances and retreats. Often, bumpers or check plates are installed to protect externally mounted components, such as couplers, from being damaged by mobile equipment. Surface mines can use similar enclosures (obviously without a height restriction) but, in the most simple form, the power center could consist of outdoor components assembled on a flat-bed trailer, using fencing or gates to discourage unauthorized entry.



(a) Tire Mounted



(b) Skid Mounted



(c) Track Mounted

Figure 11.1. Illustrations of Typical Underground Coal-Mine Power Centers.

The "standard" power center does not exist because of the variety of mining practices and the numerous types of mining equipment used. The power center may be required to supply as little as one motor or as many as 20 pieces of machinery. It may be totally a-c (feeding only a-c equipment), d-c, or a combination of a-c and d-c. The distribution voltage received could be 4.16, 7.2, 12.47, 13.2, or 13.8 kV. The outgoing a-c utilization voltage may be 480, 600, 1040 V, or a combination of 1040 V with one of the lower voltages. Direct-current can be at 300 or 600 V, but is almost always 300 V for face applications. As a result, manufacturers custom build the units to meet the individual needs and specifications of the customer. However, a general design philosophy is central to all power-center types. Thus, a general discussion of an a-c power center and a combination a-c/d-c power center will ensue in the subsequent sections.

11.3-2 Major Components

The major electrical components of a typical mine power center are shown in the schematic of Figure 11.2. The following sections will generally discuss the individual components as they function in the power center, and the circled numbers of Figure 11.2 will be referred to throughout. This is a means of indicating the component location with respect to the overall system.

11.3-3 High-Voltage Cable Coupler

Incoming power is supplied to the center from the distribution cable via the high-voltage cable coupler (No. 1). The receptacle (typically with female contacts) is cable-mounted, while the plug (male contacts) is gear-mounted. Although the conductor pins are recessed in the coupler housing, dust caps should be provided for each side of the coupler pair to protect the contacts when disengaged.

When being disconnected, the coupler is designed such that the pilot contact is broken first, the phase conductors second, and the grounding conductor last. As was discussed in Section 8.5-5, the pilot contact is interlocked with the up-stream high-voltage circuit breaker which protects the incoming line. If the incoming power is energized, the power will be tripped by the associated ground-check monitor prior to breaking the phase contacts of the coupler. Having the grounding contact break last ensures that the frame is tied to earth ground whenever the power center is energized.

A feed-through receptacle may be provided as shown in Figure 11.3. This permits supplying (or continuing) distribution power through the power center to other high-voltage loads. (This receptacle's contacts are typically female). If the feed-through

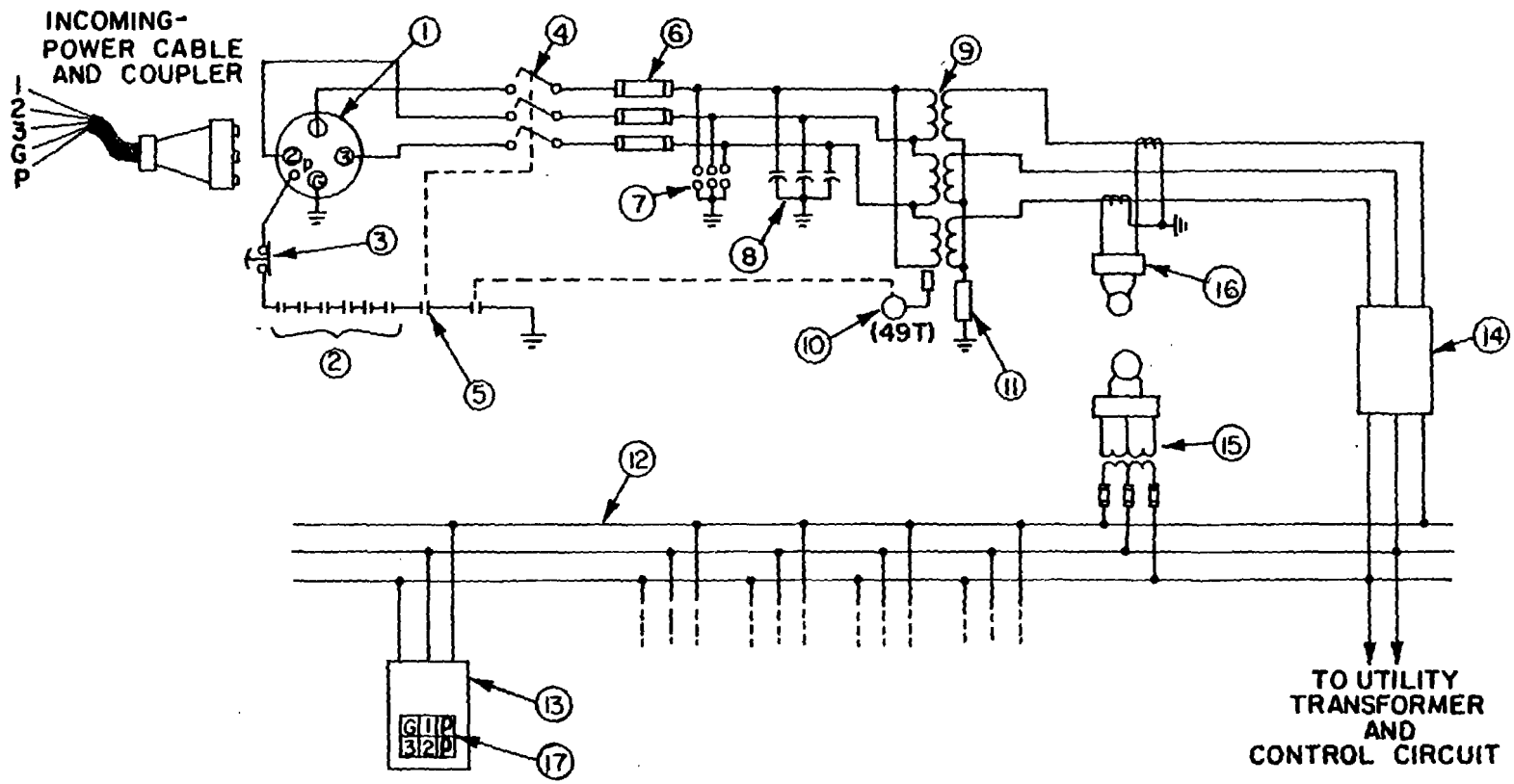


Figure 11.2. Schematic Illustrating Major Components in a Power Center.

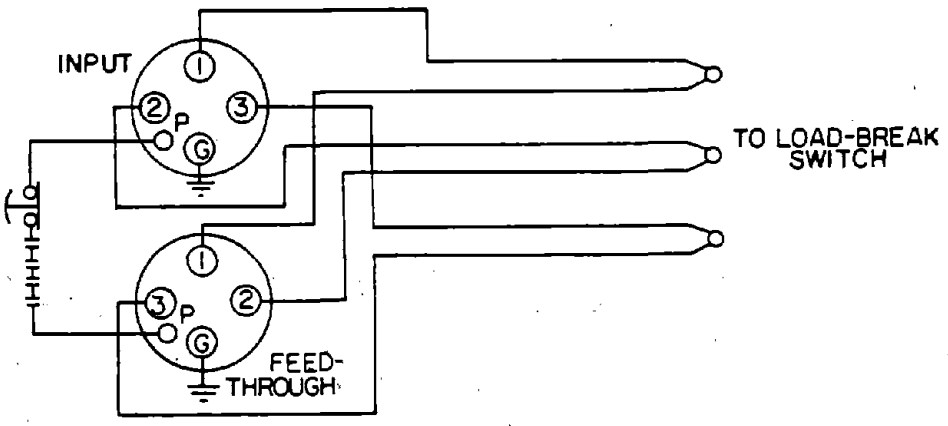


Figure 11.3. Interconnections Between Input and Feed-Through Receptacles.

receptacle is not being used, a dust cap is again provided. This time, however, the cap also shorts the pilot contact to the grounding contact to provide a closed path for the ground-check monitor interlocking with the upstream circuit breaker. The conductors between the input and feed-through receptacles should be sized to the maximum ampacity of the distribution system.

11.3-4 Interlock Switches

As a safety measure, interlock switches (No. 2) are strategically located around the top and side covers of the high-voltage and transformer compartments of the power center. The normally-opened (N.O.) contacts of the switches are connected in the pilot circuit of the incoming distribution cable as shown in Figure 11.2. With covers in place, the interlock switches are depressed, and their associated contacts are closed. This provides a closed path for the pilot circuit. However, when a cover is removed, the switch contacts are opened, thus causing the outby circuit breaker to trip due to the loss of continuity in the pilot circuit.

An emergency-stop button (No. 3) is also available and its function is similar to the interlocks. It consists of a normally-closed (N.C.) set of contacts in series with the interlock switches. If the stop button is depressed, its contacts are opened, and the outby circuit breaker trips and de-energizes the incoming line to the power center.

11.3-5 Disconnect Switch

The disconnect or load-break switch (No.4) is a mechanically operated, air-type switch. Its primary function is to allow a quick means of disconnecting the primary of the power-center transformer. A spring-loaded or torsion-bar mechanism provides quick-make and quick-break operation, independent of the speed of the manually-activated handle. With observation windows in the power-center enclosure, the switch can serve as a visual disconnect.

Disconnect switches have no interrupting capability. However, load-break switches do and are able to interrupt currents that are not in excess of their continuous-current rating. In addition, they are also rated for a maximum interrupting capacity, but they are designed only for a one-time interruption at this level. Load-break switches are more expensive than disconnects. Yet many mine power engineers prefer them because of the extra ruggedness they afford; some states require their use. Continuous-current ratings of 400 A and 600 A and a 15-kV voltage rating are common for mining applications. Table 11.2 is presented below to illustrate typical ratings of a 400-A load-break switch. (See Chapter 8 for more details.)

If a disconnect switch is allowed and employed, a pilot-break monitor (No. 5) is required to interlock the switch handle with the pilot circuit of the incoming distribution system. This results in having the upstream circuit breaker interrupt the circuit prior to opening the switch contacts. It is also desirable to use pilot interlocking on load-break switches to extend the life of the contacts. Again, some states require both load-break switches and pilot-break monitoring in order to minimize any danger of operating the switch under load.

Table 11.2. Typical Current Ratings of 400-A Load-Break Switch.

Full-load current	400 A
Rated interrupting capacity	400 A
Maximum interrupting capacity	1,200 A
Short-time current (one second)	20,000 A
Impulse current	45,000 A
Close-and-latch current	37,000 A

The balance of the chapter will use or imply the term "load-break," for all disconnect-switch applications.

The only means of activating a load-break switch should be by the manually-operated handle accessible from outside the load-center enclosure. Its operating mechanism should not be tied into the power-center protective circuitry. More will be said about this recommendation soon.

11.3-6 High-Voltage Fuses

A fuse has been defined as an overcurrent protective device with a circuit-opening fusible element that is located and severed by the passage of current through it. Current-limiting fuses (No. 6) are the types used in mine power centers. The main purpose is to protect the high-voltage section but mainly the transformer during short circuits. High-voltage circuit breakers are not recommended, because of the probability of creating transients.

For resistance-grounded mine power systems, the fuse voltage rating should be based on the line-to-line voltage. The following two rules of thumb should be considered for determining the current rating of the fuses to ensure that the fuses will not begin to operate due to the transformer inrush current.

1. The fuse should be able to withstand 12 times the rated current of the transformer for 0.1 s without element damage.
2. The element should be able to withstand 25 times the rated current of the transformer for 1/2 cycle.

Based upon the above criteria, the continuous-current rating of the current-limiting fuses usually falls in the range of 1.5 to 2.5 times the rated transformer current.

In some instances, smaller current-limiting fuses are paralleled to meet the requirements of larger fuses. The maximum peak let-through current for two parallel fuses should not exceed twice the let-through current of one fuse operated at half the available fault current. Parallel fuse operation also has no effect on the maximum arc-voltage generated (3).

Transient overvoltages can be generated during the operation of the fuses. The magnitude of the overvoltage depends upon the point of the waveform at which initiation of the fault occurs and the size and design of the fuse element. For ribbon-element fuses, the generated peak arc voltage is primarily a function of the system voltage and is shown in Figure 11.4 (3). The peak arc voltage should be compared to the minimum 60-Hz sparkover level of the surge arresters. The sparkover level of the

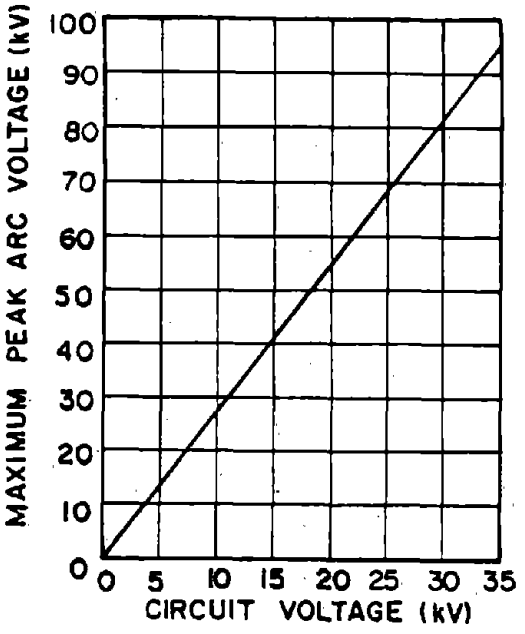


Figure 11.4. Graph Illustrating Transient Crest Voltage Caused by Ribbon-Element Current-Limiting Fuse Operation.

arresters, discussed in Section 11.3-7, should be multiplied by $\sqrt{2}$ to obtain a peak voltage. If this value is greater than the peak arc voltage, arrester sparkover will not occur from fuse interruption.

The fuses are used sometimes in conjunction with an automatic (fused) load-break switch. The objective of this switch type is to prevent the power center from operating under a single-phase condition if only one fuse blows. Commonly, the fuses are designed with actuators located at one end of their casings. In the event that a fuse element is blown, the actuator extends outward from the fuse end and activates the trip mechanism of the switch. This causes the switch to open and eliminate the single-phase condition. However, for a three-phase fault, the possibility exists that one fuse may blow before the others, which could result in the load-break switch attempting to clear a fault current higher than its designated rating. Accordingly, this type of automatic load-break switch is not recommended in power-center applications (also see Section 11.4-4).

Single-phasing protection is better accomplished at the secondary bus using relays to monitor for a single-phase or phase-reversal condition. The relay contacts can be employed to activate the undervoltage release or shunt trip of the main breaker (on the secondary). If a main breaker is not used, the contacts can be connected directly at the output of the control-transformer secondary winding so all outgoing circuit

breakers will trip through their undervoltage releases if the relay is actuated.

11.3-7 Surge Arresters

A surge arrester (No. 7) is a device which is designed to limit dangerous transient overvoltages to safe levels. Lightning, switching surges, and some faults result in transient overvoltages which can exceed the insulation levels of power-system equipment. Since it is sometimes not economically possible to rate the equipment insulation above the surges, overvoltages must be clamped or suppressed to levels which can be tolerated. The function of an arrester is:

1. to discharge the energy associated with a transient overvoltage;
2. to limit and interrupt the 60-Hz current that follows the transient current through the arrester; and
3. to return to an insulating state without interrupting the supply of power to the load.

Valve-type surge arresters of the low-sparkover distribution class are almost exclusively used in mine power centers. A complete discussion of these devices as well as application tables is given in Section 10.4-2. Important points related to power-center use follow.

The voltage rating of a surge arrester is the highest power-frequency voltage at which the arrester is designed to operate. As mine power systems utilize resistance grounding and fall into the noneffectively-grounded-system category, the surge-arrester voltage rating must be selected on a line-to-line basis. However, the rating should be 5 to 10% above the nominal distribution voltage to allow for voltage-regulation compensation.

The component that the surge arrester protects is the main power transformer. The protection key is coordination between the transformer insulation withstand (or BIL) and the characteristics of the transient voltage the arrester lets through. Dry-type transformers are used almost exclusively in present-day power centers, and their insulation strength does not increase significantly above their BIL as the duration of the applied pulse decreases. Therefore, the voltage-time withstand characteristic can be plotted as a flat line with a value equal to the BIL as shown in Figure 11.5 (4). The arrester characteristic, including impulse sparkover and discharge voltage, is also illustrated. The "margin of protection" is the difference between the transformer BIL and the arrester discharge characteristic at any given instant of time. The value should not be less than 20% if a 5000-A surge discharge current is assumed. (The "worst-case" discharge of 20,000 A need not be used in typical power-center locations.)

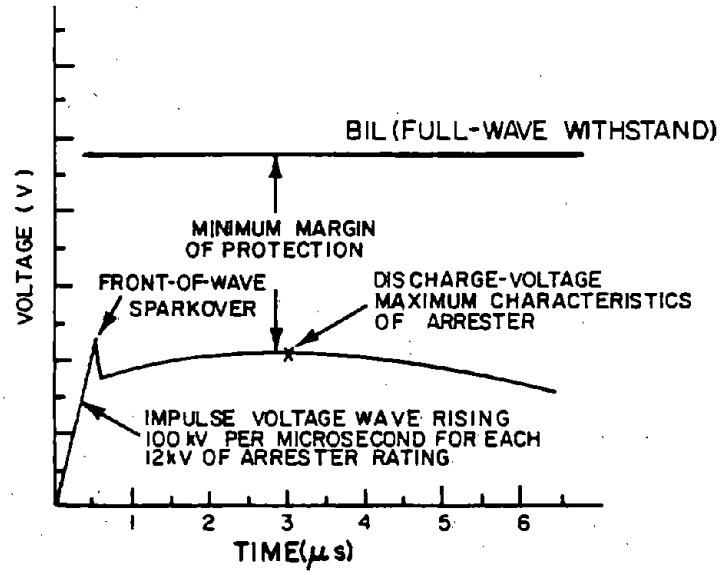


Figure 11.5. Comparison of a Transformer Withstand Characteristic to that of a Surge Arrester.

The physical location of surge arresters within the load center is important for effective operation. The two critical aspects are the conductor lengths to the phase conductor and to the power-center frame ground, and the distance between the arrester and the transformer. To maximize the effectiveness of arrester performance, the arrester leads must be as short and straight as possible and of No. 6 AWG solid copper or larger. Also the surge arrester and arrester connections to the phase conductors should be as close to the transformer terminals as possible. (Preferably, the surge-arrester leads should be connected right at these terminals.)

11.3-8 Surge Capacitors

Surge capacitors (No. 8) can be found in numerous mine power centers. Their intended purpose is to lessen the severity of transient overvoltages caused by current chopping in vacuum circuit breakers. The effectiveness is based upon their ability to limit the rate-of-rise of transient overvoltages and to reduce the system characteristic impedance. However, due to the discussion given in Section 10.4-3, surge-capacitor use in load centers is generally not recommended, as long as:

1. the surge arresters are correctly applied, and
2. a minimum practical cable length (100 ft) exists between the power center and the upstream circuit breaker.

11.3-9 Transformers

The main transformer (No. 9) can be considered the heart of the load center, since its primary function is to convert the distribution voltage to utilization. Therefore, proper selection is imperative from the standpoints of safety, efficiency, and reliability. Fortunately, the IEEE (5,6) has established classifications and specifications for determining transformer characteristics as an aid in design and application. These are in general use in the mining industry, and applicable items will be discussed.

Classification. The IEEE uses the following three items for the general classification of transformers:

1. distribution or power,
2. insulation, and
3. substation or unit substation.

The capacity or kVA rating determines whether the transformer is classed as a distribution or power unit. Distribution transformers fall in the range from 3 kVA to 500 kVA, with power transformers having capacities greater than 500 kVA. Power-center transformers can be of either classification, since they may range from 150 kVA for a rectifier or belt drive up to 2000 kVA for a longwall section. Rarely, however, are capacities greater than 1250 kVA.

A transformer may be further classified by the insulation system, liquid or dry-type. Liquid insulation includes mineral oil or synthetic fluids. Dry-type transformers are ventilated or sealed gas-filled types. Ventilated dry-type units are almost exclusively used in mine power centers. With convection cooling and air insulation, this type offers the following advantages.

1. Toxic gases cannot be released.
2. It cannot explode or catch fire.
3. There is no oil or other liquid to spill, leak, or dispose of (a critical problem of PCB, polychlorinated biphenyls).
4. It is virtually maintenance free because there are no valves, pumps, or gauges.

A substation-transformer classification refers to direct or overhead line-termination facilities, while a unit-substation transformer has an integral connection to primary or secondary switchgear. Primary refers to a voltage of 1000 V or higher, where secondary refers to a rating less than 1000 V. (For practical purposes, 1040 V is also considered 1000 V.) Therefore, a load-center transformer can be considered a unit-substation class.

Specifications. The IEEE transformer specifications (5) that apply to mine power centers include:

1. capacity or kVA rating,
2. phases,
3. frequency,
4. voltage rating,
5. voltage taps,
6. winding connections,
7. impedance,
8. basic impulse insulation level (BIL),
9. temperature rise and insulation,
10. cooling.

Each will be discussed in general terms in the next paragraphs. There are a few exceptions to the IEEE Standard.

There is no set formula for determining the kVA rating for a load-center transformer. For constant loads, allowing one kVA for each horsepower of connected load is a common rule of thumb. However, the mining process does not produce a constant load (i.e., all connected motors are not operating at the same time on a continuous basis), and using the rule of thumb will normally result in oversizing the transformer. Therefore, past experience and demand factors established by manufacturers and operators, along with the horsepower of the connected load, are essential for determining the capacity of the transformer. For typical underground-mining sections, the kVA rating may lie within range of 50% to 80% of the connected horsepower. (Note: The Power Terminology Section of Chapter 4 contains additional information on demand factors.)

As an example, consider the following continuous-mining section:

1. 370-hp continuous miner (gathering head, pump, tram, and cutter motors),
2. two 125-hp shuttle cars (traction, conveyor, and pump motors),
3. 80-hp roof bolter (traction and pump motors), and
4. 50 hp of auxiliary equipment (section fan, sump pump, hand tools, etc.).

The total connected horsepower sums to 750 hp. If the demand factor has been determined to be 60%, the effective load would be 450 kVA, and a 500-kVA transformer would be selected. However, flexibility must always be considered in mining applications, such as the possibility of powering additional equipment in the future (e.g., feeder-breaker, battery-charging stations, etc.). As a result, it may be necessary to select the higher kVA rating to accomodate anticipated additional loads.

Over the years, power-center manufacturers have arrived at certain "standard" or typical transformer capacities, created mainly by repeat demand of the industry. Table 11.3 lists these sizes, but many manufacturers will supply capacities at any increment of 50 kVA.

Table 11.3. Common Transformer Capacities Used in Mining.

a-c only[1]	d-c only[2]	Combination a-c/d-c[3]
150 kVA	100 kVA	300/150
225	150	500/150
300	200	600/150
500	300	750/150
600	500	1000/150
750	750	1250/150
1000		
1250		

[1] Alternating current output only; section may have outboard rectifier for d-c load.

[2] Often termed "rectifiers," rating of unit commonly in kW.

[3] Typical d-c capacity, on larger units 200 and 300 kW for d-c also available.

In many power centers, three-winding transformers are necessary. The needs include a-c face equipment with two rated voltages (e.g., 950-V continuous miner working with 550-V machines) and the common application of mixed a-c and d-c machinery. In these cases, the capacity of each transformer winding (primary, secondary, and tertiary) must be individually rated. Table 11.3 also contains examples for a-c/d-c units.

All mine-power-center transformers are three-phase, being either three single-phase units or integral three-phase types. For single-phase instances, each transformer is rated at one-third the total required capacity. However, by far the majority of centers contain one integral transformer with construction often allowing field replacement of failed windings. This results (over the single-phase types) in equal reliability, lower cost, higher efficiency, less space, and elimination of exposed interconnections.

The standard commercial frequency in the United States is 60 Hz; thus, transformers should be rated at this frequency. If a transformer, rated at 60 Hz, is applied to a 50-Hz system, the voltage and the kVA rating must be reduced by 20%. Transformers that are rated at 50 Hz, can be operated at 60 Hz, but the efficiency and regulation are reduced since the reactance is directly proportional to the frequency.

The primary voltage rating of the transformer is dictated by the distribution voltage (i.e., 4.16 kV, 7.2 kV, 12.47 kV, etc.). The voltage rating of the secondary winding must match the voltage of the utilization equipment. Actually, the transformer secondary should be rated at a higher voltage (10% is common) than shown on the nameplate of the utilization equipment, allowing for a voltage drop in the trailing cables. The secondary winding of power-center transformers is most commonly rated at 480 V or 600 V, relating to 440 V or 550 V equipment, respectively. Secondaries supplying 950-V machines are usually rated at 1040 V, except in states where face voltages over 1000 V are not allowed. In these instances, 995 V is often specified. The transformer voltage for d-c applications is dictated by the rectifier and will be presented under that section.

Power-center transformers should be provided with voltage taps on the primary windings to account for voltage fluctuations and line losses in the distribution system. Five fully-rated taps, at 2.5% increments, are usually available, with the middle tap being rated at the nominal distribution voltage. Figure 11.6 illustrates this arrangement for a 7.2-kV primary on a per-phase basis.

Delta primary and wye secondary are the preferable connections for standard two-winding power transformers and are commonly used in mine power centers. An external busing from the neutral of the wye secondary provides an easy means for resistance grounding, as required by federal regulations. The delta-connected primary provides isolation of the distribution circuit from the utilization circuit with respect to zero-sequence currents resulting from exciting currents or secondary ground faults. The delta-wye connection also stabilizes the secondary neutral point and minimizes the production of third-harmonic voltages. Additional information concerning the desires behind using delta-wye transformers can be found in Chapters 4 and 8. Included are the reasons why wye-wye transformers are not recommended.

In certain situations, a delta-connected secondary may be specified or required. (The primary may be delta or wye in this case.) If neutral grounding is desired or required, a grounding transformer is needed to derive a neutral. A zig-zag grounding transformer is illustrated in Figure 11.7. It is sized according to the continuous-current rating of the neutral-grounding resistor. Standard single-phase or integral three-phase transformers, arranged in a wye-delta configuration, can be used as grounding transformers in lieu of the special zig-zag type as shown in Figure 11.8.

The transformer impedance is sometimes referred to as "impedance voltage" due to the common means of measurement. Impedance voltage is the voltage required to circulate rated current through one of two windings of a transformer when the other winding is short circuited, with the windings connected as for rated-voltage operation (5).

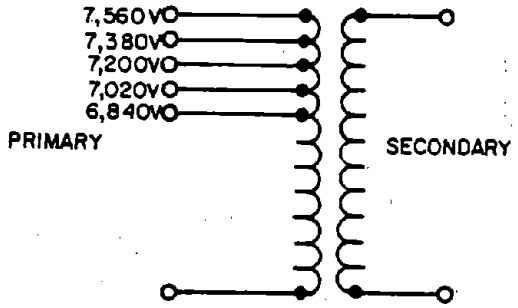


Figure 11.6. Typical Primary Winding Taps on a Power Cable Transformer.

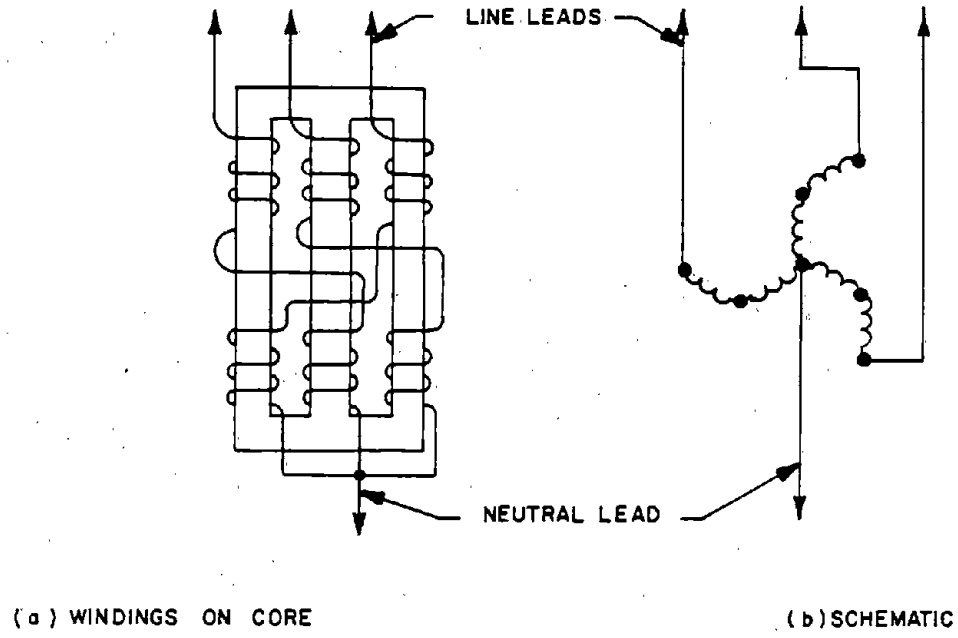


Figure 11.7. Zig-Zag Grounding Transformer.

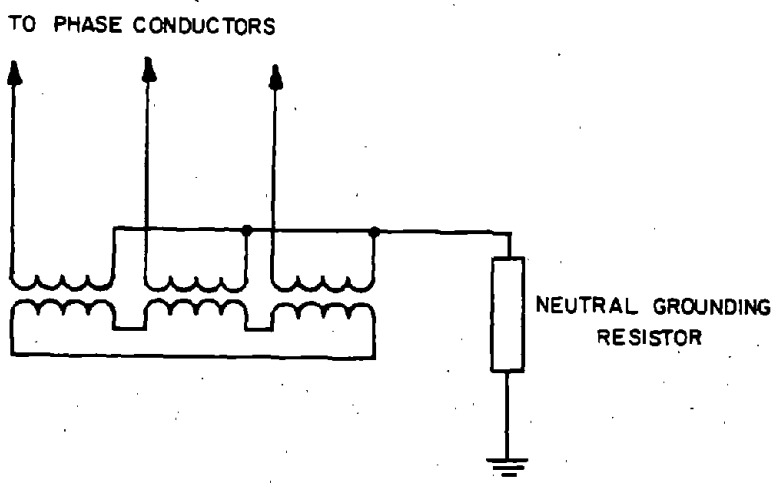


Figure 11.8. A Delta-Wye Connection for Deriving a Neutral.

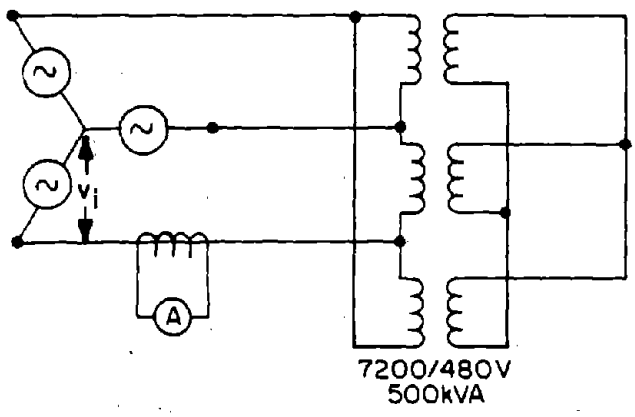


Figure 11.9. Transformer-Impedance Measurement Technique.

An example will help to illustrate this procedure. Figure 11.9 shows a three-phase delta-wye distribution transformer with the indicated ratings. The secondary to the transformer is short circuited while a three-phase variable voltage source is connected to the primary. The voltage source is wye connected so the impedance voltage, V_i, will be a line-to-neutral voltage. The source voltage is increased until the ammeter reads the rated (full-load) current of the transformer, which can be determined by:

$$I_{FL} = \frac{kVA}{\sqrt{3}\ kV} = \frac{500}{\sqrt{3}(7.2)} = 40.1\ A.$$

Consider the case where V_i = 250 V, when the ammeter reads 40.1 A. The impedance voltage is normally expressed in terms of a per-unit value, therefore,

$$V_i = \frac{250\ V}{4160\ V} = 0.06\ pu.$$

The line-to-neutral rating of the transformer (4160 V) is used, since the impedance is being measured as a line-to-neutral potential. For this example, the line-to-neutral impedance of the transformer, with all quantities reflected to the primary would be:

$$Z_T = \frac{V_i}{I_{FL}} = \frac{250\ V}{40.1\ A} = 6.23\ \Omega.$$

The transformer impedance can be measured in terms of a per-unit quantity by using the ratings of the transformer as base values, as follows:

$$kVA_{BASE} = 500\ kVA$$

$$kV_{BASE} = \frac{7200}{\sqrt{3}} = 4.16\ kV\ (line\ to\ neutral)$$

$$I_{BASE} = \frac{kVA_{BASE}}{\sqrt{3}\ kV_{L-L}} = \frac{500}{\sqrt{3}\ (7.2)} = 40.1\ A$$

$$Z_{BASE} = \frac{V_{BASE}}{I_{BASE}} = \frac{4160}{40.1} = 103.7\ \Omega.$$

Thus, the per-unit value of the transformer impedance is

$$Z_T = \frac{6.23\ \Omega}{103.7\ \Omega} = 0.06\ \text{pu.}$$

This yields the same results; therefore, in terms of per-unit quantities, the terms "impedance" and "impedance voltage" are interchangeable.

The vector sum of the leakage reactance and the resistance of the windings comprise the impedance of a transformer. Figure 11.10 shows that the X/R ratio of a transformer increases as the size (MVA rating) increases (7).

The transformer impedance is extremely important since it plays a major role in dictating the amount of current that can be delivered to a secondary fault. For the previous example, the maximum symmetrical secondary-fault current (three-phase fault) can quickly be determined by

$$I_{f(max)} = \frac{I_{FL(sec)}[A]}{Z_T[pu]} = \frac{601}{0.06} = 10{,}023\ \text{A.}$$

The technique produces a more pessimistic value than would actually occur, since it assumes the transformer primary is connected to an infinite bus. A more realistic fault-current value would take into account the system impedance upstream from the transformer as well as an equivalent impedance for the utility. However, this system impedance is constantly changing due to the dynamic nature of the mining process. By using the above method, adequate determination of required interrupting capacity for the protective circuitry serving the utilization equipment can be assured.

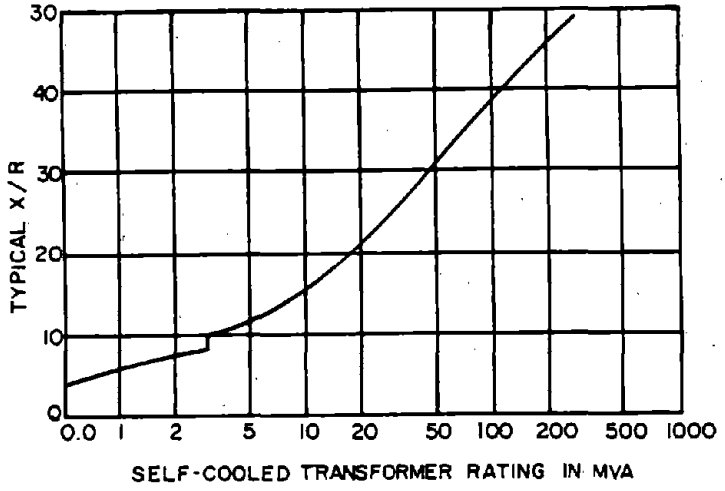


Figure 11.10. Typical Reactance-to-Resistance Ratio Versus Transformer Capacity.

For transformers used in mine power centers, the per-unit values of impedance normally lie in the following range:

1. 0.04 to 0.05 pu for 150 to 450 kVA, and
2. 0.05 to 0.06 pu for 500 to 1250 kVA.

The need for the 0.04-pu lower limit is to limit short-circuit currents to reasonably safe values. For large power transformers, the leakage reactance may be intentionally increased in the design of the transformer to further limit the available fault current. External air-core reactors in series with the secondary windings are sometimes used to restrict fault current from transformers that feed rectifiers. This will be detailed in the section on a-c/d-c combination power centers.

For transformers used in mine power centers, the following minimum insulation ratings should be used (the parenthetically stated BIL's are optional):

1. 4.16-kV primary, 30-kV (60-kV) BIL;
2. 7.2-kV, 45-kV (60-kV, 75-kV) BIL;
3. 12.47-kV (13.2 and 13.8 kV), 60-kV (95-kV); and
4. 23-kV, 150-kV BIL.

Coordination with surge-arrester characteristics must be maintained, as discussed earlier. (See Chapter 10 for further information.)

The kVA rating of a transformer is based upon the continuous operation at rated voltage and frequency without exceeding the specified temperature rise or limiting temperature. The temperature rise depends upon the core and conductor losses. The core losses remain constant with load, while the conductor losses are determined by the I^2R of the windings.

Dry-type transformers used in mine load centers should have Class-220°C insulation. This classification terminology recently replaced the old Class-H, 150°C-rise notation (6). Class H was based on an average ambient temperature of 30°C, allowing a maximum 150°C temperature rise in the windings. This restricted the average insulation temperature to 180°C, but a 220°C hot-spot temperature was also allowed. The new classification simply places an absolute allowable maximum temperature on the transformer when operating continuously under full capacity at rated voltage and current.

The windings should also be designed to withstand the thermal and magnetic stresses resulting from current flow not exceeding 25 times the rated current of any winding for a period of two seconds.

Temperature sensing devices (No. 10 of Figure 11.2) can be placed in the transformer windings to prevent damage from overheating. The device can control a set of contacts located in the pilot circuit of the incoming distribution line. If the

transformer temperature exceeds the specified limit, the contacts in the pilot circuit are opened, which results in tripping the upstream circuit breaker. As an alternative, the contacts can be used to activate the tripping element of a main secondary breaker or all outgoing breakers.

Mine power centers are usually cooled by natural convection, and the side panels of the transformer compartment normally have louvers to allow air circulation. The transformer windings are designed such that the heat generated by the I^2R losses is exposed to an adequate amount of cooling to handle the expected loads. The effective cooling areas are the inside of the winding, the outside of the winding, and the cooling ducts within the winding. The movement of air by convection carries away the heat generated by the winding (7).

Transformer Construction. The two main transformer components are the core and the windings. Figures 11.11 and 11.12 show a typical mine-load-center transformer in the process of being constructed and in completed form.

The transformer core provides a path of low reluctance to the flux produced by the primary windings. In effect, it comprises the magnetic circuit of the transformer. To reduce eddy currents, the core is constructed of laminated sheet steel. The eddy-current losses vary as the square of the thickness of the laminations, and core laminations are usually from 0.01 to 0.02-in. thick (7). The laminated material is cut from silicon-iron sheets. The silicon reduces the reluctance to hysteresis and prevents increased loss with age. The lamination material is specially annealed to obtain a high permeability. It is also treated with a chemical coating to insulate the laminations from each other. The laminations are stacked one upon another to construct a closed magnetic path. Alternate layers are staggered in an interlaminar core-and-gap construction so all joints do not meet at the same place. This is done to reduce the effect of the air gap between the joints and make the entire structure function more like a solid piece of iron (7).

The primary and secondary windings comprise the current circuit of the transformer. The windings are designed to get the required number of turns into a minimum of space through the core opening, while providing enough room for insulation and cooling ducts. Transformer windings are made of copper or aluminum. However, due to its lower conductivity, aluminum requires a larger cross section of conductor and thus a larger opening in the core. The conductors used in the windings may be round, square, or rectangular in cross section. Aluminum secondaries are often wound using sheet metal. All windings may be insulated with enamel, mica paper, NOMEX paper, silicon glass tape, or a combination of these materials (8).

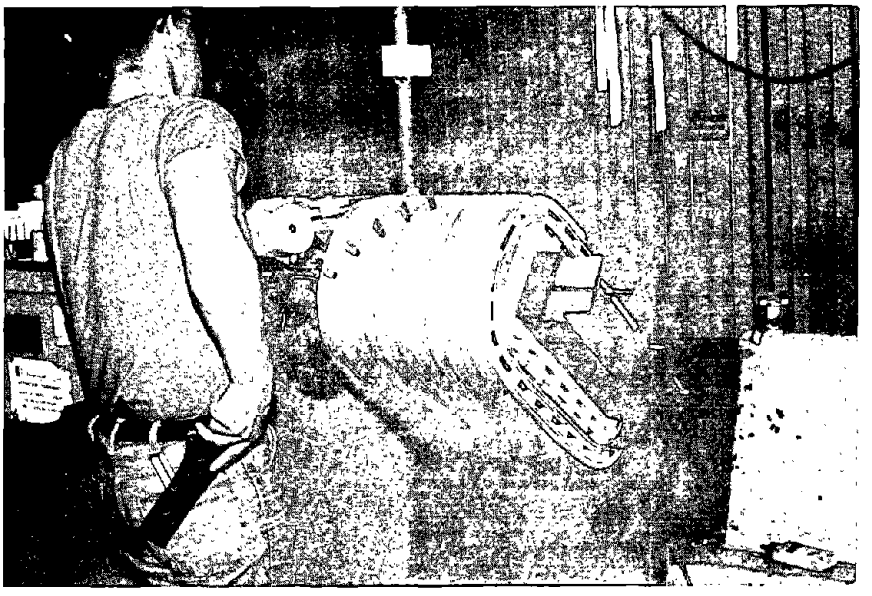


Figure 11.11. A Typical Mine-Load-Center Transformer Under Construction (courtesy PEMCO Corp.).

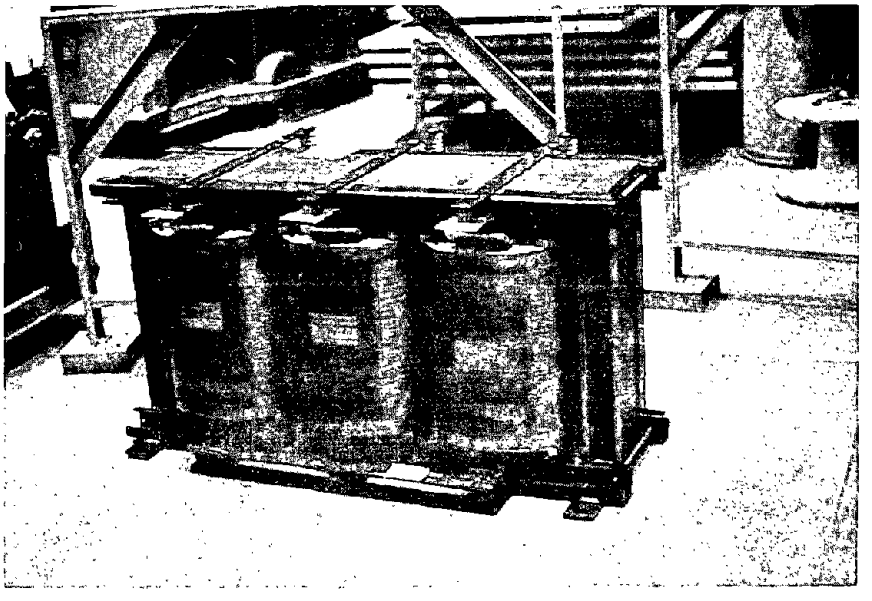


Figure 11.12. A Complete Transformer Prior to Installation (courtesy PEMCO Corp.).

Faraday Shields. Transformer windings can be provided with a grounded Faraday or electrostatic shield to destroy interwinding capacitance between the primary and secondary, thus reducing the danger of transferring distribution transients to utilization. Another important use for the shield is to prevent interwinding faults between layered windings. This is especially critical when the secondaries are isolated above ground, as the primary voltage can be impressed on the secondary (without detection). A ground fault must occur using the shield, and the resulting ground current can be detected by upstream ground-fault relaying.

The shield consists of a layer of nonmagnetic metal placed between the primary and secondary windings, insulated from all windings, and connected solidly to ground (9). Aluminum or copper can be used, but it should be of the same material as the main windings. Physically, it may be a single turn or sheet metal or a closely wound single-layer of wire. To obtain interwinding-fault protection, the shield must have the same ampacity as the grounding conductors leading to the power center, in order to carry maximum available ground-fault current (at least, equivalent to one-half the cross-sectional area of the primary-winding wire).

11.3-10 Grounding Resistor

Federal regulations require the maximum frame potential on medium- and low-voltage circuits to be limited to 40 V. In an attempt to insure this situation, the regulations further require the maximum ground-fault current of these circuits to be limited to 25 A. However, many modern power centers are designed to limit the ground-fault current to 15 A for an additional factor of safety. Limiting the ground-fault current also results in the following additional benefits (10):

1. reduction in burning and melting of faulted electrical equipment,
2. reduction in mechanical stress of faulted electrical equipment,
3. ability to selectively clear the faulted circuit, and
4. reduction in overvoltages that might cause insulation failure.

A grounding resistor (No. 11 of Figure 11.2) is inserted between the neutral of the transformer and the power-center frame as a means of limiting the ground-fault current. The ohmic value of the grounding resistor is based on the maximum ground-fault current condition (i.e., a ground fault at a secondary terminal of the transformer). For this condition, the following equation can be written:

$$I_f = \frac{3V_{L-N}}{Z_1 + Z_2 + Z_o + 3R_G} \qquad (11.1)$$

where,

I_f = maximum ground-fault current (A)

V_{L-N} = secondary line-to-neutral voltage (V)

Z_1 = positive-sequence impedance of the transformer (Ω)

Z_2 = negative-sequence impedance of the transformer (Ω)

Z_o = zero-sequence impedance of the transformer (Ω)

R_g = resistance of the neutral-grounding resistor (Ω).

Since the sequence impedances of the transformer are equal, the above equation can be written as

$$I_f = \frac{3V_{L-N}}{3Z_T + 3R_g} = \frac{V_{L-N}}{Z_T + R_G}. \qquad (11.2)$$

The transformer impedance can be neglected, and R_G is determined by

$$R_G = \frac{V_{L-N}}{I_f}. \qquad (11.3)$$

As an example, consider sizing a grounding resistor to limit the ground-fault current to 15 A for a 480-V system. The ohmic value of the resistor would be

$$R_G = \frac{480/\sqrt{3}}{15} = 18.5\ \Omega.$$

When sizing a grounding resistor, the time rating must also be considered. Under normal operating conditions, an insignificant amount of current flows through the resistor. However during the worst-case situation, 15 A may flow through the resistor. Thus, the power dissipated by the neutral-grounding resistor would be

$$P = I_f^2 R_G = (15)^2(18.5) = 4{,}162\ \text{W}.$$

Normally, the resistor would only be required to dissipate this

power for the time it takes for a circuit breaker to trip. However, the possibility of the circuit breaker failing to trip must be considered. Federal regulations require the resistor rating to be based on an "extended time rating." This has been defined as 90 days of operation per year. The end of the resistor, which is connected to the neutral of the transformer, is also required to be insulated for line-to-line voltage.

11.3-11 Busway

The power-center output requires numerous taps for feeding the utilization circuits. A busway (or busbar) provides a convenient and economical means of providing these taps, as shown in Figure 11.2. The busway consists of flat, bare conductors supported within the power-center enclosure by means of insulators made of glass polyester or porcelain. Busways are available with either copper or aluminum conductors. However, aluminum has a lower electrical conductivity, lower mechanical strength, and quickly forms an insulating film on its surface when exposed to the atmosphere. If aluminum conductors are used, they should have electroplated contact surfaces (tin or silver); at electrical joints, bolting practices which accomodate aluminum mechanical properties should be used (11).

The continuous-current rating of the busway is based on the conductor's cross-sectional area and a maximum temperature rise of 55°C from ambient. Its short-circuit rating should exceed the maximum available fault current. In general, the sizing is basically no different than that covered for other conductors in Chapter 7. Figure 11.13 is a view of a typical busbar arrangement in a mine power center under construction.

11.3-12 Outgoing Circuit Breakers

Molded-case circuit breakers (No. 13) are usually employed to protect a-c utilization equipment and their associated cables. Some manufacturers have special "mine-duty" breakers available with increased ruggedness and reliability to meet the demands of mining practices. Dual-element fuses could be used but seldom find application because of single-phasing worries and no auxiliary protective-relaying capabilities. A complete discussion of molded-case-breaker and fuse applications, sizing, and problems is available in Chapters 8 and 9. A presentation of molded-case devices with solid-state tripping elements is contained in Chapter 12.

The load-center circuit-breaker compartment must be designed for easy access, but protection is necessary against exposure to energized terminals and conductors. Dead-front panels are preferred, with the breaker mounted to a panel inside and only the operating handle and adjustments accessible from

outside. As an alternative, the breakers can be surface mounted as long as a barrier covers the power terminals. Doors should be used on the exterior frame of the center to minimize exposure of the compartment to dust and other contaminants.

The three kinds of protection that can be directly provided by molded-case circuit breakers are short circuit, overload, and undervoltage. Short-circuit protection is required on all outgoing power (ungrounded) conductors, and maximum allowable instantaneous-trip settings are established by federal regulations. Overload protection is mandated in some states. Magnetic and thermal elements afford these kinds, respectively. Pickup settings for both are based on the smallest size of cable being protected. Undervoltage protection of each outgoing circuit is rarely not required, the only exception being if the protected equipment has its own. An undervoltage release (UVR) is almost always used and is an auxiliary solenoid which trips the operating mechanism of the breaker whenever its coil voltage drops below 40% to 60% of rated. Other protective relaying, external from the breaker, can be afforded to the outgoing circuit through the UVR. (Note: Even though undervoltage protection may be needed, each outgoing breaker in a mine power center should contain an UVR. Outgoing breakers are not usually provided with shunt-trip solenoids.)

Terminal connectors are available for molded-case breakers for either single or multiple conductor entry. Copper conductors require the use of copper terminals, and aluminum conductors require aluminum-compatible terminals. If multiple conductor terminals are employed, the terminal must be constructed so each conductor can be tightened without removing another conductor. Figure 11.14 is a representative view of conductor connections to a molded-case breaker.

The selection of molded-case circuit breakers is based on the voltage, frequency, interrupting capacity, continuous-current rating, and trip settings. Even though a discussion is presented in Chapters 8 and 9, practical considerations for interrupting-capacity and continuous-current selection are warranted here.

Molded-case circuit breakers often begin interruption of short-circuit currents during the first cycle after the fault. Thus, they must be selected on a basis of maximum first-cycle asymmetrical fault current. The breakers are rated on a symmetrical current basis, which eliminates applying d-c offset multipliers when selecting the breaker. Using calculated symmetrical short-circuit currents is generally considered adequate for load-center applications.

As an example, consider a 750-kVA power center with a secondary utilization voltage of 600 V. If the transformer impedance is 6%, the maximum symmetrical fault current, I_f, can be calculated as:

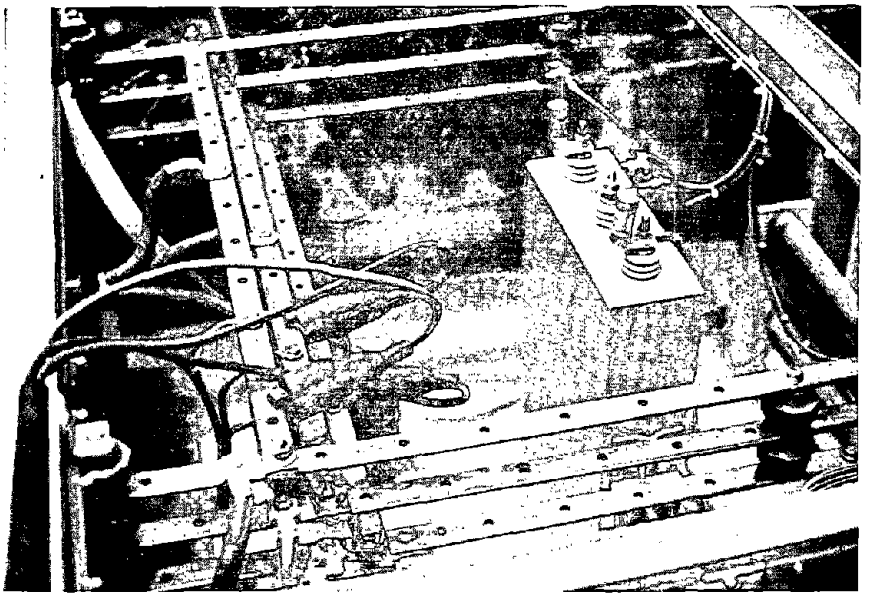


Figure 11.13. Typical Bus Work in a Load Center Under Construction (courtesy PEMCO Corp.).

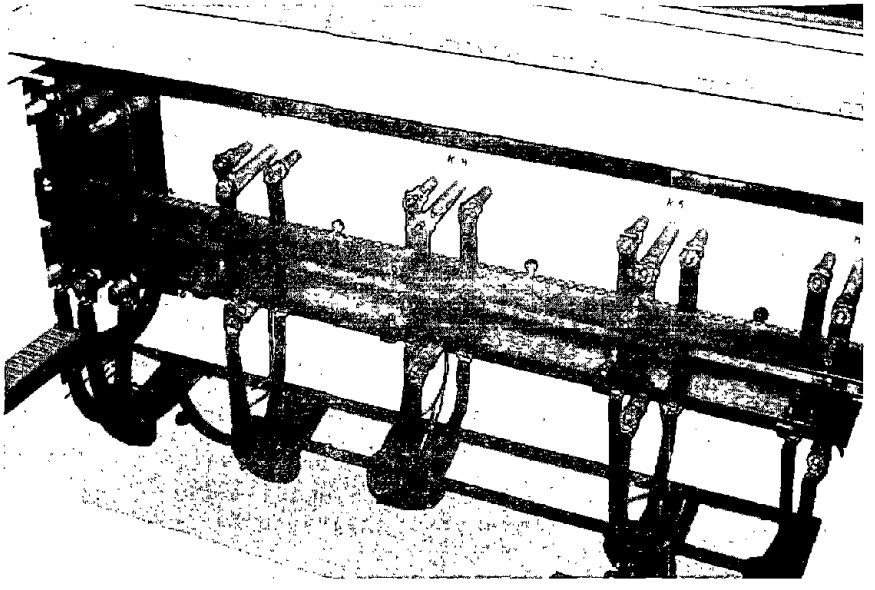


Figure 11.14. Representative Conductor Connection to a Molded-Case Circuit Breaker (courtesy PEMCO Corp.).

$$I_{FL} = \frac{750}{\sqrt{3}\ (0.6)} = 722\ A$$

$$I_f = \frac{722}{0.06} = 12{,}033\ A.$$

This of course assumes a worst-case condition, since transformer impedance is the only limiting factor for fault current. In this case, even a 100-A standard mine-duty breaker could interrupt the fault; the typical interrupting capacity is 14,000-A symmetrical at 600 V. However, if the power center contains a 1000-kVA transformer with 6% impedance, fault current becomes:

$$I_{FL} = \frac{1000}{\sqrt{3}\ (0.6)} = 962\ A$$

$$I_f = \frac{962}{0.06} = 16{,}038\ A.$$

Under this situation, the standard 100-A molded-case breaker would have inadequate interrupting capacity. (A premium-duty 100-A unit would be safe; typical interrupting capacity is 18,000-A symmetrical at 600 V. See Chapter 8 for other typical ratings.) The simple example given here shows just one reason for the minimum transformer impedance stated earlier under that section. The continuous-current rating for a molded-case circuit breaker is actually the rating of the thermal-trip element, which can be less than the breaker frame size (i.e., a thermal-magnetic breaker). Magnetic-only devices have the continuous-current rating equal to the frame size. The rating is based upon 100% continuous current at 40°C, but sizing the breaker is normally related to 80% of the rating. This means that sizing is based upon 1.25 times the cable ampacity or the full-load circuit current. In other words, the breaker operates at 80% of the continuous-current rating at full-load current. (Note: Some molded-case breakers are applied at 100% full-load current, e.g., those with solid-state tripping elements.)

For instance, consider sizing a breaker to protect a 4/0 cable for overload. A typical ampacity for 4/0, three-conductor, unshielded trailing cable is 287 A. Thus, the breaker continuous-current rating would be [1.25][287] or 359 A. The next highest standard size, or a 400-A rating, would then be the selection. However, when sizing outgoing breakers for a mine power center, the selection means is not as simple. The process can approach something of an art based on prior experience, especially when underground coal-mining equipment is involved. An actual situation will be used to illustrate some difficulties that can be encountered.

From a practical standpoint, 4/0 is the largest trailing-cable size that can be used in underground mining. It is the

most common conductor size for continuous-miner applications. Assume that the continuous miner has the following motors:

1. cutting motors, two at 90 hp;
2. pump motor, 50 hp;
3. gathering-head motor, 70 hp; and
4. traction motors, two at 35 hp.

Assuming a 480-V system, an average efficiency of 90%, and an average power factor of 90%, the maximum theoretical full-load current for the machine (370 connected hp) would be:

$$I_{FL} = \frac{(370)(0.746)}{\sqrt{3}\ (0.48)(0.9)(0.9)} = 410 \text{ A.}$$

This current exceeds the cable ampacity; thus, breaker sizing based on cable ampacity is not applicable. It should be realized that having all motors draw rated current would be a rare situation. Each motor or motor pair has its own non-continuous duty cycle, which is a function of many variables. It is for this reason that an "undersized" trailing cable can be used. Yet the circuit breaker must be selected to handle the load demands of the continuous miner; therefore the sizing of the continuous-current rating for a breaker does not follow a set procedure. Most power-center manufacturers are well aware of the machinery available and can usually provide the optimum circuit-breaker size for specifications. (Again, see Chapter 8 for additional discussion.)

A main circuit breaker (No. 14 of Figure 11.2) is often recommended if the number of outgoing circuits exceeds three. The breaker has the bus work as its primary protection zone, but also serves as back up to the outgoing breakers. The rating can be based upon the full-load current of the transformer secondary or the ampacity of the bus work, whichever is lower. In general, bus work is sized on the transformer full-load current. For example, the full-load current for the 600-V secondary of a 750-kVA power center is:

$$I_{rated} = \frac{750}{\sqrt{3}\ (0.6)} = 722 \text{ A.}$$

Thus, the breaker continuous-current rating should be based on:

$$I_{FL} = (1.25)(722) = 902 \text{ A.}$$

A 1200-A frame with a 1000-A continuous-current rating would be selected. The thermal elements would provide overload protection to the transformer and bus work; magnetic elements can be set to give short-circuit protection to the bus work. Some main breakers only provide the latter (no thermal elements). Obviously, the main breaker must be coordinated with the outgoing breakers and the high-voltage fuses on the transformer primary.

11.3-13 Ground-Fault Protection

As mentioned earlier, a grounding resistor is placed between the transformer neutral and the power-center frame to limit ground-fault current to 25 A. Ground-fault relaying must be used on each outgoing a-c circuit to initiate circuit interruption for malfunctions. The common relay schemes for a-c applications in load centers are zero-sequence, neutral (direct), and potential.

Zero-sequence relaying is the most common ground-fault protection and is utilized on practically all outgoing a-c circuits. As shown in Figure 11.15, the three phase conductors are passed through a window-type CT, and burden for the CT secondary is a ground-trip relay. Operation is described in Section 8.5-4.

The ground-trip relay must be set to pick up at 40% or less of the maximum ground-fault current. For this situation, a low-ratio CT might be expected to be used, such as 25:5 or 50:5 (ampere-turns ratio). However, better sensitivity has been realized by using a high-ratio CT, 350:5 or higher, with a voltage-sensitive relay (about 1.5-V pickup) instead of a current-sensitive relay for the tripping device. Some manufacturers employ a slight variation to this conventional scheme by rectifying the CT output and using a d-c voltage-sensitive relay. Either way, these schemes work with a low-cost, low-burden CT. Since the CT is drastically under-utilized, its

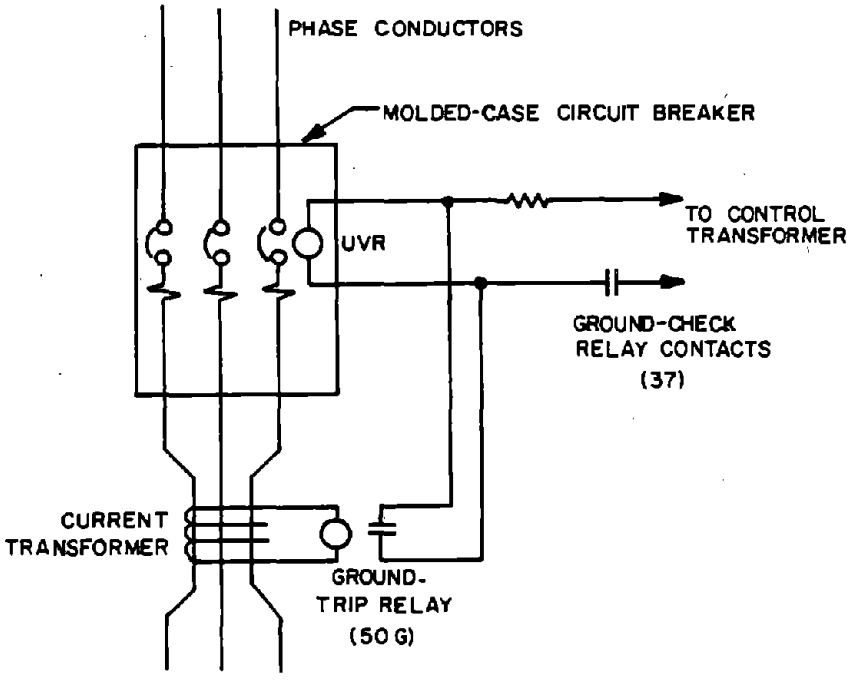


Figure 11.15. Zero-Sequence Relaying on an Outgoing Circuit with Control Connections to a Breaker.

secondary current cannot be predicted by knowing the turns-ratio of the CT. The pick-up values must be determined by testing.

The N.O. contacts of the relay usually parallel the UVR of the associated circuit breaker. When the relay pick-up value is exceeded, its associated contacts close and short out the UVR coil. This technique has been adopted to eliminate the nuisance tripping due to bounce and vibration which hampers circuits that have the contacts in series. One problem, however, with paralleled contacts, as shown in Figure 11.15, is that ground-fault protection is lost if the relay is removed from its socket. To prevent this, UVR power can be supplied through a "jumper" in the ground-fault relay case (Figure 11.16). Without the relay, the circuit breaker cannot be closed (except for some small molded-case units, such as 50 A).

Neutral relaying is sometimes used in mine power centers when a main breaker is used. The neutral conductor from the transformer is encircled by a CT as shown in Figure 11.16. The CT and the ground-trip relay are the same as discussed for zero-sequence relaying. However, a time delay should be introduced by the ground-trip relay so only interruption of the faulted circuit occurs. If the circuit breaker of the faulted circuit fails to trip, the main circuit breaker will provide back-up protection after the prescribed time delay. The time delay is on the order of 0.5 s and can be achieved by pneumatic or electronic means. The breaker trip device may be either a shunt trip or UVR, but the UVR is preferred.

Potential relaying can also be used as back-up protection in conjunction with a main circuit breaker. Unlike zero-sequence and neutral relaying, potential relaying has the advantage of being able to detect a ground-fault with the neutral grounding resistor open. Figure 11.18a shows a potential-relaying scheme using a PT for obtaining a voltage within the relays operating range; whereas Figure 11.18b shows a voltage divider to provide the same function.

The maximum pick-up voltage of the relay for both schemes should correspond to the voltage developed across the relay at 40% of the maximum fault current. Care must be taken in sizing the resistors when using a voltage-divider circuit so as not to significantly reduce the total equivalent resistance of the parallel combination. The combined value ($R_1 + R_2$) must be significantly higher than the value of the neutral grounding resistor. The impedance of the relay should also be significantly higher than the resistance of R_2 for the same reason. The power (I^2R) rating of the resistors should be capable of withstanding the currents expected through them under a maximum ground-fault condition.

Figure 11.18c illustrates a popular alternative to back-up relaying. Here, a red warning light, in a rugged or explosion-proof housing mounted on the outside of the load center,

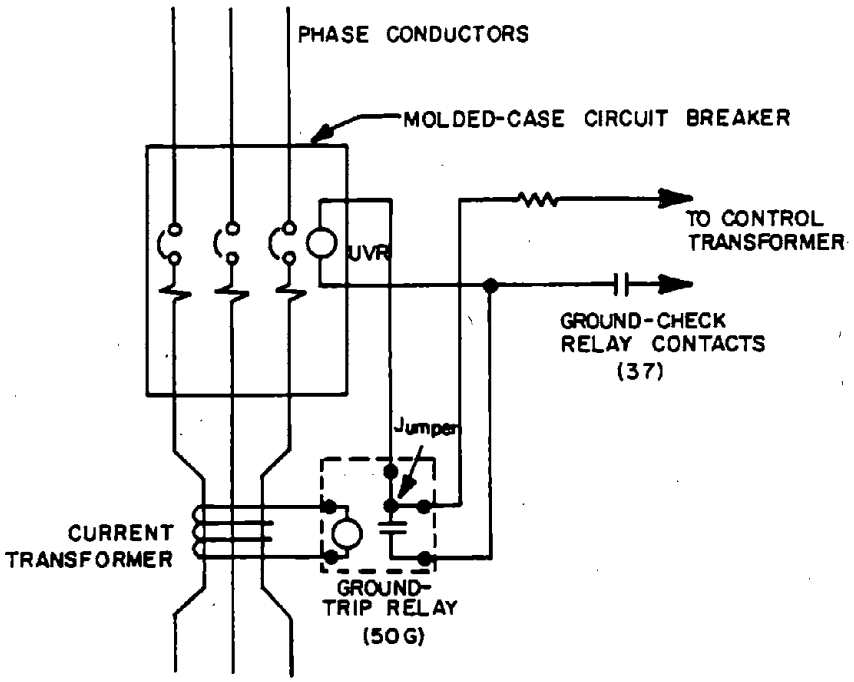


Figure 11.16. Zero-Sequence Relaying with Jumper in Relay Case.

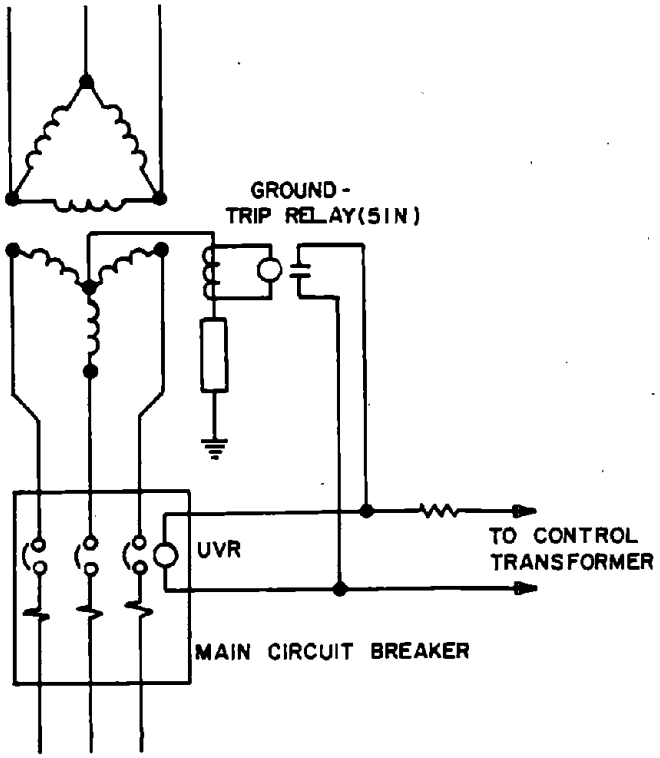
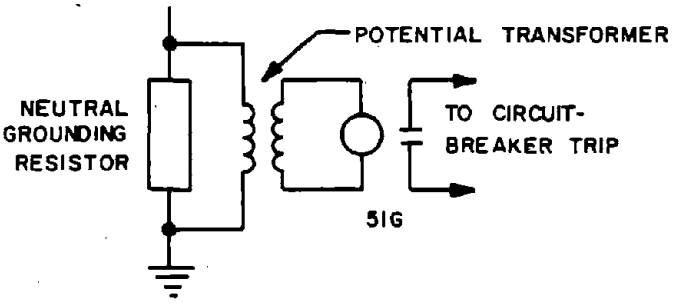
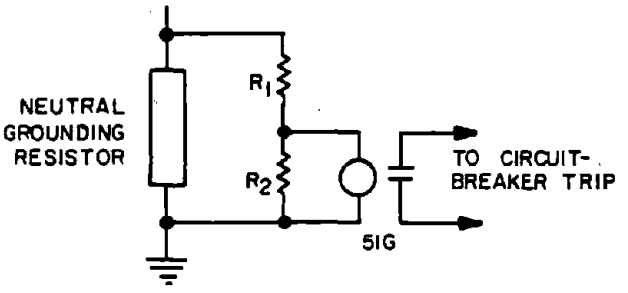


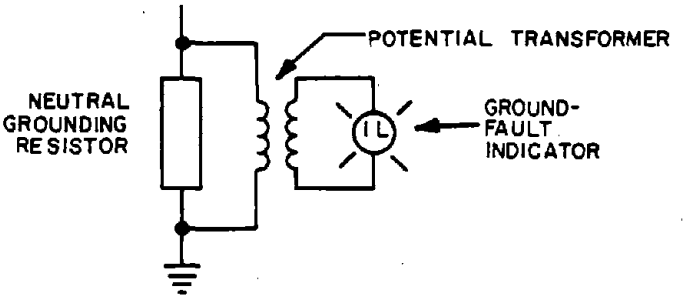
Figure 11.17. Neutral Relaying Applied to Grounding-Resistor Current as Back-up Protection.



(a) POTENTIAL TRANSFORMER



(b) RESISTIVE VOLTAGE DIVIDER



(c) WARNING LIGHT

Figure 11.18. Back-up Protection Devices Associated with Mine Power Centers.

replaces the relay coil. The light-bulb voltage is matched to the PT to give maximum brilliance under maximum ground-fault conditions, but noticeable light output at 40% of current limit. Many engineers prefer this technique, as it provides an obvious indication of ground-fault presence, especially useful when primary ground-fault relaying is inoperative either through tampering or malfunctions.

Test circuits for ensuring pick-up at 40% of the maximum ground-fault current can be incorporated into the power center. Figure 11.19 is an example. A control transformer with a secondary voltage of 12 V is used as a current source. The 12-Ω resistor is inserted in the circuit to limit the secondary current to 1.0 A. The six turns through the CT at 1.0 A produce the same effect as 6.0 A of zero-sequence current for the power conductors. The current corresponds to 40% of a 15-A system. Therefore, depressing the test button simulates a ground fault at 40% of the maximum current, and the associated circuit breaker should trip.

11.3-14 Single-Phase Transformers

Single-phase transformers are used to supply 120 V to the control circuit and 240/120 V to convenience outlets. The control circuit consists primarily of ground-monitoring systems, undervoltage releases, and ground-fault circuitry for each associated machine circuit, as well as relay connections for other protection kinds. Convenience outlets can be used for portable power tools, area lighting, or external test instrumentation. Control-transformer capacity normally ranges from 50 VA to 500 VA, while transformer capacity for 120/240-V outlets often falls in the range of 5 kVA to 10 kVA. Larger capacities may be found, particularly in mine power centers with extensive control circuitry. A simple control circuit and convenience-outlet circuit are shown in Figures 11.20 and 11.21, respectively. In both circuits, fuses are used to protect the transformer primaries. This is recommended for control-power circuits, but

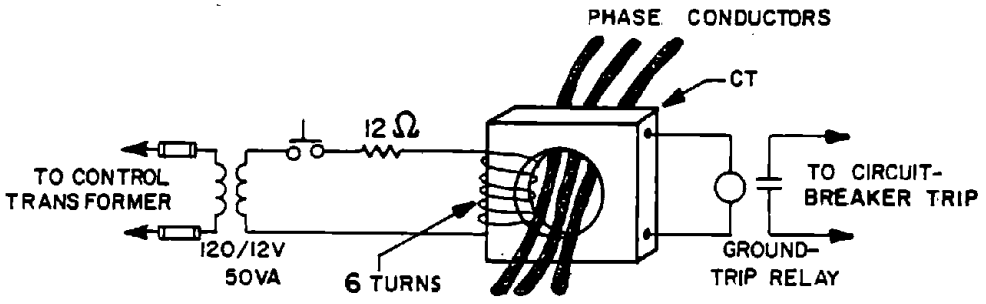


Figure 11.19. A Typical Test Circuit for Zero-Sequence Relaying.

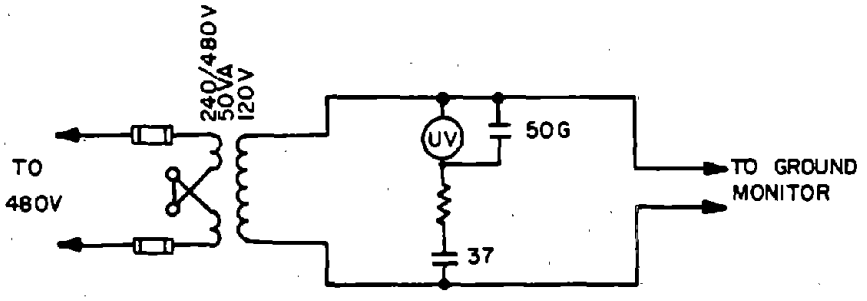


Figure 11.20. A Simple Control Circuit Incorporating One Ground-Fault Relay (GFR) and One Ground-Check Relay (GCR).

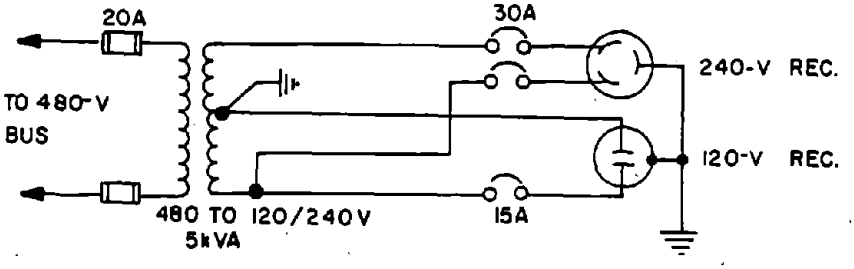


Figure 11.21. A Simple Convenience-Outlet Circuit for 120-V or 240-V Single Phase.

circuit breakers can be employed to protect convenience-transformer primaries. (Breakers on control circuits can be tripped by a casual miner, deactivating the load center.) For replacement, the fuses can be accessible through a bolted cover to authorized personnel.

A variety of schemes exist for obtaining the control and utility circuit voltages. Each machine circuit can have its own individual control transformer, or a single control transformer can supply all of the control circuits. When all of the control circuits are supplied by a single source, the control circuit transformer can be eliminated, and the control voltage can be supplied by the secondary of the utility transformer. This combination is not recommended by many mine-power engineers, as a failure or misuse of a convenience-outlet circuit could result in blowing the transformer fusing, which in turn would cause the loss of control power. In this case, all power to the mining machinery would stop. Accordingly, some prefer not to incorporate 120/240-V outlets in their load centers, even with separate transformers.

11.3-15 Metering Circuits

The mine power center should include metering circuits to monitor line voltages and currents of all three phases (No. 15 and No. 16 of Figure 11.2, respectively). The built-in instrumentation is an invaluable aid to maintenance, as it allows a first-hand look at the electrical operation of the load center and thus the composite of the loads it serves. The metering is usually for distribution or utilization voltages and currents, but rarely for both.

Figure 11.22 illustrates a common approach for metering voltage. Potential transformers are used to reduce the line voltage to a value within the rating of the voltmeter potential coil. Two single-phase transformers are connected in open delta, and a four-position switch allows monitoring the three phase-to-phase voltages as well as an off position.

Two CT's are sufficient for metering the current in all three phases, as shown in Figure 11.23. The CT isolates the meter circuit from the line. The CT ratio should be as low as possible without exceeding rated current in the secondary winding. A common recommendation is that the ratio be such that normal CT secondary current be 0.5 to 0.75 the full-scale rating of the meter (11). The CT turns ratio can cause dangerously high voltage on the secondary if it is opened. Thus, the ammeter switch must be designed so the secondary is not open circuited during the transition from one switch position to another (known as "shorting" type switch contacts).

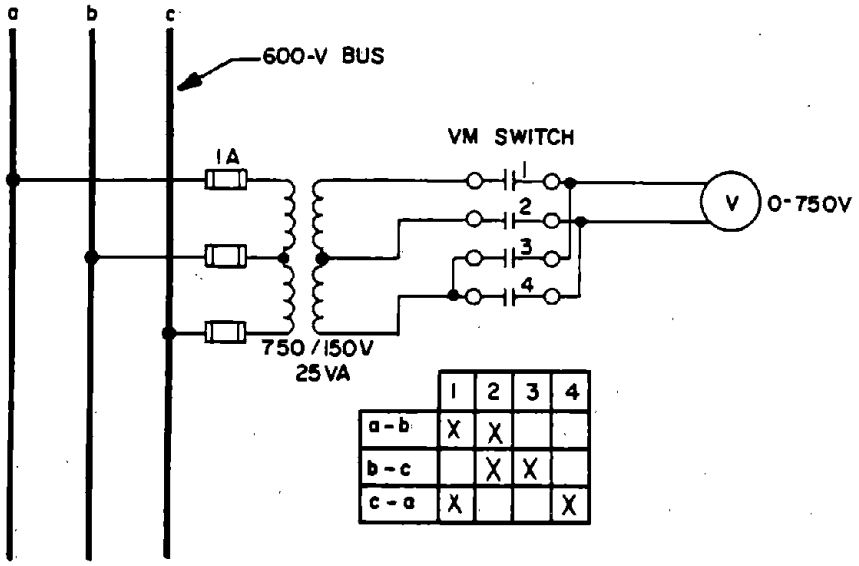


Figure 11.22. A Typical Metering Circuit for Phase-to-Phase Voltages.

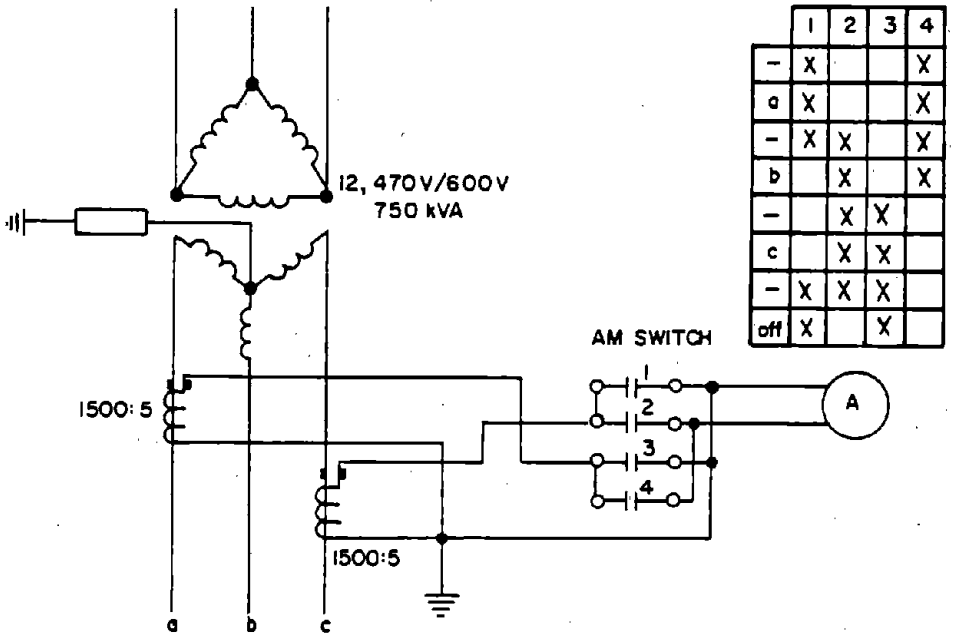


Figure 11.23. A Typical Metering Circuit for Phase Currents.

11.3-16 Outgoing Cable Couplers

The utilization-equipment trailing cables are almost always connected to the power center by means of low- or medium-voltage cable couplers (No. 17 of Figure 11.2). These also provide a visual disconnect for performing maintenance on the equipment. The receptacles (female contacts) are gear-mounted, while the plugs (male contacts) are line-mounted. As with high-voltage couplers, the opening of contacts must follow a sequential order when disconnecting the coupler. Both coupler sections should be provided with dust covers to prevent damage to the contacts when disconnected. Couplers are rated at 600 V for low-voltage operation and 1000 V for medium voltages. Standard current ratings are 100, 225, 400, and 800 A, but larger sizes are readily available. Additional information can be found in the coupler section of Chapter 7.

11.3-17 Ground-Check Monitors

Low- and medium-voltage resistance-grounded systems are required to have a fail-safe ground-check circuit to continuously monitor the continuity of the grounding conductor. The monitor must cause its associated circuit breaker to trip if the grounding conductor or a pilot wire is broken. An indicator lamp on the monitor should indicate a tripped condition. The monitors are usually enclosed in a dead-front package and mounted near the associated circuit breaker. From the information given in Section 8.5-5, monitors in common use in mining can be divided into two general classifications, impedance types and continuity types.

Impedance-type monitors require the trailing cable to have a pilot conductor. The monitor is calibrated to the impedance of the loop formed by the pilot and grounding conductors. The device then monitors the change of impedance from the initial calibration. If the impedance of the loop increases beyond a preset value, the monitor must trip its associated circuit breaker by opening a set of contacts in series with the undervoltage release.

The maximum allowable increase in impedance is dependent upon the maximum ground-fault current permitted by the system. For a 15-A neutral-grounding resistor, the monitor should cause tripping as the impedance increases by 2.7 Ω. This value is based upon the maximum allowable frame-to-ground potential of 40 V, as follows:

$$Z = \frac{V_{max}}{I_f} = \frac{40}{15} \qquad 2.7\ \Omega .$$

From the above, it is apparent that a ground-check monitor does not ensure that the frame potential of a piece of equipment will

not rise above 40 V, since the device only monitors the change in impedance of the pilot and grounding-conductor loop and not the actual impedance of the grounding conductor.

A schematic of a common impedance-type monitor is shown in Figure 11.24. This specific monitor is powered from a 24-V to 32-V source (others do not use 120-V power). Out-of-phase induced currents during motor starting can result in canceling out the monitoring current, which in turn can cause nuisance tripping. As a result, a polarity-reversal switch should be provided to change the phase relationship of the pilot current with respect to the induced current. Some manufacturers use impedance-matching transformers to amplify the change in impedance for easy detection. The monitor should also provide a test button. With the button depressed, the appropriately-sized resistor is inserted into the pilot circuit and should result in tripping the circuit breaker.

A disadvantage of the impedance-type monitor is that it cannot detect a pilot-to-ground fault. This type of monitor is also susceptible to problems with parallel paths.

Continuity monitors do not monitor impedance change, but only the grounding-conductor continuity. However, they must be adequately immune to parallel paths. Continuity types (also termed "pilotless" or "wireless" as in Chapter 8) are of the audio type and do not require a pilot conductor for operation. Figure 11.25a contains a block diagram of common unit. Most makes can also be wired for pilot operation (see Figure 11.25b), but only the operation of the pilotless configuration will be discussed.

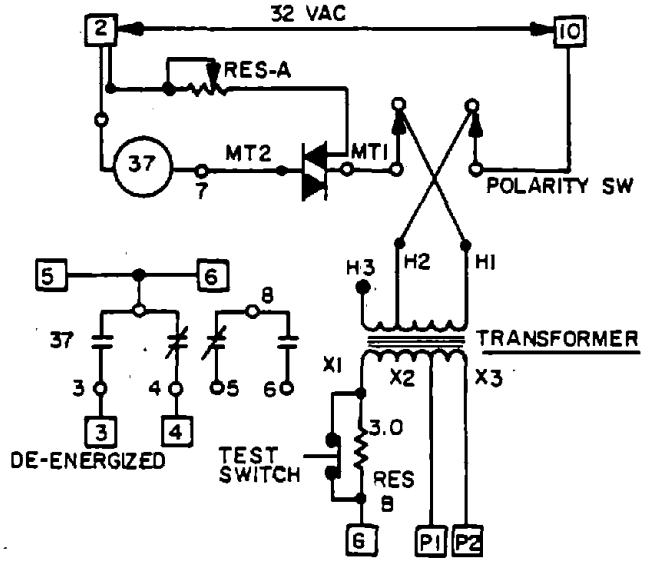


Figure 11.24. A Typical Impedance-Monitor Circuit.

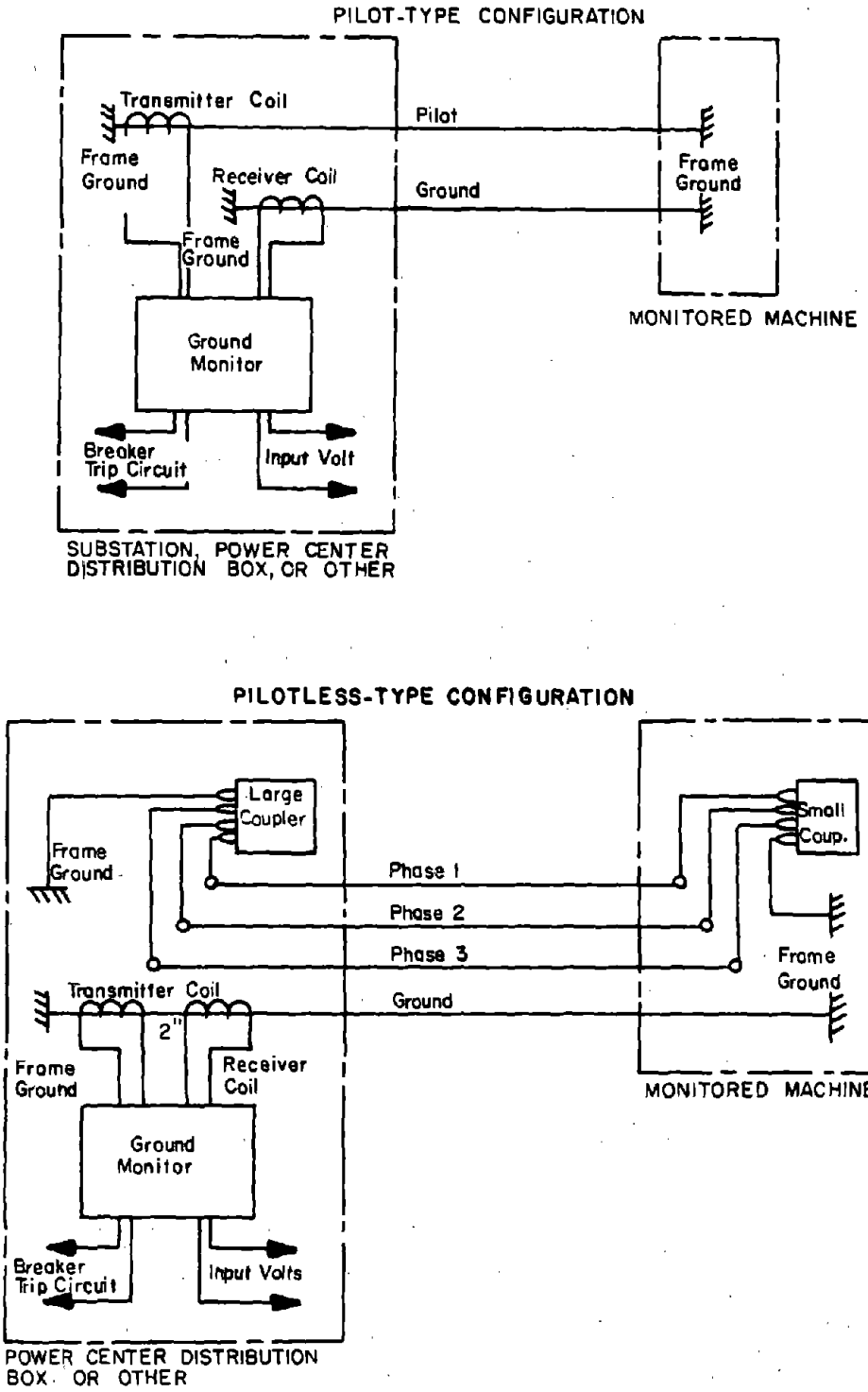


Figure 11.25. Typical Continuity-Type Monitor Block Diagrams.

The monitor generates an audio frequency which is coupled to the grounding conductor by means of the transmitting coil. The pilot wire is eliminated by using the phase conductors as a return path. A filter at the monitoring location and within the monitored machine is necessary for coupling and uncoupling the audio signal from the phase conductors. If the grounding conductor is intact, the receiver coil picks up the audio signal. If the grounding conductor is open, the receiver coil will pick up no signal, and the monitor will cause a set of contacts to open in the undervoltage circuit of its associated circuit breaker. Section 8.5-5 contains a discussion of a continuity monitor which operates in a somewhat different fashion; the signal is impressed and removed from the phase conductors with the grounding conductor used for the return path.

The major advantage of the continuity monitor is that it is immune to parallel paths and stray currents. It is also immune to pilot-to-ground faults, if a pilot conductor is not used. However, the continuity monitor is expensive and complex when compared to an impedance monitor. A pilotless monitor must still be wired into the pilot and grounding contacts of the coupler in order to trip the circuit breakers when disconnecting the coupler. Another problem is that the grounding conductor must be isolated from the coupler shell or the intended monitoring is bypassed. (For metallic shells, a separate grounding conductor must be supplied through a spare coupler contact.)

11.3-18 Power-Factor Correction

Some mining machines have notoriously poor power factors resulting from under-utilization of induction motors. Perhaps the most outstanding examples are continuous miners; during the operational cycle, their typical power factor can average 0.6 lagging. Be it this machine or others creating excessive reactive power, the result is poor power-system efficiency and utilization. Discussions of the associated worries are available in Chapters 3, 4, and 5. Regardless, if the power factor is poor (say under 0.80 and even higher) at the purchase point, the utility company will attach a penalty to the power bill.

There are many opinions on where to improve power factors. The most obvious place should be at the utilization points where they occur. Such is common in surface mines, for instance, in excavating machines. However, this equipment has an advantage not usually available to underground mining machines, room to place the correction equipment. If improvement is made at a convenient location immediately upstream from the offending motors, the entire system to and including the substation can benefit through lower apparent power, reduced phase currents, and better voltage regulation. This location is commonly on the utilization bus work in power centers. On the other hand, if correction is not attempted here, power factors will be increased by the

inherent distribution-system capacitance (e.g., that associated with shielded cables) or somewhat cancelled by the diversity of operation which always exists between mining machinery and equipment sections. Accordingly, some engineers would rather correct the overall power factor at the distribution side of the substation. Consequently, three general locations are usually considered if power factors need correction. Should it be at the machine, in the power centers, or at the substation?

The answer to this question has no definite solution. Each mine power system must be analyzed on its own, and the final decision cannot only consider electrical operation, but also economics. One thought would be the cost of load-center correction versus that at the substation versus the penalty added to the power bill. If the decision is to add correction, the common approach is to use a bank of capacitors (also known as a "static" bank). Synchronous rotating machinery is not logistically practical for most cases.

The application of correction-capacitor banks has related precautions, regardless of location. First, they are a system load and, thus, the bank must not be grounded on resistance-grounded systems. In the past, the common capacitor insulation has been PCB (polychlorinated biphenyl). Because of the environmental hazards associated with this material, capacitors containing PCB must not be used. Next, due to the dynamic operation of mining equipment, correction should never attempt to obtain unity power factor on an average basis. If this is done, the resultant power factor could be leading (capacitive) for a significant portion of operation time, and overall system operation might be worse than if no correction was added. The last precaution to be mentioned is resonance. There is a chance that the added capacitance from the static bank can create a RCL combination with the system portion that causes undesirable resonance. Here, problems have been observed particularly with power centers (belt transformers) supplying solid-state belt starters, manifesting itself as voltage and current frequencies other than 60 Hz.

Figure 11.26 shows the application of power-factor correction in a mine power center. The schematic is basically a reproduction of Figure 11.2 with the additional items No. 18 and No. 19, a static capacitor bank and its associated protection, respectively. Three capacitors connected in ungrounded wye are shown, but an integral three-phase capacitor with the same configuration can also be used. A molded-case circuit breaker affords short-circuit and overload protection, but also acts as a switch for removing the bank from the line. Sizing of this breaker is the same as related earlier for other applications and can be based on normal capacitor current. The current can be easily calculated from the per-phase capacity (kvar) and the system voltage. Some load centers are designed with more than one capacitor bank so the magnitude of correction can be changed.

The sizing of capacitor is also straightforward and follows the basic prodecures presented in Chapters 3 and 4. For instance,

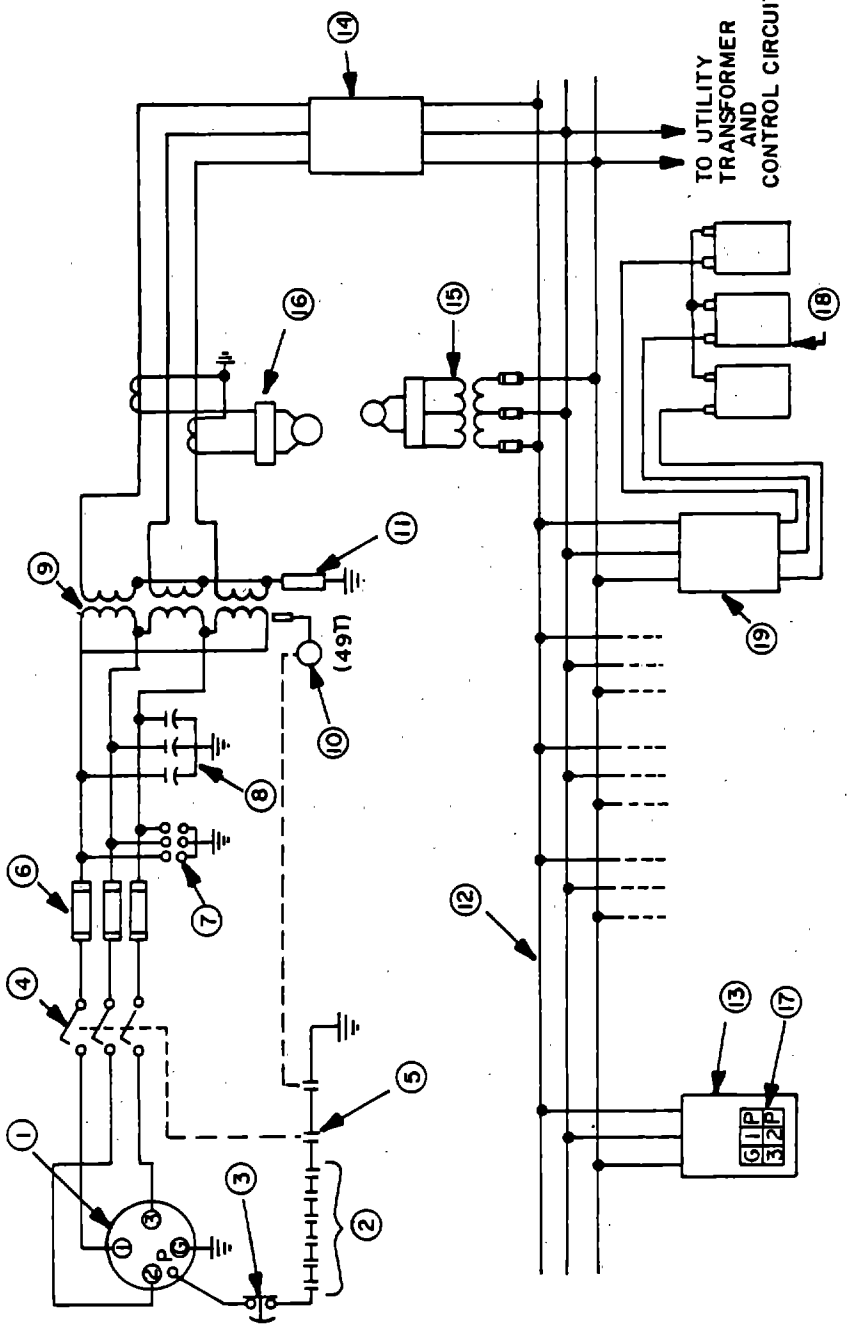


Figure 11.26. The Addition of Static Power-Factor Correction on Figure 11.2.

consider a mining section that has been found to be consuming 172 kW at an average power factor of 0.6 lagging. The average apparent and reactive power are then:

$$S = \frac{P}{pf} = \frac{172}{0.6} = 287 \text{ kVA}$$

$$Q_L = S[\sin(\cos^{-1} pf)] = 287\ (0.8) = 230 \text{ kvar.}$$

With a 90-kvar capacitor bank, the resultant reactive power and new power factor would be

$$Q_T = Q_L - Q_C = 230 - 90 = 140 \text{ kvar inductive}$$

$$\text{Tan } \Theta_T = \frac{Q_T}{P} = \frac{140}{172}, \quad \Theta_T = 39^\circ$$

$$pf = \cos^{-1} 39^\circ = 0.78.$$

Thus, the average power factor has been improved from 0.6 to 0.78. As a general recommendation, power-factor correction in mine power centers should not try to correct above 0.85 average power factor.

Figure 11.26 also serves as a summary of the material presented in the foregoing paragraphs on a-c mine power centers. As has been seen, the internal components can be generally grouped into those associated with the high-voltage side, the transformer, and the utilization side.

11.3-19 Direct-Current Utilization

Although a-c utilization now dominates the mining industry, some segments of the mining process still remain better suited to the use of d-c motors. The classic example is the use of d-c series-wound motors for traction. The speed-torque characteristics of these motors are particularly advantageous for this application, especially for locomotives and shuttle cars. It is for this reason that d-c utilization still plays a significant role in the mining process.

There are various ways of obtaining a d-c voltage for powering the face equipment. If a mine uses rail haulage at a working section, the d-c equipment can be powered directly from the trolley-feeder line. However, if a working section does not have direct access to a trolley-feeder line, a rectifier must be used to convert the three-phase a-c voltage to a d-c voltage. The "rectifier" can be a separate piece of equipment housed in its own enclosure and powered by means of a feeder cable from the a-c power center, with the total unit being referred to as an a-c/d-c "combination" power center. Some mining-machinery manufacturers offer face equipment with on-board rectifiers so

the benefits of d-c motors can be obtained without the need of a section rectifier (see Chapter 12).

Even if the rectifier is supplying a trolley, the basic internal components of d-c power equipment remain essentially the same. Thus, only the d-c section of a combination power center will be discussed in the subsequent section. A general arrangement of the d-c components is illustrated in Figure 11.27. This diagram will be referred to in order to indicate the placement of individual components with respect to the overall system. The d-c circuits that are more commonly associated with trolley-feeder lines will also be mentioned. Components and circuits that have been discussed in the preceding chapter sections will only be presented as required for clarity.

11.3-20 Rectifier Transformer

A three-winding transformer (No. 1) is commonly used in a combination power center, consisting of primary, secondary, and tertiary windings. Normally the primary winding is delta connected with the secondary and tertiary windings wye connected. However, the transformer can be designed such that the primary winding can be connected in either a delta or a wye configuration so it can be applied at two different distribution voltages (e.g., 4160 V-delta, 7200 V-wye). For this situation, either the secondary or tertiary winding must be delta connected. Thus, if a resistance-grounded system is to be used on the delta-connected winding, a zig-zag or grounding transformer must derive a neutral.

The full-wave bridge (Figure 11.28) is the most popular rectifier configuration used in combination power centers or section rectifiers. For this type, the relationship of the a-c rms input voltage to the d-c output voltage is as follows:

$$V_{ac} = 0.74V_{dc}.$$

The nominal 300-V system voltage is the most commonly used in mining applications, although some 600-V systems are still in operation but usually for trolley supplies. For a nominal system voltage of 300 V, the line-to-line a-c voltage feeding the input to the rectifier would be

$$V_{ac} = 0.74(300) = 222 \text{ V}.$$

Therefore the voltage rating of the transformer winding feeding the rectifier would be 222 V. Expanding on Table 11.3, some of the common ratings used in combination power centers are listed in Table 11.4.

A direct current is much more difficult to interrupt than an alternating current, and the amount of available short-circuit current must be limited to less than that of a-c equipment with

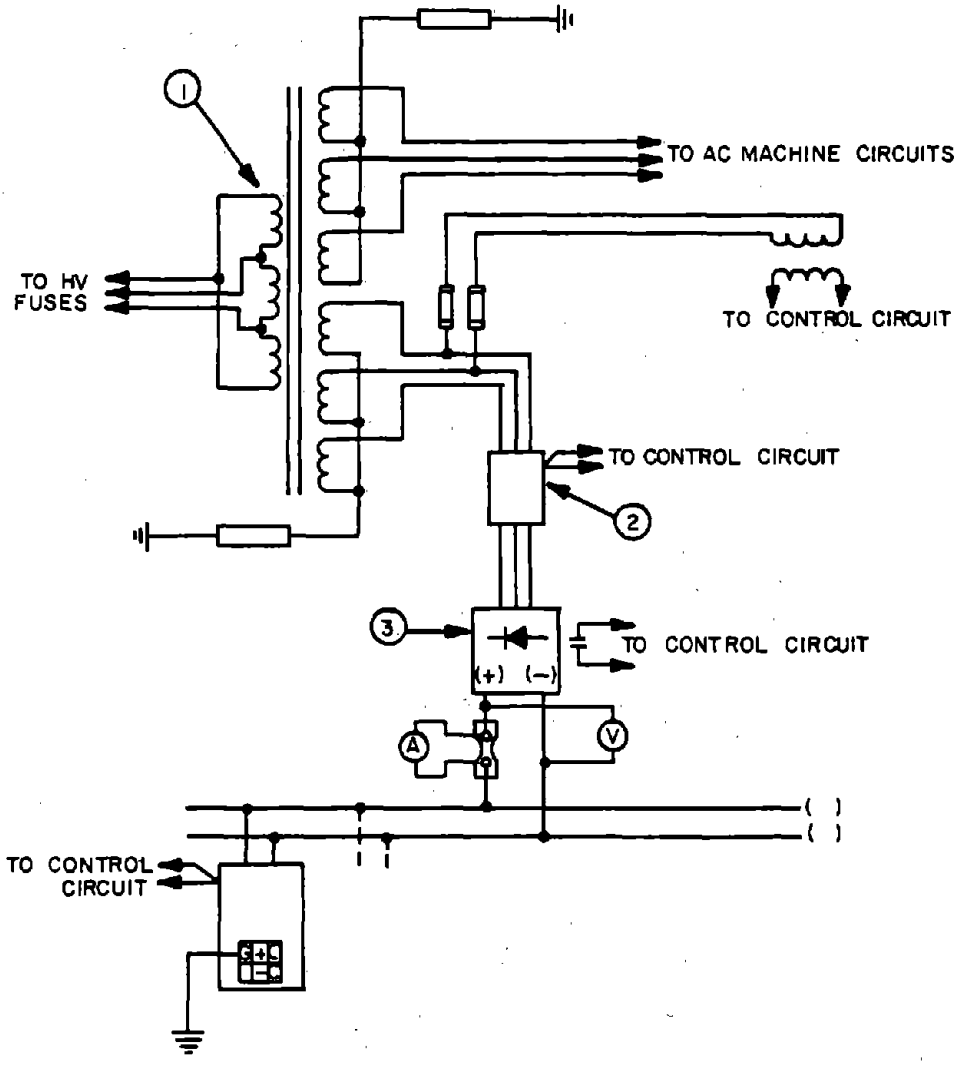


Figure 11.27. General Arrangement of D-C Components for a Combination Power Center.

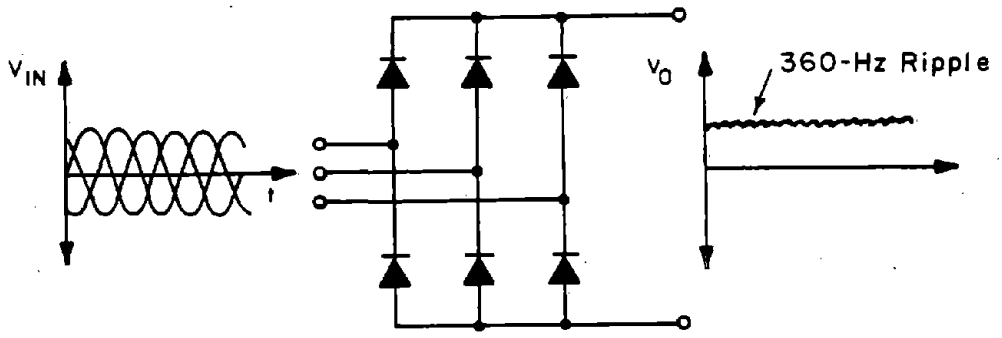


Figure 11.28. Full-Wave Bridge Rectifier.

similar capacity. As a result, the impedance of transformer windings feeding rectifier circuits are normally in the range of 0.06 pu to 0.08 pu. In order to obtain this high impedance, the leakage reactance of the associated winding is often deliberately increased during transformer fabrication. If this method does not provide the adequate impedance, a small additional impedance can be obtained by using air-core reactors at the output of the transformer, as shown in Figure 11.29. However, in some circumstances it is necessary to use a separate transformer (Figure 11.30) to limit the maximum fault current to a level that can be safely interrupted and a magnitude that will not damage the rectifier bridge.

Table 11.4. Typical Ratings for Combination Power Centers.

DC (kW)	AC (kVA)	AC Voltage (V)	DC Voltage (V)	Input Voltage (V)
75	300	480Y/277	300	7200
150	375	480Y/277	300	4160
150	400	480Y/277	300	7200
300	500	480Y/277	300	7200
200	600	600/220	300	7620/13,200
300	750	600/220	300	7620/13,200
300	1000	600/220	300	7200/4160

A main circuit breaker (No. 2) can be provided to protect the transformer winding that supplies the d-c circuit. The thermal-trip setting of this breaker is usually based upon 125% of the rated current of the winding. As an example, a winding rated at 150 kVA would have a full-load current of

$$I_{FL} = \frac{150}{\sqrt{3}\ (.222)} = 390\ \text{A.}$$

The thermal-trip setting would be the next rated value above 1.25 (390) or 488 A. If the transformer impedance is 0.06 pu, the breaker should be capable of interrupting a fault current of

$$I_f = \frac{390}{0.06} = 6500\ \text{A.}$$

11.3-21 Rectifier

As seen in Figure 11.27, the output of the transformer tertiary winding feeds the rectifier (No. 3) via the main circuit breaker. (Again, the rectifier configuration is almost always a three-phase full-wave bridge.) The power or kW rating of rectifiers used in mining applications is normally too high to permit the use of a single diode in each leg of the bridge. The current rating of the rectifier bridge, and thus the diodes, is selected on the expected bolted-fault current (faulted d-c output) with the power-center input connected to an infinite bus. This current should also incorporate a multiplier to account for a worst-case offset. The rectifier should be capable of handling this current for the time required to have the circuit breakers interrupt current flow. To achieve the adequate current-carrying capacity, diodes are paralleled in each rectifier with two diodes paralled per leg to share the current.

Figure 11.31 shows a full-wave bridge rectifier with two diodes paralleled per leg. The number of parallel diodes is determined by the individual diode current rating (all must be rated equally) along with the maximum available fault current.

Each diode must also be rated in terms of a "peak inverse voltage," (PIV), which is the maximum voltage that can be applied across the diode in a reverse-bias mode without causing breakdown. For mine-rectifier applications, the diode PIV should not be less than 2.5 times the nominal d-c system voltage if proper transient suppression is used. Thus for a 300-V system, a rating of 800 V is commonly employed.

Matched diode characteristics could allow a sufficient means of sharing current when used in a parallel configuration. Replacement through failure of any diode, however, would easily upset the balance. Therefore, although rectifiers are supplied with matched diodes, most manufacturers use current-balancing reactors (No. 2 of Figure 11.31) to force uniform conduction of

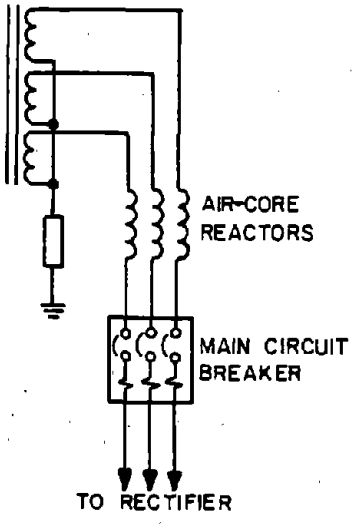


Figure 11.29. Series Reactance to Reduce Available Short-Circuit Current.

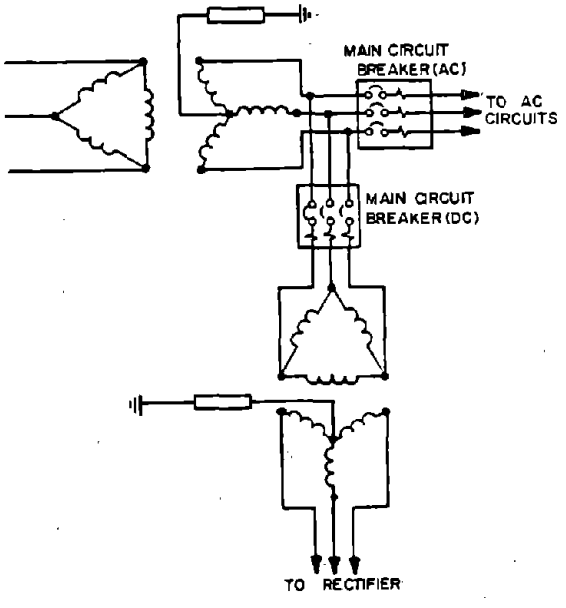


Figure 11.30. Separate Transformer to Increase Impedance of Direct-Current Circuit.

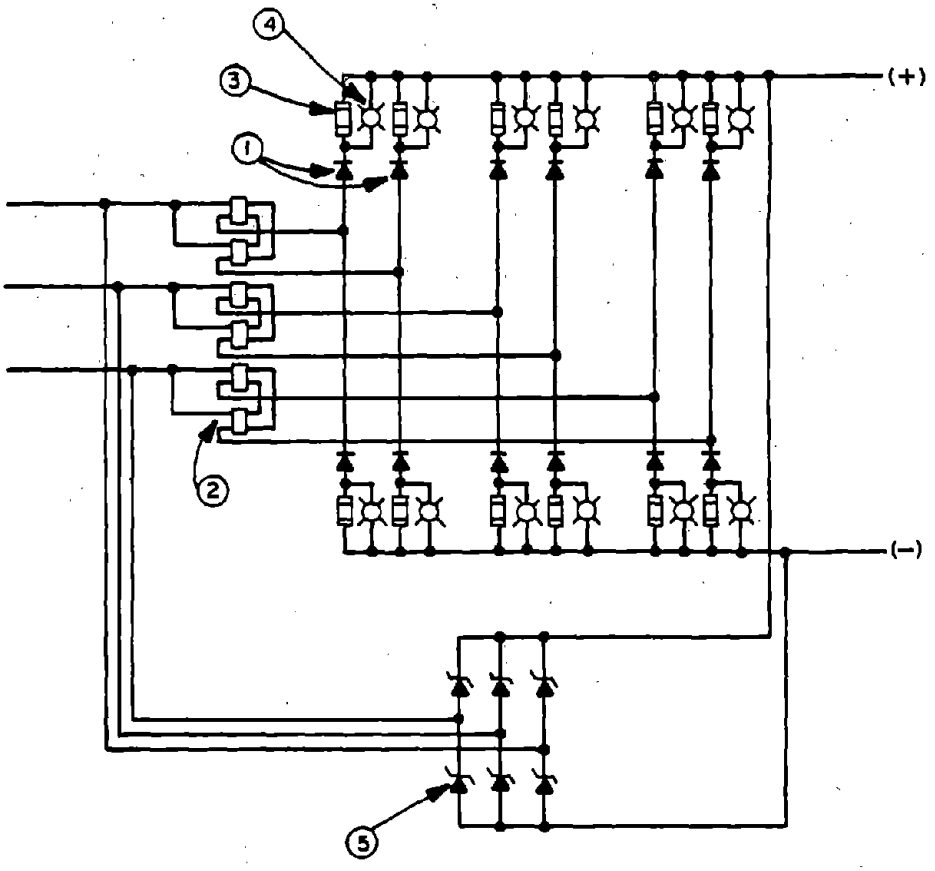


Figure 11.31. A Typical Full-Wave Bridge Rectifier with Two Diodes in Parallel Per Leg.

all diodes in parallel. (See Chapter 4 for an explanation of operation.)

Each diode is accompanied with a circuit-protection fuse (No. 3). The purpose is not to protect the diode but to prevent a catastrophic failure to a bridge leg (these diodes fail in a shorted mode). The fuse current rating must be such that it will not initiate interruption for a bolted fault at the d-c bus until the clearing time for the downstream circuit-interrupting devices has elapsed (i.e., the time-current characteristics of the two must be coordinated). Each fuse is paralleled with a light (No. 4) to indicate that the fuse has blown and the diode needs to be replaced.

Suppression devices should always be used to protect the rectifier from transient overvoltages occurring from both the a-c or d-c side. Due to their successful history in mining applications, selenium voltage suppressors (No. 5) are presently the most popular devices used in rectifiers. These devices are available with rms ratings ranging from 30 V to 480 V in 30-V increments. The clamping voltage at rated discharge is approximately 2.5 times the rms voltage rating. For instance, the input a-c voltage to a 300-V rectifier would be 222-V rms. Therefore, a selenium-suppressor rating of 240-V rms would be selected. The resulting clamping voltage would be 600 V, which is significantly below the 800-V PIV rating determined earlier. Although not shown in Figure 11.31, the suppressor often has every connection (five in all) protected by a fuse with again a paralled light to indicate failure. For rectifiers serving face equipment (e.g., 150 or 300 kW), one selenium suppressor is used, but two or more may be paralleled for trolley rectifiers (i.e., 450 kW or more).

An RC-snubber circuit, as shown in Figure 11.32, is sometimes provided to reduce commutation transients. The circuit serves to reduce the voltage rate-of-rise that might be developed across the diode. Although snubber circuits are common in mine rectifiers, some manufacturers have realized reliable diode operation

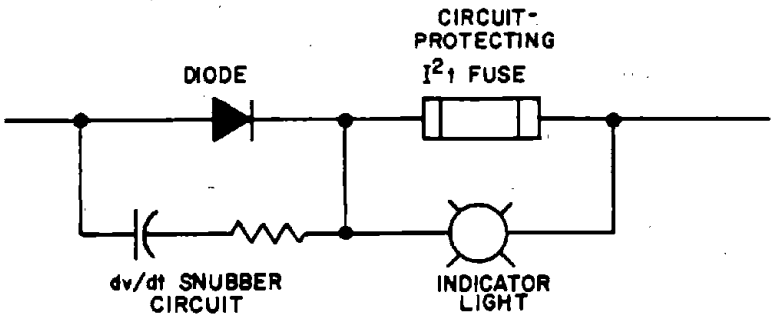


Figure 11.32. Diode with RC-Snubber Protection.

without their use. The application of this protection technique is discussed in Chapter 12 (dv/dt protection is required on thyristors).

11.3-22 Direct-Current Ground-Fault Protection Schemes

Five basic systems of d-c ground-fault protection are presently being used in the U.S.:

1. diode grounding,
2. basic grounding conductors,
3. relayed grounding conductor,
4. neutral shift, and
5. differential current.

These are illustrated respectively in Figures 11.33 through 11.37. The technique used dictates the complexity of the circuitry associated with each outlet from the rectifier section. However, because a complete discussion is contained in Section 8.6-2, the systems will only be summarized here. The first three systems are more commonly used when a trolley-feeder is the d-c source. The neutral-shift and differential-current systems can only be used in conjunction with rectifiers serving face equipment. It should be noted that recitfiers for trolley systems must have both positive and negative conductors isolated above frame ground. Thus, the subject of grounding is not applicable to that particular use.

The diode-grounded system (Figure 11.33) has the machine frame tied to the grounded conductor through a grounding diode. The basic grounding-conductor system (Figure 11.34) uses a separate conductor to provide grounding to the machine frame. In essence, adequate ground-fault protection is not available from either system. For example, ground faults in the trailing cable rely on an interrupting device for sensing and clearing. No additional circuitry, other than the grounded power conductor, is used in the power center.

The relayed grounding-conductor system (Figure 11.35) can be sensitive to ground faults. A ground-fault-relay coil is placed in series with the grounding conductor and, when a current threshold is reached, contact pick up can be used to trip a breaker UVR. However, parallel paths existing through the earth can cause fault current to partially bypass the relay coil, making for unreliable protection.

The neutral-shift system is shown in Figure 11.36, where resistors R_1 and R_2 create a d-c neutral point. Ground-faults on either the positive or negative conductor will cause the neutral to shift. Voltage-sensing relays, M_1 and M_2, detect the change. The result is sensitive ground-fault relaying, but the system is not selective with more than one outgoing circuit.

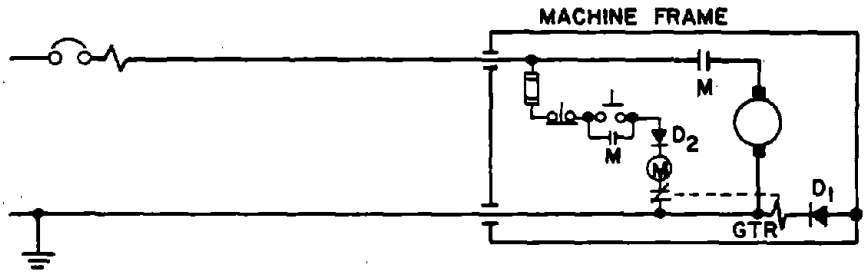


Figure 11.33. Diode-Grounded System.

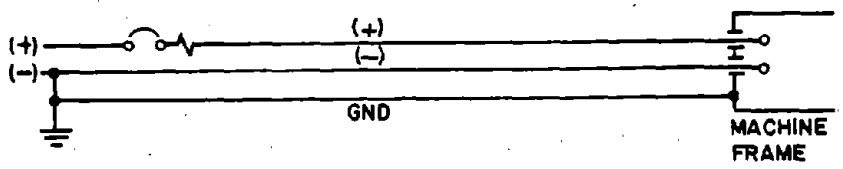


Figure 11.34. Basic Grounding-Conductor System.

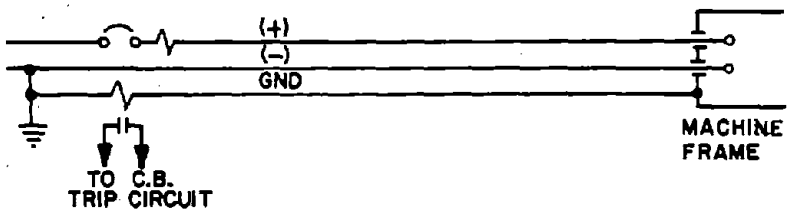


Figure 11.35. Relayed Grounding-Conductor System.

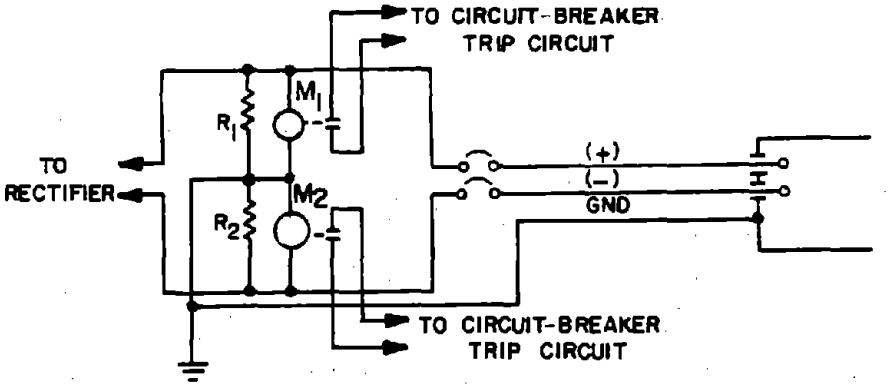


Figure 11.36. Neutral-Shift System.

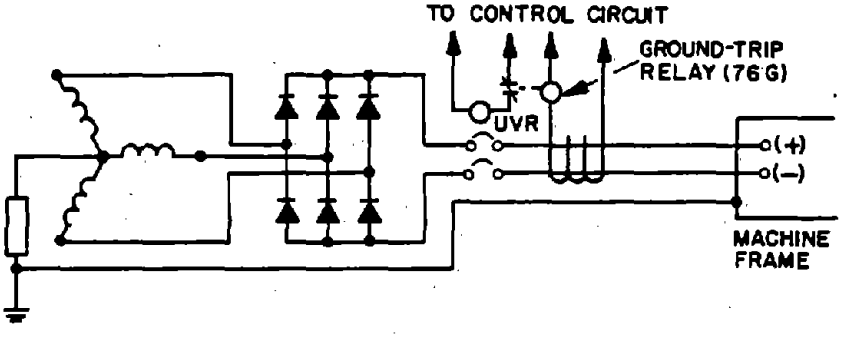


Figure 11.37. Differential-Current Scheme.

For one differential-current system (Figure 11.37), a grounding resistor is placed between the transformer neutral and load-center frame. Both positive and negative conductors pass through a saturable reactor. The differential current created by a ground fault causes magnetic saturation of the reactor core, which in turn allows the ground-fault relay to pick-up. The system is sensitive and selective. By using the technique for each outgoing d-c circuit, practical ground-fault protection is available. Therefore, only this system will be used in the following discussion.

11.3-23 Direct-Current Control Circuitry

As evidenced by the preceding, a variety of control-circuit schemes can be found. A control circuit using one differential-current technique for ground-fault relaying is illustrated in Figure 11.38. A main control transformer supplies 120 V to the entire circuit. Heat-sensing devices are mounted to the heat sink for each leg of the bridge rectifier. The overtemperature-relay coil (OTR) is connected in series with the heat-sensing devices and is energized by a filtered single-phase bridge rectifier. The relay contacts are in series with the UVR of the main breaker so, upon a rectifier overtemperature condition, a sensing device will open, the relay resets, and the UVR trips the breaker.

This version of differential-current relaying is supplied from the control power through a step-down transformer with a 6-V secondary. With a ground-fault current from 4 to 6 A, voltage is impressed across the ground-trip relay (GTR), sufficient in magnitude to cause contact pick up. This de-energizes the UVR on the machine circuit breaker, which in turn interrupts the offending circuit.

11.3-24 Direct-Current Interrupting Devices

The problem mentioned earlier about interruption of direct current requires that the interrupting device must force the current to zero with an arc voltage greater than the line voltage. The device must be capable of withstanding the energy dissipated during the time that the arc exists across its contacts. This energy is a function of the circuit inductance as well as the current magnitude (12,13). There are two basic interrupters used to protect d-c machine circuits, the d-c contactor and the molded-case circuit breaker. For trolley systems, power circuit breakers are employed.

A cross-sectional view of a d-c contactor is shown in Figure 11.39. This device primarily consists of stationary and movable contacts, which make and break upon energizing and de-energizing the operating coil. When the operating coil is energized, the armature assembly is attracted to the pole piece,

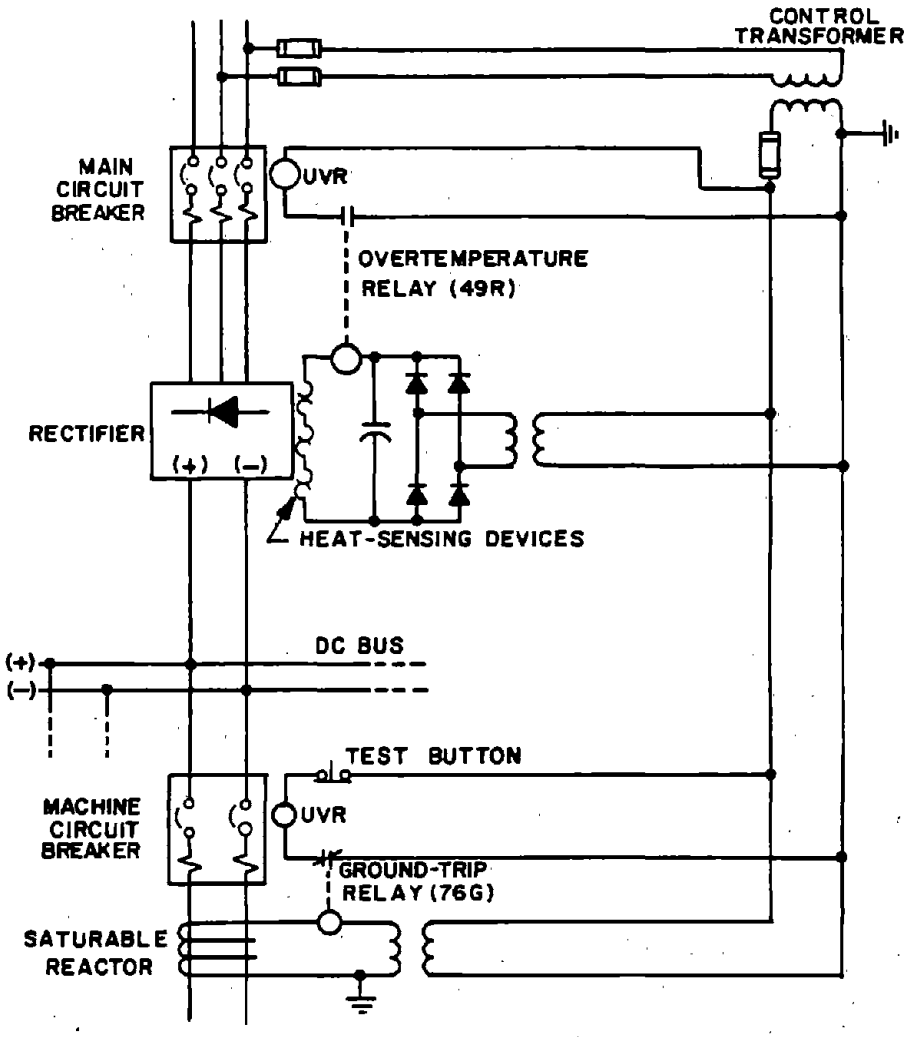


Figure 11.38. A Representative Control Circuit for a Rectifier.

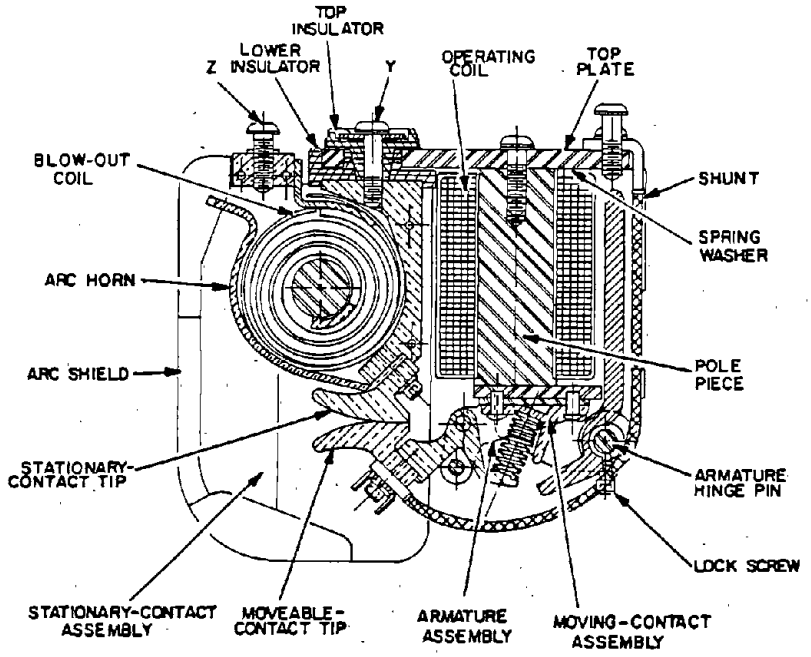


Figure 11.39. Cross Section of a Direct-Current Contactor.

which completes the magnetic circuit and causes the contacts to close. The contactor is designed so the contacts close with a self-cleaning, wiping action to ensure a good electrical contact (14).

Arc termination is similar to that of an air-magnetic circuit breaker (see Section 8.2-4). A blow-out coil is located between the front power terminal (Z) and the stationary contact. The purpose of the coil is to aid in extinguishing the arc, which results in minimizing the burning of the contact tips. It produces a magnetic field perpendicular to the arc, which causes the arc to be lengthened and ruptured by deflection. Since the blow-out coil is connected in series with the circuit to be interrupted, the strength of the magnetic field is proportional to the current. A flexible braided shunt completes the connection from the movable contact to the rear power terminal (Y). The arc horn protects the insulation of the blow-out coil from being burnt from the arc, and an arc shield encloses the contacts to confine the arc and protect the adjacent parts (14).

The contactors most commonly used as interrupting devices for d-c machine circuits have a continuous-current rating of 250 A or 500 A. The interrupting capability is approximately ten times their continuous-current rating, which is significantly less than that given for molded-case circuit breakers. One advantage of the d-c contactor is its simplistic design and ease of maintenance. In some applications, molded-case circuit breakers are used as back-up protection for d-c contactors. It should be noted that molded-case circuit breakers are not rated for 600-V applications. However, d-c contactors can be applied at this voltage.

Molded-case circuit breakers are rated at 600 Vac and also normally rated at 300 Vdc, and the d-c interrupting-duty rating for mine-duty breakers is either 10,000 A or 20,000 A, depending on the product. However, as with the d-c contactor, the actual interrupting capability varies with the inductance of the circuit being interrupted. Laboratory tests have indicated that for d-c operation, the instantaneous d-c tripping current is about 1.3 times the magnetic-element trip setting for a-c (12).

Even with the higher interrupting capacity, many engineers in mining operations have expressed concern over using molded-case breakers for d-c applications. They relate that molded-case devices, in use, cannot adequately interrupt d-c faults, whereas low-voltage power circuit breakers appear to work satisfactorily. Some manufacturers, however, relate that they have had very few problems with field applications of molded-case breakers on d-c.

11.3-25 Mine-Power-Center Summary

The principal concept that should be realized from this power-center presentation is that the equipment is assembled to match the mining operation and application. This is true if the unit is a belt transformer, trolley rectifier, or a combination a-c/d-c power center. Accordingly, there cannot be a "standard" mine power center, but there are many recommended practices for their construction.

11.4 Switchhouses

11.4-1 General

Switchhouses are contained in metal-clad enclosures, similar in construction to that discussed for power centers. This power equipment actually includes two unit types, visible disconnects and sectionalizing units. However, the term, "switchhouse," is normally equated with sectionalizing equipment.

The principal function of the disconnect switch is the manual removal of power from downstream mine power equipment connected to distribution. The main internal component, as might be expected, is a disconnect or load-break switch. A requirement of this equipment (as with power centers) is that the switch position (open or closed) be determined by visual examination through a window in the enclosure wall. In underground coal mining, the function provided by the switch must be available within 500 ft of the point where power enters the mine. Furthermore, the function is incorporated into all power equipment which receive power from high-voltage distribution. Thus,

disconnect-switch equipment can be described simultaneously with switchhouses. Frankly, the high-voltage side of Figure 11.2 contains the same components.

The prime roles of switchhouses are to provide protective relaying in the distribution system and to afford branching of the radial system. The principal component is an automatic circuit breaker. The equipment name is modified depending upon the number of circuit breakers and associated protected outgoing circuits. For example, a double switchhouse contains two. Because of size limitations, underground-mine power systems rarely have larger units than double switchhouses. Surface mines, however, can incorporate four-breaker switchhouses, or "switching skids" as they are commonly referred to in these operations. The schematic diagram for surface or underground applications is practically the same. The only basic difference is the repetition of internal components to correspond to the number of circuit breakers used.

11.4-2 Internal Components

A general arrangement for a single-breaker switchhouse is illustrated in Figure 11.40. Incoming high-voltage power enters the switchhouse through the input receptacle to the load-break switch and the feed-through receptacle. Some circuit-interrupting devices have disconnect switches incorporated in their construction, as shown in the diagram. Otherwise, a load-break switch is located on the line side of the breaker. In any event, the switch must have an external operating handle with provision to lock the switch in the open position. The output (load side) of the interrupting device feeds the branch receptacle. The current-sensing devices for the protective-relaying circuits are usually situated between the breaker and the branch receptacle, while the control transformer is located on the incoming side. The associated control circuitry for Figure 11.40 is given in Figure 11.41. The operation of this circuit will be discussed later.

As with mine power centers, interlock switches are positioned around the side and top covers of the switchhouse and are wired into the incoming pilot circuit to trip the upstream breaker in the event that a cover is removed. An emergency-stop button is also provided.

A typical arrangement of a double switchhouse is presented in Figure 11.42 with control circuitry in Figure 11.43. The repetition of circuitry mentioned earlier is obvious. In addition, the circuits in Branch A work independently of Branch B (and vice versa). Breakers with incorporated switches are again shown. Without the internal provision, usually one load-break switch is located upstream from both breakers, and serves as a disconnect for all branch circuits (but not the feed-through).

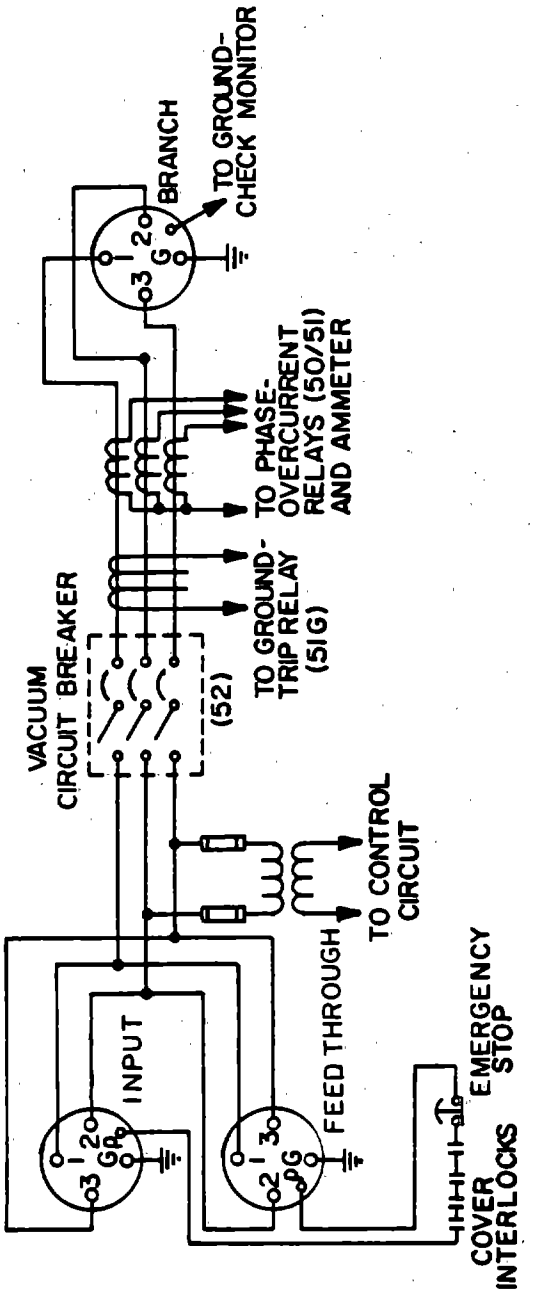


Figure 11.40. Typical Diagram of a Single Switchhouse.

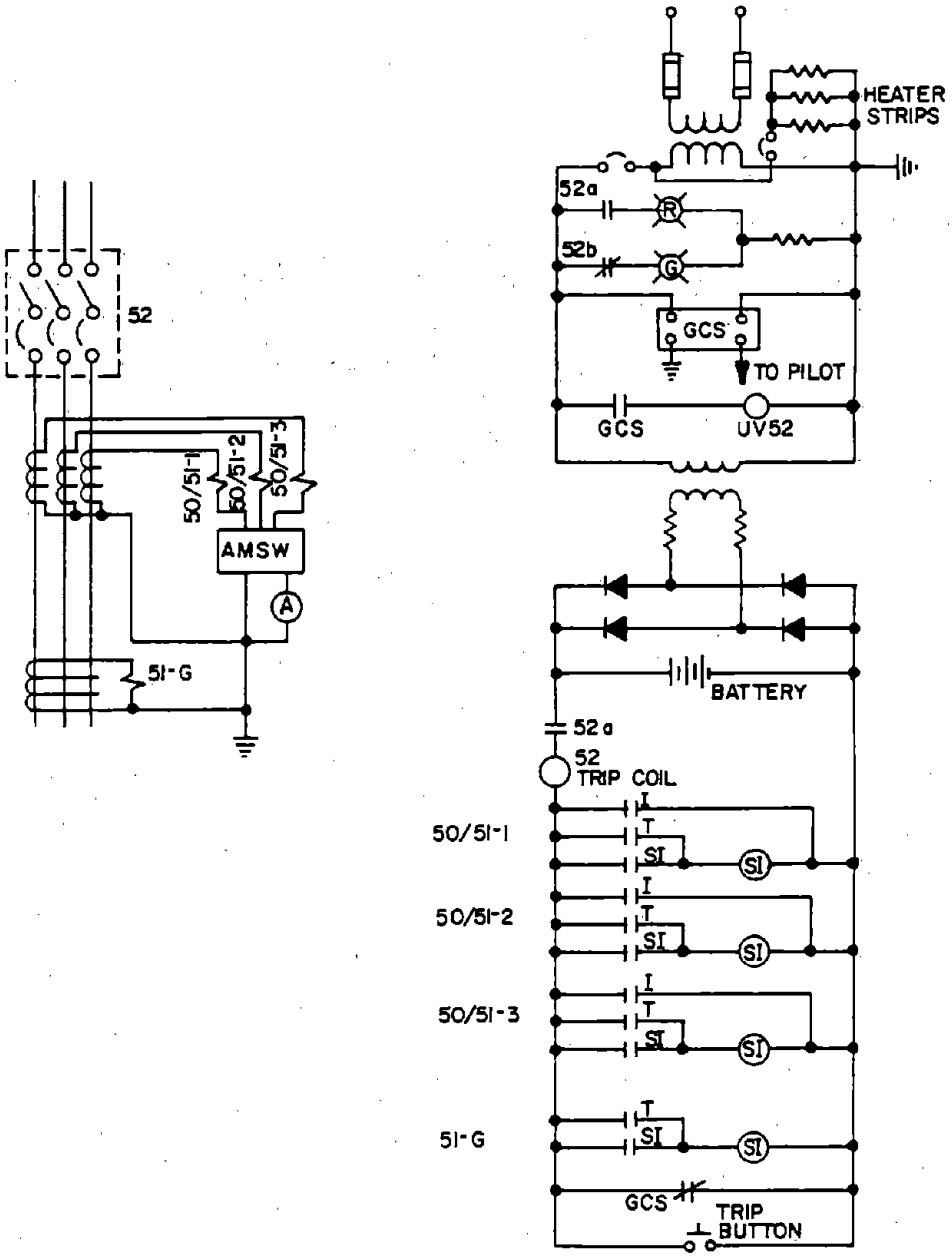


Figure 11.41. Associated Control Circuit to Figure 11.40 Using Battery Tripping.

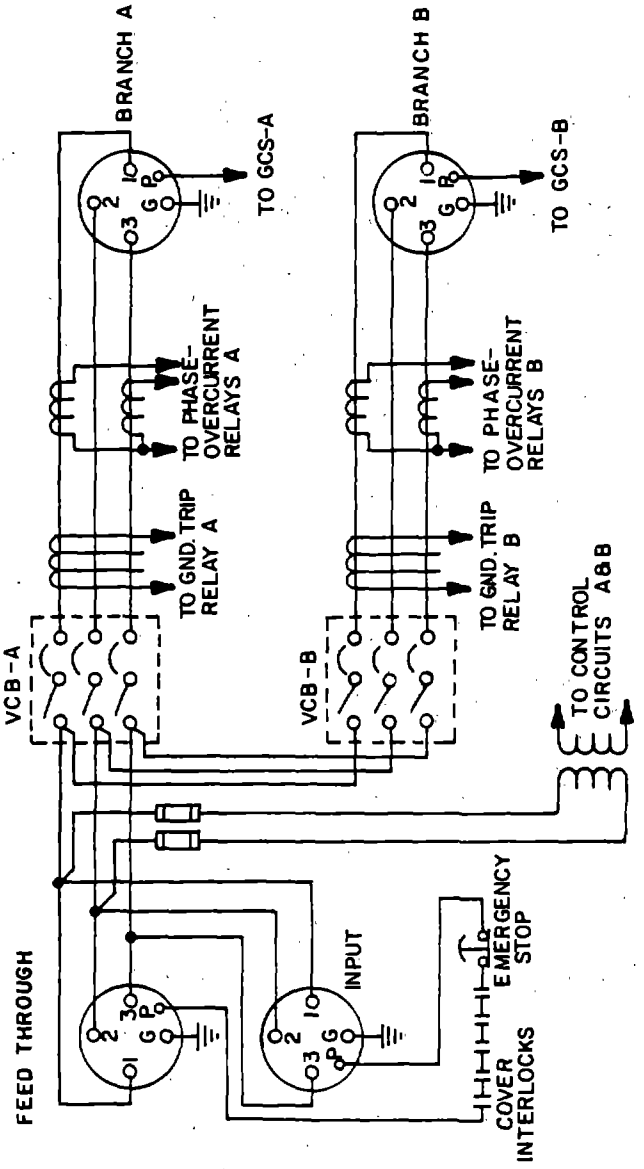


Figure 11.42. Typical Diagram for a Double Switchhouse.

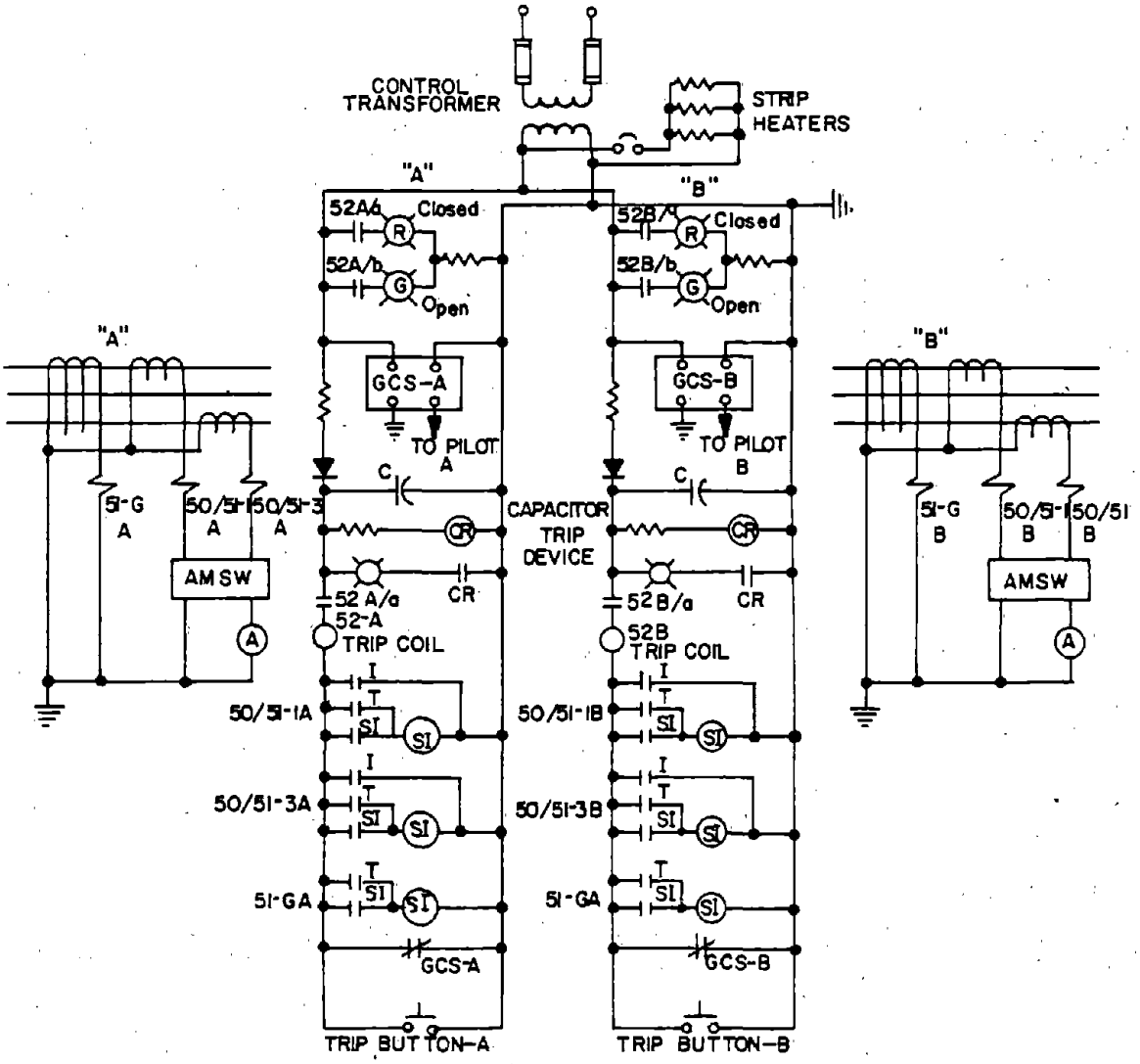


Figure 11.43. Associated Control Circuit for the Double Switchhouse in Figure 11.42 Using Capacitor Tripping.

The incoming circuitry of Figure 11.2 to the transformer and that of Figures 11.40 and 11.42 to the circuit breakers are nearly identical. Surge arresters and switch pre-break monitors are not incorporated in the switchhouse schematics but are often found in practice and are recommended. A typical schematic for the disconnect switch (the equipment not the component) would be similar to Figure 11.40 if the circuit breaker and current transformers were removed. The similarity mentioned here is important in mine power-equipment design. Where circuits serving identical functions have the same arrangement and construction, maintenance crews can work on all equipment containing these circuits without surprise. As a result, when compared to systems of non-uniform design, training at the mine should be simplified, and safety to maintenance personnel should be increased.

11.4-3 Protective Relaying

Induction-disk overcurrent relays are used for most protective-relaying applications in switchhouses. Relay operation and characteristics are discussed in Section 8.3. For mining applications, inverse-time characteristics are usually employed for phase-overcurrent relaying, while very-inverse-time relays are commonly used for ground-fault protection.

These relays have a range of adjustment so they can be applied to a variety of situations. The operating time can be controlled by the time-dial setting. Pickup current is adjusted by the main coil taps. Since the resulting time-current characteristics are the same for each taps, curves are plotted in terms of the multiples of the pickup value. A typical family of curves for an inverse-time relay is given in Figure 11.44 (15). An instantaneous relay can be incorporated with the induction-disk (timed) relay to respond to the same actuating quantity.

Applications and precautions related to the use of induction-disk relays will be covered in the following paragraphs. Additional information may also be found in Chapter 9. (Some of the presentation in that chapter will be reviewed here.)

Induction-disk-relay operation should not be relied upon if the magnitude of actuating current is only slightly above pickup, because the net actuating force is so low that any additional friction in the rotating-disk mechanism may prevent operation, or may increase the operating time. Even if the relay closes its contacts, the contact pressure can be so low that contamination on the contact surface may prevent electrical contact. It is common practice to apply induction relays so their actuating quantities are at least 1.5 times pickup. For this reason, some time-current curves are not shown for less than 1.5 times pickup (15).

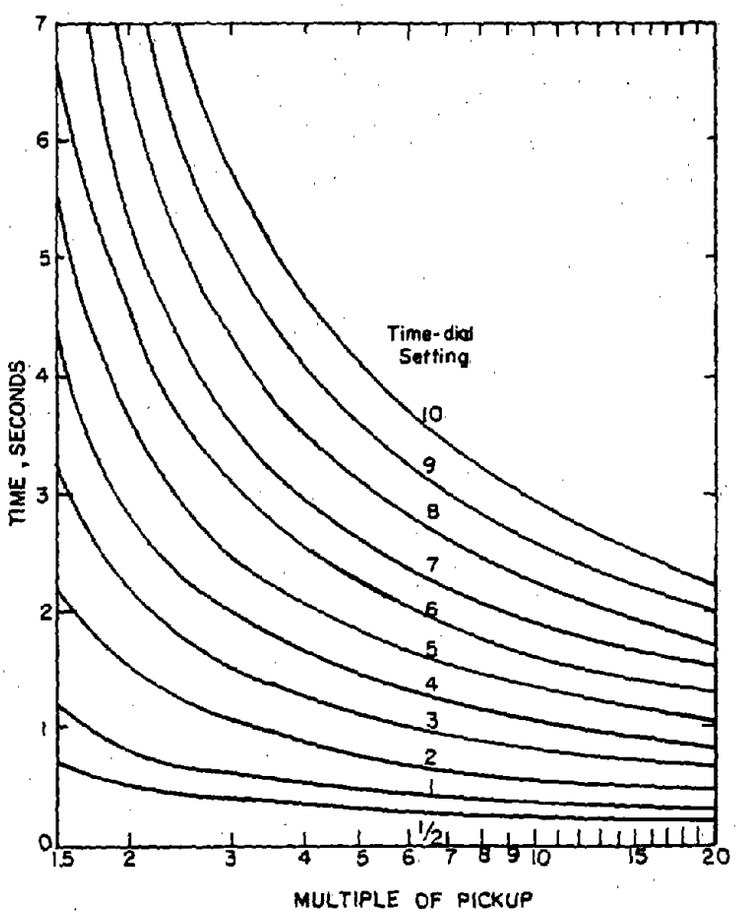


Figure 11.44. A Typical Family of Curves for an Inverse-Time Relay.

An induction relay is most effective if its pickup is selected so it will operate on the most inverse part of its time curve. Thus, the minimum value of actuating current should only be slightly higher than 1.5 times pickup.

The actuating currents that are delivered to overcurrent relays are obtained by current transformers. The current transformers provide insulation from the high-voltage circuit and supply the relays with currents that are proportional to the currents of the power circuit, but sufficiently reduced.

When applying a current transformer, consideration should be given to its burden. The burden refers to the impedance of the external load applied to the current-transformer secondary. For applications in switchhouses, the burden would include the impedance of the overcurrent relay and its associated wiring connections. A model of a current transformer and its burden is shown in Figure 11.45. The dependent current source delivers a current equal to the primary current (I_p) divided by the turns ratio (N) of the CT. The remaining voltages, currents, and impedance are defined as:

Z_e = secondary-excitation impedance,

Z_s = secondary-winding impedance,

Z_b = burden impedance,

E_s = secondary-excitation voltage,

V_t = secondary terminal voltage,

I_e = secondary-excitation current, and

I_s = secondary current.

As shown in the figure, a portion of the current (I_e) is consumed in exciting the CT core. The remainder of the current (I_s) is the true value of the secondary current. It is apparent that the percent ratio correction error (I_e/I_s) will remain small as long as the excitation current is small. The magnitude of the excitation current is a function of the excitation voltage (E_s), as illustrated in the secondary-excitation characteristic of Figure 11.46. It should be noted that the secondary-excitation characteristic is linear until the saturation point is reached. Beyond the saturation point, a small increase of E_s results in a large increase of I_e. This in turn causes the percent ratio error to dramatically increase. The magnitude of E_s is primarily a function of the secondary current (I_s) and the relay impedance (Z_b). Therefore, to minimize the inaccuracies of the system, the relay impedance should be kept as low as possible. The pickup value for the relay must always result in the excitation current lying in the linear portion of the secondary-excitation characteristic. It should also be noted that the impedance of the relay

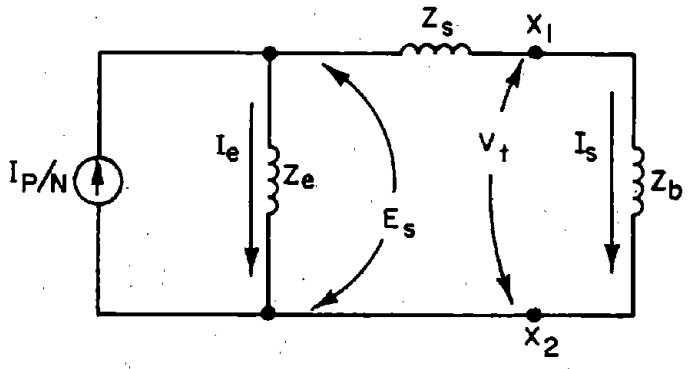


Figure 11.45. Model of a Current Transformer and Its Burden.

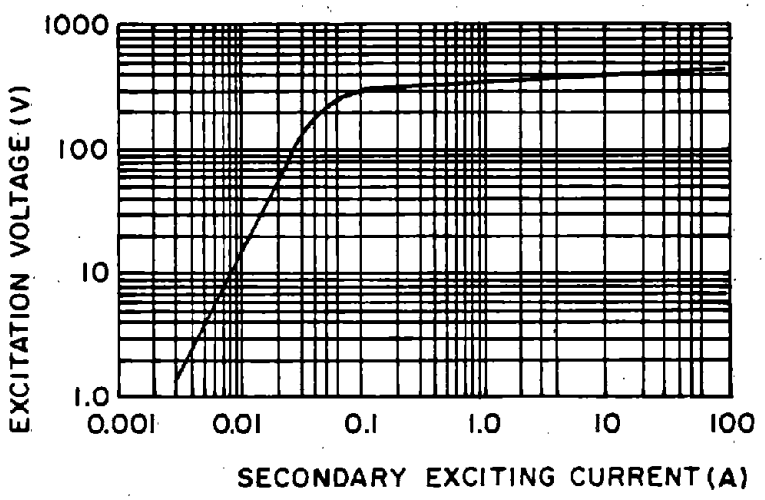


Figure 11.46. Secondary-Excitation Characteristic for a Typical Current Transformer.

is not constant. Since it is a magnetic device, the impedance decreases as the secondary current increases due to saturation. Thus, the relay impedance should be considered over the entire operation range of currents when matching the relay to the current transformer.

The pickup of an overcurrent relay should be selected so it will operate for all short circuits in its own line and provide backup protection in adjoining lines. Figure 11.47 will be referred to as an example. Breaker 1 should provide primary protection for lines 2 and 3. To ensure selectivity under all circumstances, the pickup of a given relay should be somewhat higher than that of other relays nearer to the fault, and higher in cases where the relay must be selective. The time delay of overcurrent relays must also be adjusted to provide selectivity with the relays of the immediately adjoining lines.

To provide proper selectivity, a bolted three-phase fault would be assumed for adjusting phase-overcurrent relays, and a bolted line-to-ground fault for the ground relay. Selectivity under these conditions will ensure selectivity at lower currents.

For the fault shown in Figure 11.47, the relay at Breaker 2 must close its contacts, and Breaker 2 must trip and interrupt the flow of short-circuit current before the relay at Breaker 1 closes its contacts. The overtravel of the relay at Breaker 1 must also be accounted for. The time delay of Breaker 1 that is necessary to provide selectivity with Breaker 2 can be determined by

$$T_1 = T_2 + B_2 + O_1 + F$$

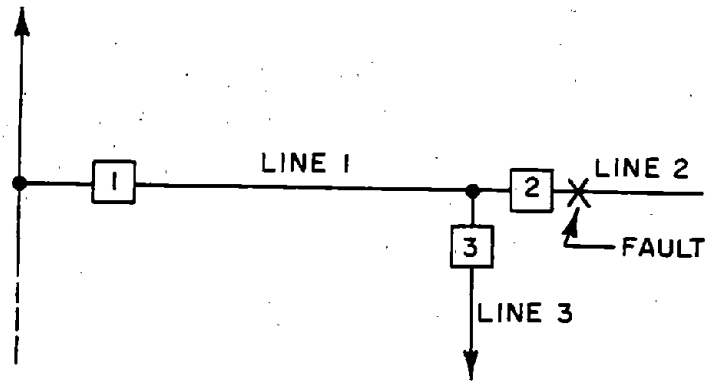


Figure 11.47. Illustration of Fault Location for Adjusting Selectivity.

where,

T_1 = operating time of relays at Breaker 1

T_2 = operating time of relays at Breaker 2

B_2 = short-circuit interrupting time of Breaker 2

O_1 = overtravel time of relays at Breaker 1

F = factor of safety.

The sum of B_2, O_1 and F can normally be assumed to be 0.4 s. When coordinating the time delays of inverse-time relays, the process should start with the most downstream relays and work back to the substation.

The typical connections of the phase-overcurrent relays and current transformers that are used in switchhouses are illustrated in Figures 11.41 and 11.43. The inverse-time units are labeled 51, while the instantaneous units are labeled 50. Figure 11.41 shows three wye-connected CTs driving three wye-connected overcurrent relays; whereas, Figure 11.43 shows two open-delta-connected current transformers driving two open-delta-connected overcurrent relays. Although protection for all three phases can be obtained with the open-delta connection, this approach is not as accurate or reliable as the wye connection.

Best ground-fault protection is obtained through zero-sequence relaying, which is shown in both Figure 11.41 and 11.43. The CT ratio is typically 50:5. Unlike the preceding discussion on power-center applications, the secondary current from the CT, with the induction-disk relay as burden, is proportional to the ground-fault current as dictated by the turns ratio of the CT. However, because of the necessarily large CT windows, burden matching and actual testing are critical to obtain reliable sensitive relay pickup (40% of current limit is desirable).

Residual ground-fault relaying can be found in some switchhouses. Adequate sensitivity is usually not available due to errors caused by CT saturation and unmatched characteristics. (Some success has been obtained using solid-state relays, see Chapter 12.)

11.4-4 Power Circuit Breakers

Three types of power circuit breakers can be found in mine switchhouses: live-tank (or minimum) oil, dead-tank oil (OCB), and vacuum (VCB). Live-tank oil breakers have been found to be plagued with maintenance problems, the most outstanding being inadequate oil levels after five or less interruptions. This requires extremely frequent inspections, which are impracticable for most mining operations. Three-phase dead-tank oil breakers, in 250 to 500 MVA interrupting capacities, are used exclusively

by many mining companies with tremendous success. However, availability problems, large physical size, PCB contamination, and cost have substantially curtailed their use in recent years. In fact, some states prohibit the use of oil breakers in underground applications above 10 kV. Vacuum circuit breakers have been criticized in terms of the transient overvoltages that their high efficiency can create. However, as demonstrated in Chapter 10, offending situations usually can be related to poor power-system design practices. When reasonable precautions are met, VCB's are perhaps the most effective high-voltage power circuit breakers in comparison with other types of equal voltage and interrupting-capacity ratings. They are by far the most popular circuit breaker used in switchhouses. The voltage ratings of power circuit breakers correspond to the insulation class used in the mine distribution system, but manufacturers offer vacuum breakers rated at 15 kV, which are applicable for 4.16-kV through 14.4-kV nominal-voltage systems. Continuous-current ratings of 400 A and 600 A are the common in-switchhouse applications. Since high-voltage circuit breakers begin interruption a few cycles after the first-cycle fault-current peak, the interrupting rating of these breakers is based on symmetrical fault current. (Many power breakers are also rated on an asymmetrical interrupting-current basis.) A 400-A VCB has a typical interrupting rating of 4000-A symmetrical, with the 600-A model rated at 12,000 A. The breaker must also be able to withstand the physical stresses resulting from first-cycle fault currents. Thus the breaker must have a close-and-latch rating, based on asymmetrical current, which should be greater than 1.6 times the maximum symmetrical fault current.

Some application has been found in the industry to use the automatic load-break switch interlocked with fuses [that was covered in the power-center section of this chapter] in place of a power circuit breaker for the most downstream switchhouse in the distribution system. To remove the problem of the switch trying to clear fault currents, a small delay is built into the switch tripping circuit. The time is coordinated with the maximum period that a second fuse must clear a phase-to-phase or three-phase fault. The manual interlocking with fuse elements is therefore not applicable, and the only automatic load-break switch suitable for this approach is the type described in Section 8.2-5. The fuses in that case have elements that upon separation activate a contact set, which can be used in conjunction with the control circuitry to power the tripping mechanism.

As can be seen in the preceding paragraphs, Chapter 8 contains extensive information about power-circuit-breaker types and their advantages and disadvantages. Chapter 9 covers the selection of continuous-current, interrupting, and close-and-latch ratings for these devices.

11.4-5 Control Circuits

The general operation of most control-circuit schemes found in switchhouses is similar. Thus, the typical control of Figures 11.41 and 11.43 will be discussed. These are reproduced in Figure 11.48 and 11.49, inversely, for convenience.

Figure 11.48 illustrates the control circuit of a double-breaker switchhouse. Each circuit breaker has its own control circuit, which functions independently of each other. Control circuit "B" is an exact duplicate of control circuit "A"; therefore, only circuit "A" will be discussed.

The actuating currents for the phase overcurrent relays (50/51-1A and 50/51-GA) are obtained by the open-delta connected current transformers. The relays are also connected in an open-delta configuration through the ammeter and ammeter switch. The ground relay 51-GA is used in a zero-sequence ground-trip circuit.

A single-phase control transformer steps down the distribution voltage to 120 V to supply both control circuits and the strip heaters. The strip heaters are resistive devices placed in the switchhouse enclosure to provide heat to minimize moisture accumulation. The red lamp is connected in series with the normally-open auxiliary contacts (52 A/a) of the circuit breaker, while the green lamp is in series with the normally-closed auxiliary contacts (52 A/b). The auxiliary contacts are mechanically controlled by the opening and closing mechanism of the breaker. When the breaker is closed, 52 A/a also closes and causes the red lamp to give a visual indication that the breaker is closed. At the same time, 52 A/b opens, which causes the green (open) lamp to be extinguished. The reverse procedure follows when the circuit breaker is opened.

The ground-check system of branch A (GCS-A) also obtains its power from the control circuit as shown. The output of the ground-check system is connected to the pilot and grounding conductors of the outgoing cable of branch A to ensure continuity of the grounding conductor downstream.

A capacitor-trip device is used to supply power to the circuit-breaker trip circuit in the event of a fault or overcurrent condition. A diode is used as a half-wave rectifier to charge the capacitor C. The capacitor stores energy to provide reliable tripping of the breaker (also minimizing nuisance trips). The voltage-sensing relay (CR) operates when the capacitor is fully charged and causes the lamp to provide a visual indication of a full charge.

Another normally-open set of auxiliary contacts (52 A/a) are placed in series with the trip coil of the circuit breaker to disconnect the tripping circuit from the control voltage when the breaker is open. The contacts of the phase-overcurrent relays and the ground-fault relays are connected in parallel as shown. If either the instantaneous or the inverse-time unit of

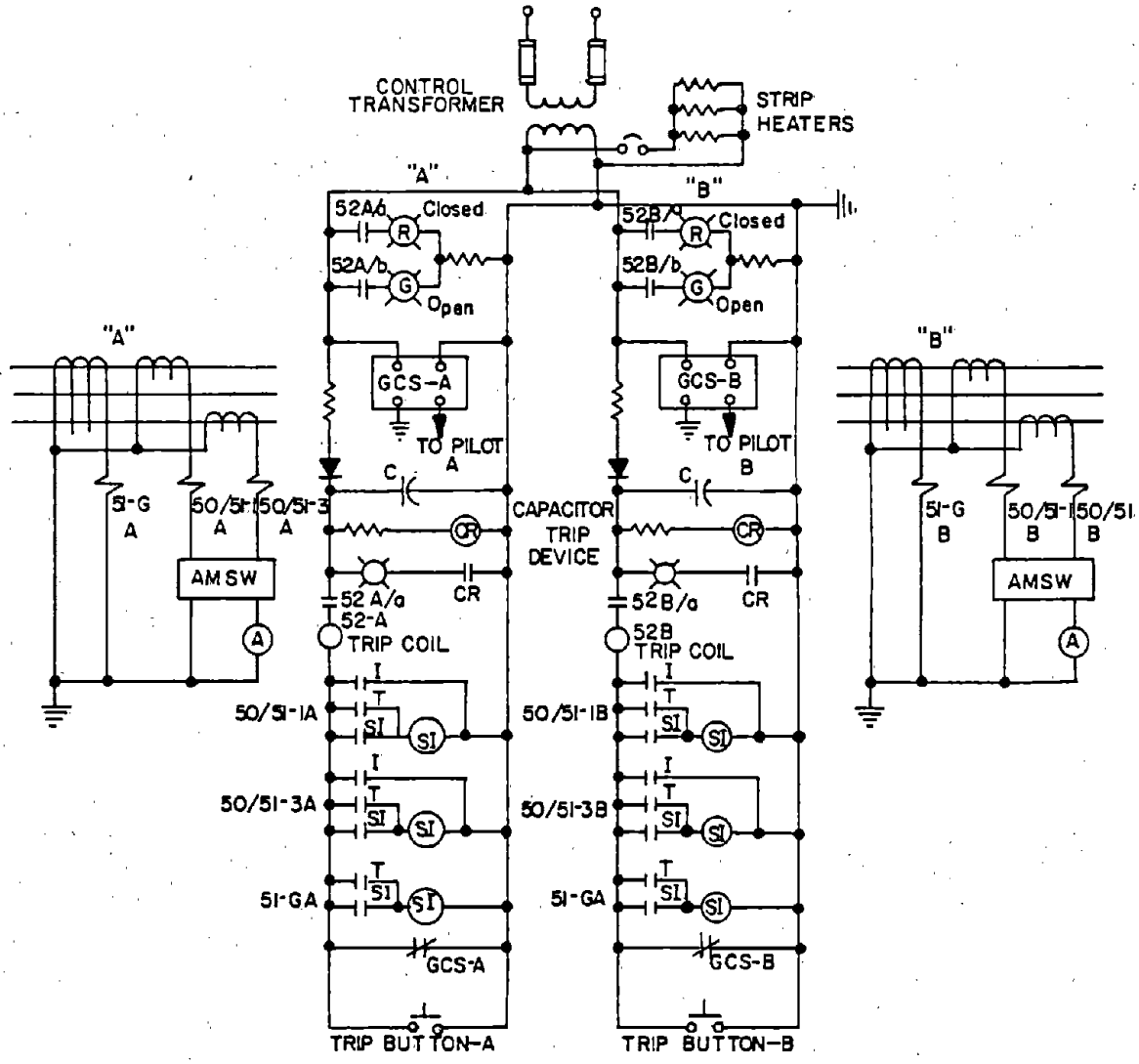


Figure 11.48. Typical Control Circuit for a Double Switchhouse Using Capacitor Tripping.

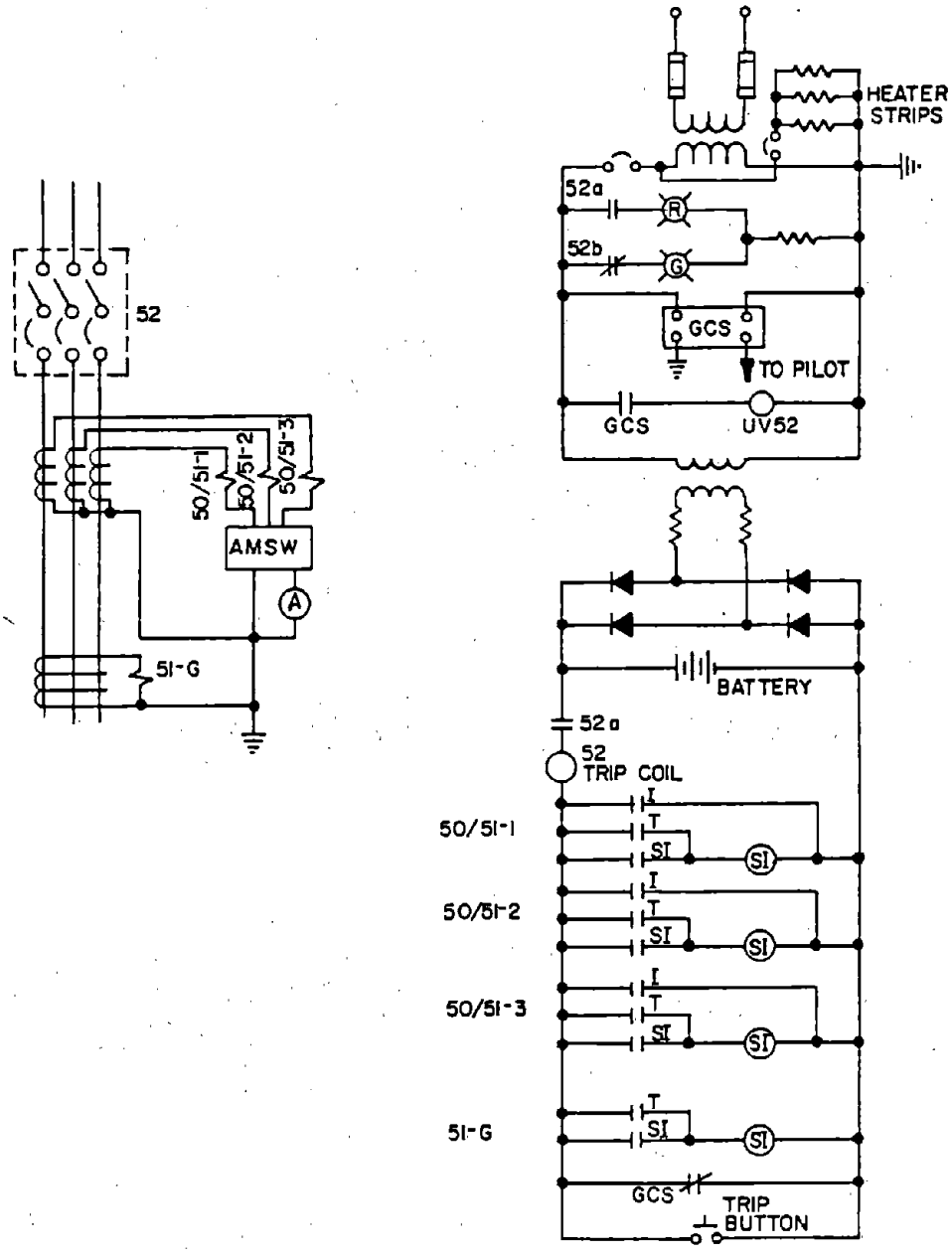


Figure 11.49. Typical Control Circuit for a Single Switchhouse Using Battery Tripping.

any of these relays is actuated, its associated contacts close, which completes the path and allows the capacitor to discharge through the trip coil. When the trip coil becomes energized, it causes the trip mechanism of the breaker to release and open the breaker.

A push button and a normally-closed set of ground-check contacts (GCS-A) are also paralleled with the contacts of the overcurrent relays. The GCS-A contacts should remain open, provided the control circuit is energized and the integrity of the associated pilot and grounding conductor is maintained. If the continuity of the loop circuit is lost, the GCS-A contacts will close and result in tripping the breaker. Depressing the push button provides a convenient means of tripping the breaker, as well as a means of testing the operation of the capacitor-trip device.

The control circuit of Figure 11.49 is similar to the control circuit just covered, with some minor exceptions. Three CT's and three phase-overcurrent relays are connected in a wye configuration to provide a more precise and reliable operation. A battery, which is charged by a full-wave bridge rectifier, is used as the energy storage device, rather than a capacitor. An undervoltage release (UV 52) is also included, with a normally-open set of ground-check contacts in series with it.

11.4-6 Switchhouse Summary

The design of switchhouses, at first glance, is not nearly as complicated as mine power centers. However, the simpler circuitry can be misleading. Incorrect sizing and adjustment of the internal components can have a disastrous effect on the mining operation. Perhaps the most serious is coordination, as it is in these units where most adjustments are made to obtain sensitive and selective protective relaying. For this reason alone, load-flow and fault analysis of the entire mine-power system must be available. Comparison with these data allow the selection of required transformer ratios, relay time-current characteristics, range pickup, and device ratings. Some additional comments about the process are in order.

Because of the need for a uniform design, it is best to have all switchhouses assembled identically. In other words, all single switchhouses should have the same components; one section of multiple-breaker switchhouses would be basically equivalent to a single switchhouse. This may not be economically possible in some mines and not practical in others. Yet there is a specific advantage; switchhouses can be placed anywhere in the mine then adjusted to suit that location. This would benefit any major movement of equipment within the complex.

To have this uniformity means that all power circuit breakers would be the same with:

1. the continuous-current rating sized to the maximum continuous current through any switchouse in the mine (demand factor should be applied);
2. the interrupting-current rating selected to stop the maximum short-circuit current at any location in the distribution (opposed to the preceding statement, the required rating here might be greater than symmetrical rms short-circuit current, depending upon the time to interruption); and
3. close-and-latch rating sized to the maximum asymmetrical first-cycle rms fault current (convention is to use 1.6 times the interrupting-current rating).

Load-break switches need this same close-and-latch rating, not a multiple of their interrupting duty. The ampacity of all power conductors within the equipment would be sized and braced accordingly, but should never be less than 4/0.

For overload and short-circuit protection, multi-ratio CT's might be necessary, but experience has shown that no more than one or two types are necessary for the majority of applications. For example, 150/300/600:5 A, 300/600:5 A, 75/150/300:5 A, and 150/300:5 A are common ampere-turns ratios. With precise burden matching and accuracy calculations, common induction-disk relays can work reliably and selectively. Obviously, the pickup range for the timed and instantaneous elements must correspond to the entire range needed by coordination. One range for each element might not be adequate for the mine's needs, but the relays are easily interchangeable. Thus, one or two spare sets of relays may be maintained at the mine to meet all demands of phase-overcurrent protection. Correct burden and accuracy must be verified for any relay-CT combination.

Adequate ground-fault protection, however, is often not an easy goal to attain. Burden and accuracy matching, as stated earlier, become critical. Yet, even with precise matching, reliable pickup at a desirable ground-fault-current threshold sometimes cannot be achieved. The large window required on the zero-sequence CT provides induction problems that can cause inadequate secondary current at rated burden. The main result is that both the timed and instantaneous elements of induction-disk relays cannot be used simultaneously for ground-fault protection with a 50:5 CT ratio. A solution here is to use only timed elements and apply the minimum time-dial setting to the most downstream switchhouse. Then establish the radial distribution arrangement such that no more than four relays exist between the substation and the extreme end of distribution (see Chapter 9 for discussion). This enables one tap-setting range (and only one relay type) to obtain practical ground-fault coordination. However, problems can still remain such as tolerances in off-shelf components. The best recourse is to apply testing, simulating a ground-fault through the CT and observing the induction-disk-relay response. The optimum place to perform this is with the switchhouse at its location in the mine.

During initial equipment installation, the tests are not difficult, but maintenance checks thereafter may be impractical. Thus, a test circuit, such as shown in Figure 11.19, could be included in the switchhouse circuitry for each ground-fault relay. The resistor and wire turns about the CT would be adjusted for required relay pickup. For instance, 2 A and 6 turns would simulate 12-A ground-fault current or 48% pickup on 25-A ground-current limit.

A final point must be made about switchhouse construction. There has been reference made to surge capacitors in this chapter In the past, some manufacturers and operators have incorporated them in an attempt to limit transient overvoltages created by VCB chopping by increasing the system characteristic impedance. However, the use of discrete capacitors of any kind, including power-factor correction types, on the load side of a vacuum interrupter can open the stage to prestrike and capacitance-switching transients. Thus, such devices should never be specified within a switchhouse. (Surge capacitor used directly across transformer and motor windings to limit the rate of voltage rise is feasible protection if needed.) For similar reasons, switchhouse and power-center components must never be combined into a single enclosure, for instance, by using a VCB in place of the high-voltage fuses in Figure 11.2. Conversely, surge arresters are desirable transient protection, and low-sparkover distribution-class types should be installed in all switchhouses. (Chapter 10 contains more discussion.)

11.5 Substations

11.5-1 General

It is common practice in the mining industry to purchase electrical power from a utility company whenever possible. A substation is required to receive the utility power before distribution to the mine and other facilities. This complex of equipment contains switching and protective relaying, establishes the grounding system, and may or may not involve transformation to a distribution voltage. The substation design should be based on personnel safety; reliability of operation; maintenance ease; and limitation of damage from fire, lightning, and equipment malfunction (16).

The utility supply voltage for mines may range from 230 kV to 13.2 kV and less, depending upon utility-company availability and the economics and location of the mine.

The substation components are often mounted on concrete pads. Power-conductor terminal structures, commonly made of galvanized steel but also of wood, suspend conductors and cables which provide connections for the transformers and circuit breakers. Insulators are usually made of glazed porcelain or Pyrex to insulate the overhead conductors from the supports. An

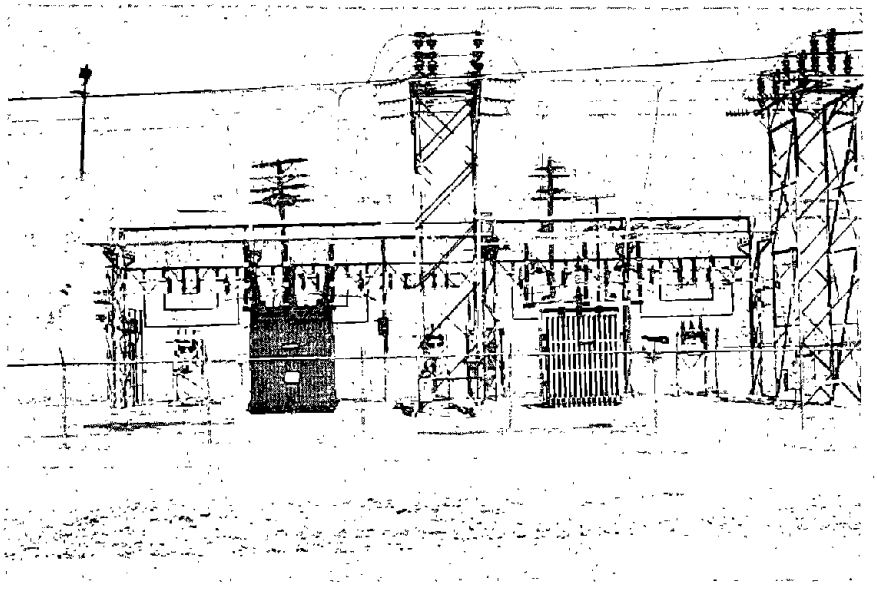


Figure 11.50. An Overall View of a Main Substation Serving a Mine.

overall view of a typical mine substation is given in Figure 11.50.

The main substation is usually a permanent installation. However, portable or unit substations are becoming very popular for small load requirements.

11.5-2 Basic Components

The most popular distribution system used in mining is expanded radial. A simplified sketch of this system is illustrated in Figure 11.51; the substation is noted. Radial techniques have the lowest initial cost since a single transformer supplies all mine circuits, and there is no duplication of equipment. Operation and expansion is simple, but the simplicity leads to its major disadvantage. If a major component fails, the entire system can be effected. However, the logistics of mining, especially underground mining, often dictate the use of radial.

Single-Ended. The substation design employed for radial systems is often termed "single-ended." Figure 11.52 and 11.53 are one-line-diagram examples, and the only difference between the two is on the primary side of the transformer. The substation components, much like those contained in power centers, can be grouped into three general sections. The primary section provides connection with one or more incoming utility lines, switching and interrupting devices, and transformer protection.

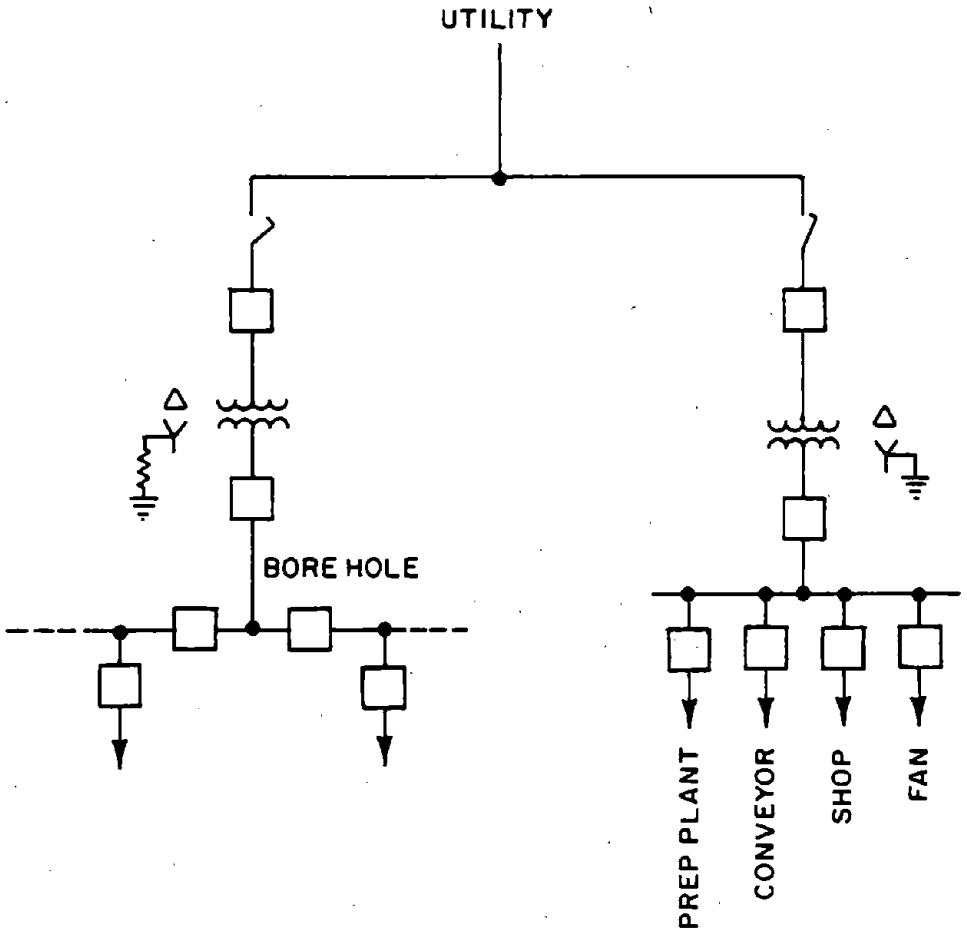


Figure 11.51. Radial Distribution Applied to an Underground Mine and Its Surface Facilities.

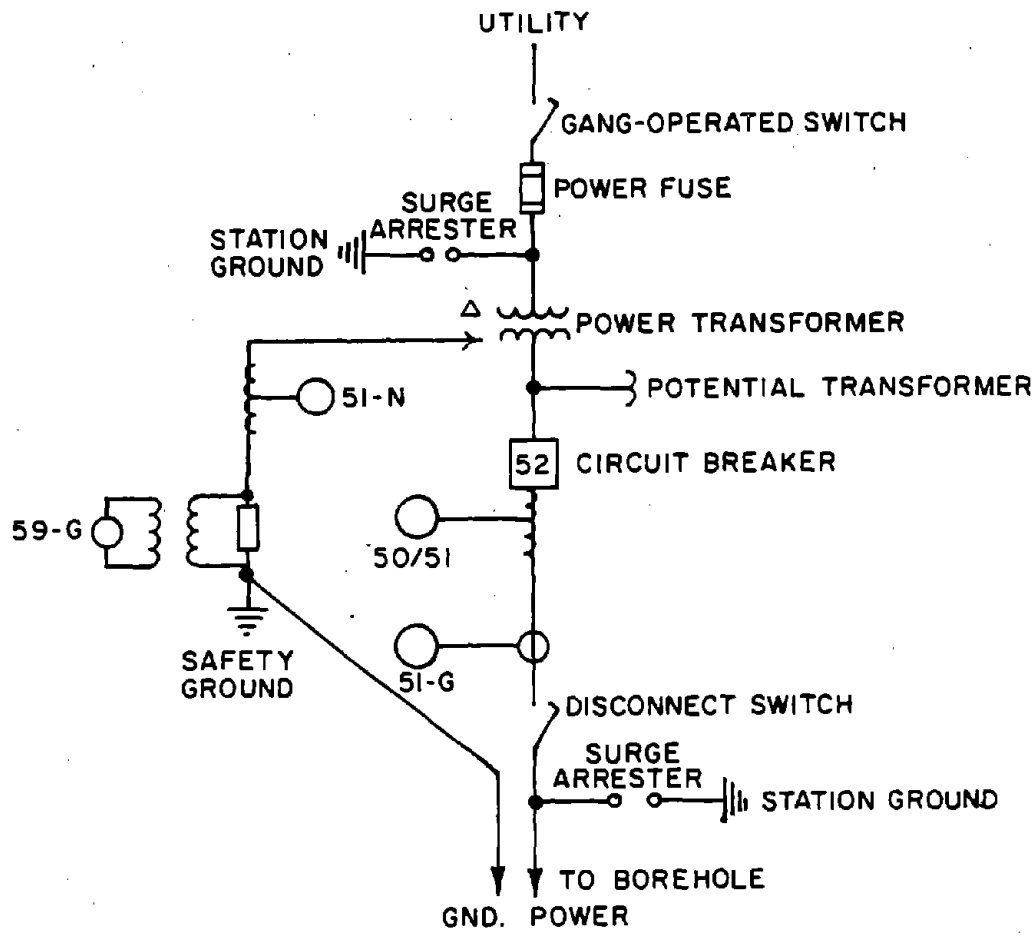


Figure 11.52. One-Line Diagram for a Single-Ended Substation with Fuse-Protected Transformer.

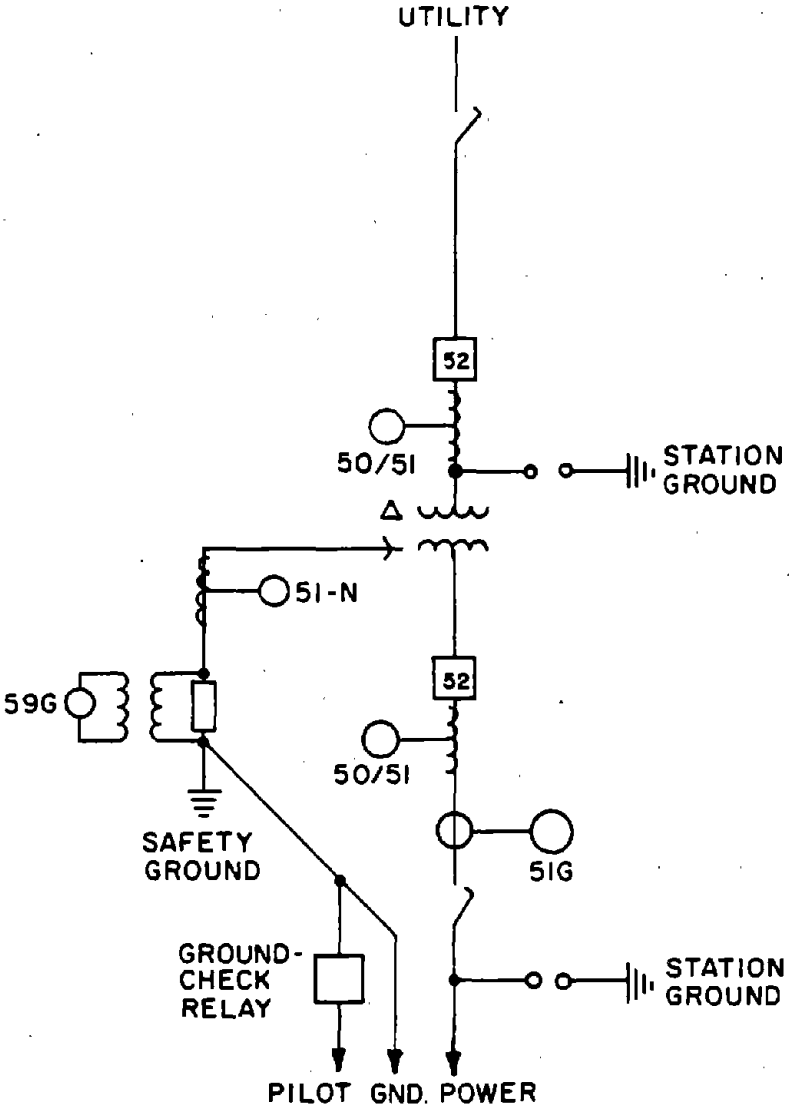


Figure 11.53. One-Line Diagram for a Single-Ended Substation with Circuit-Breaker-Protected Transformer.

The transformer portion may include one or more transformers, a neutral point to establish grounding, and automatic tap-changing (if used). The secondary section (or distribution side) provides for connection of one or more secondary feeders, each having switching and interrupting devices.

Transformer protection (primary side) may be by high-voltage fuses (Figure 11.52), with a circuit breaker and associated overload and short-circuit relaying (Figure 11.53), or by both (usually either is satisfactory). Ground-fault protection could also be provided on the primary (not shown), but this might depend on the utility-company devices. The sizing of these components has already been presented, for instance, the fuses on power-center transformers.

The outgoing-circuit protective relaying has zero sequence, overload, and short circuit. This establishes a primary protection zone to the first downstream switchhouse. Two backup ground-fault relays are recommended: neutral-current sensing between the transformer bushing and the top of the grounding resistor, and potential relaying about the grounding resistor. The first ensures backup if the resistor shorts, while potential relaying provides protection against open-resistor hazards. Both problems can occur in this surface installation. The ground-fault protection must be coordinated with that in the downstream switchhouses. Phase relays must coordinate with downstream protection as well as the transformer primary protection and the utility. Again, circuit-breaker, relay, and transformer sizing and selection generally follow the procedures given earlier, this time closely related to switchhouses.

The substation has two separated ground beds: the station (or system) and the safety (or mine). The grounding resistor is tied to the safety bed and a grounding conductor extends into the mine. Ground-check monitoring of this conductor is required. The surge arresters, substation fencing, and other metallic parts are grounded to the station ground bed.

All substation components should be located within a posted (with danger signs) fence; the internal area including the fence is called the "substation area." Specific concerns about substation components will be given in the following section.

Double-Ended. To enhance the reliability of the distribution circuit, some mines utilize a secondary-selective system. Two secondaries, as shown in Figure 11.54, are connected with a normally-open tie circuit breaker. The combination is commonly (but may not be) in the same substation area. Both substation halfs are identical, each basically a single-ended unit, often with only one station and one safety ground bed. Under normal operation, each substation independently feed 50% of the load, and the distribution system on either side is actually expanded radial. If a primary feeder or a transformer fails, the main secondary breaker on the inoperative circuit is opened,

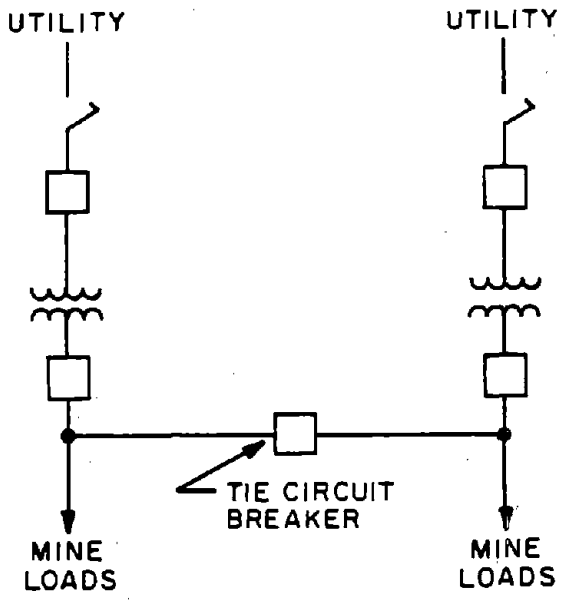


Figure 11.54. Simplified One-Line Diagram for a Double-Ended Substation.

and the tie breaker is closed either manually or automatically. With automatic operation, relaying between the secondary breakers and the tie breaker must be interlocked so the tie breaker will not close on a faulted distribution system. For instance, if the main secondary breaker is tripped by its associated relaying, the same relays should prevent tie-breaker closure.

To permit continued operation with one transformer, consideration must be given to the following (11):

1. oversizing both transformers (instead of 50% of load, 80%) so one can temporarily carry all load (at 125% of its capacity),
2. providing forced-air cooling to the transformer remaining in service for the emergency period,or
3. oversizing both transformers so one can carry total load.

These substations, also called "double-ended," are often economical when total substation capacity is above 5 MVA. Two separate incoming utility lines maximize the advantage of secondary-selective over radial systems. However, because of high transformer reliability, the economics of using a double-ended substation with one incoming line is considered questionable by some. Yet, a definite advantage of this technique over single-ended types is that maintenance chores can be performed without power outage, such as insulator cleaning, component adjustment and replacement, and no-load tap changing.

11.5-3 Transformers

Transformers for permanent surface substations are almost always liquid (oil) immersed and built to IEEE Standards (17). A typical substation transformer is shown in Figure 11.55. Capacities commonly range from 5000 to 30,000 kVA (sometimes less but often not more). The loads may consist of not only the mine but also a preparation plant and general surface loads, like pumps, ventilation fans, maintenance shops, and office and bath-house facilities. However, when an underground mine is involved, it is recommended that a separate transformer be used for the underground power system. The reasons will be presented in Section 11.5-8.

The selection of transformer capacity must come from an estimation of electrical load. Up to 2000 or 3000 kVA, the basis of one kVA per horsepower of connected load is perhaps adequate. This provides more than adequate capacity for the load and will allow minimal load growth. (A worst-case demand factor of 0.75 to 0.85 is built into the selection.) The oversizing will also allow for an adverse power factor.

When the requirements are greater than above, a more precise load estimate is required if optimum equipment costs are to be achieved. Considering the common capacity needs for the majority of mining operations, load-flow analysis must be performed. However, estimation may be made using the demand factors discussed in Chapter 4. Furthermore, in some cases, capacity might be determined on a per-connected kVA basis (about 0.75 per connected horsepower) to allow for growth through the demand factor that always exists.

Recommended impedance values on a percent basis for liquid-immersed transformer are shown in Table 11.5 (17). These cover a capacity range from 500 to 30,000 kVA and are based on primary voltage. (Mine-power-center values are based on capacity.) To reasonably limit short-circuit currents, the reactance should never be less than 5.0% (0.05 pu).

Past practice in the industry was to use three single-phase transformers for easy replacement of failed units. A spare was often included to facilitate change over. However, recent manufacturing techniques have resulted in transformers being among the most reliable components (18). Thus, the common practice today is to install three-phase integral units, and the same advantages given for power centers hold for substations.

The standard ratings for substation liquid-immersed transformers are based on an allowable average-winding-temperature rise of 65°C. A rating related to a 55°C rise is also available but is no longer listed as a standard (17). A transformer rated

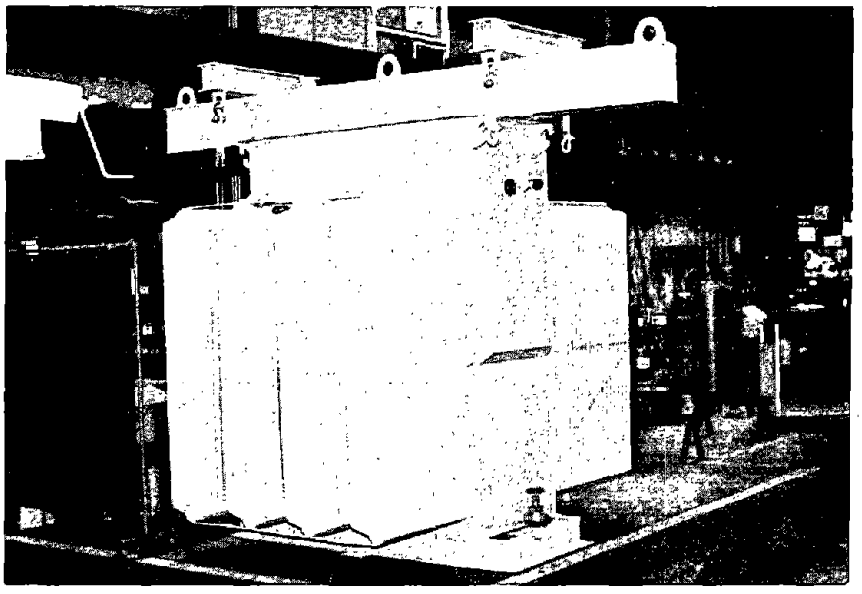


Figure 11.55. A Typical Liquid-Immersed Transformer in a Substation.

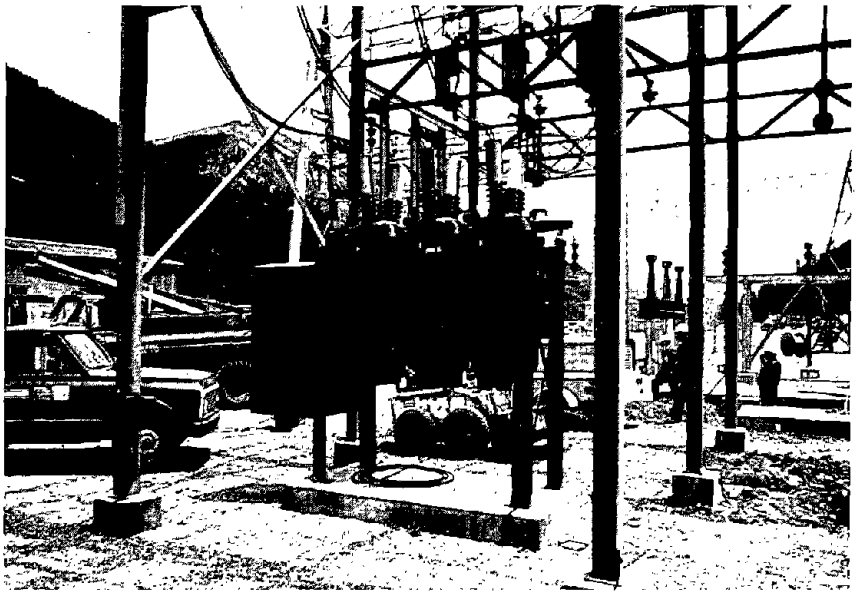


Figure 11.56. A Common Dead-Tank Oil Circuit Breaker in a Substation.

with the 65°C rise can be loaded at 112% of that allowed for a 55°C-rise specification. The transformer capacity always involves a self-cooled ("OA") rating but may also have a forced-air-cooled ("FA") rating. Table 11.6 relates standard capacities for OA- and FA-rated substation transformers (11). If the transformer is so equipped, the unit could also have a forced-oil-and-air (FOA) rating.

11.5-4 Switching Apparatus

Circuit Breakers. Dead-tank oil circuit breakers, such as illustrated in Figure 11.56, are the most common interrupters used in substations. In recent years, air-magnetic and vacuum breakers have gained in popularity due to their ease and reduction of maintenance. However, for applications at utility voltages of 69 kV or higher, OCB's are almost exclusively employed (18). Furthermore, the use of OCB's at lower substation voltages often results in lower cost and easier installation than the alternatives.

Because of the transformer overload capacity and the lack of overload capacity in circuit breakers, main breakers of the transformer secondary should have a continuous-current rating 25% greater than the anticipated top continuous-current rating of the transformer. Obviously, the voltage, interrupting-current, and close-and-latch ratings must be sufficient for the system to which the breaker is applied. These demands may be greater than for interrupters in switchhouses.

Oil circuit reclosers have been proven to be extremely reliable as interrupters on the transformer secondary at distribution voltages to 15 kV (18). A circuit recloser is a self-contained device with the necessary intelligence to sense phase overcurrents, time and interrupt the overcurrents, and to reclose automatically to re-energize the line. If the phase overcurrent is permanent, the recloser will lock open after a preset number of operations (usually three of four) and isolate the fault. Thus, the recloser can eliminate prolonged outages of the distribution system due to temporary faults or transient overvoltage conditions (4).

Reclosers can be hydraulically or electronically controlled (4). With the hydraulic control, an overcurrent is sensed by a trip coil in series with the line. When the minimum trip current of the recloser is exceeded, the trip coil actuates a plunger and causes the recloser contacts to open. The timing and sequencing are accomplished by the pumping of oil through separate hydraulic chambers. Electronically controlled reclosers provide a more easily adjusted, flexible, and accurate control as compared to the hydraulically controlled recloser. The electronic control permits a convenient means of changing the time-current characteristics, trip-current level, and sequence of recloser operation without de-energizing the recloser.

Table 11.5. Standard Impedances for Liquid-Immersed Three-Phase Transformers.

Primary Voltage	Percent Impedance Voltage	
	Secondary <1000 V	Secondary 2400 V and above
2400 to 22,000 V	5.75	5.5
26,400 to 34,500 V	6.25	6.0
43,800 V	6.75	6.5
67,000 V		7.0
115,000 V		7.5
138,000 V		8.0

Table 11.6. Standard Self-Cooled and Single-Stage Forced-Air-Cooled Ratings for Oil-Immersed Three-Phase Transformers in kVA.

55°C OA	65°C OA	55°C FA	65°C FA
500	560	575	644
750	840	862	966
1000	1120	1150	1288
1500	1680	1725	1932
2000	2240	2300	2576
2500	2800	3125	3500
3750	4200	4687	5250
5000	5600	6250	7000
7500	8400	9375	10500
10000	11200	12500	14000
12000	13440	16000	17920
15000	16800	20000	22400
20000	22400	26667	29867
25000	28000	33333	37333
30000	33600	40000	44800

Auxiliary tripping devices are available to allow additional protection, such as ground-fault and ground-check monitoring. Activation of the auxiliary tripping causes the recloser to lock open.

Selection and application of a recloser is basically the same as for an interrupter. The necessary items to consider are system voltage, maximum available fault current at the recloser location, maximum load current, maximum fault current in the zone protected by the recloser, coordination with other protective devices upstream and downstream, and ground-fault tripping or sensing. The common ratings are voltage, BIL, continuous current, minimum trip current, and interrupting current.

Disconnect Switches and Fuses. To provide a visual disconnect for maintenance purposes, knife-blade load-break switches or fuse cutouts are located on the cutouts and secondary of the substation transformer. The switches are usually housed in metal-clad enclosures, while the cutouts are pole mounted. Gang-operated switches are recommended over hook-stick operated devices. Pulling one phase at a time with the circuit under load can obviously single phase the system.

Fuse cutouts have an interrupting capacity instead of a short-time current rating. They should be used to isolate parts of a de-energized circuit, even if the cutouts used are designed with mountings that operate as a load-break switch. Cutouts alone usually cannot be relied upon to protect the transformer, especially in cases where the available short-circuit current is above their interrupting rating. Therefore power fuses are used as backup protection.

High-voltage fuses may be employed as the main means of transformer protection. As with any protective device, their time-current characteristics must be coordinated with upstream and downstream devices, here the utility and the protective relaying on the secondary. However, fuses alone cannot provide necessary ground-fault protection of the transformer primary. When fuses are used, ground-fault relaying could be used to trip the mechanism of an automatic load-break switch. A general protection rule, though, is to use a primary circuit breaker with protective relaying when the three-phase transformer capacity is 5000 kVA and above (18). For any capacity, the primary breaker prevents the single phasing that fuses allow and permits easier coordination with other relaying.

11.5-5 Protective Relaying

The sizing of overload, short-circuit, and ground-fault relays is basically no different than that covered already in this chapter for other power equipment. Regardless, a protective-relaying problem in substations is transformer protection. With larger substation capacities, relay pickup for overloads and short

circuits is normally too high to provide adequate protection alone. "Sudden-pressure" relays, sensing the rate of pressure rise in the gas cushion of the transformer tank, are sensitive to small arcs under oil and are warranted (18). Further, although not a widespread practice, percentage-differential relaying is also strongly suggested for internal fault protection of transformers rated at 5000 kVA or higher.

A standard percentage-differential relaying system is illustrated in Figure 11.57. Figure 11.58 is a typical one-line diagram of a substation with differential relaying added. The current transformers on a wye-connected winding of a transformer should be connected in delta, while CT's on a delta winding are connected in wye. There are two basic requirements that percentage-differential relaying must satisfy (15).

1. The relays must not operate for load currents or external faults.
2. The relays must operate when internal faults are severe enough.

Relay pickup is used to trip the breaker on the transformer primary.

Differential relays usually have coil taps to compensate when the current transformers are not perfectly matched. When selecting a CT for differential relaying, the common practice is to choose the highest CT ratio that will give a secondary current as close as possible to the lowest-rated relay tap. This minimizes the effect of the impedance in the wiring connections between the current transformers and the relays. To assure that the relay will be operating at maximum sensitivity, the current supplied to the relay under maximum load conditions should be as close as possible to the continuous-current rating of the tap (15).

Percentage-differential relays are usually provided with an adjustment to vary the percent slopes. The adjustment allows a means of preventing unreliable relay operation due to unbalances between current transformers during external faults. Unbalances can occur from the following:

1. tap changing of the power transformer,
2. mismatch between CT secondary currents, and
3. the difference between CT errors on either side of the power transformer.

If a power transformer is rated at 10,000 kVA or greater, a harmonic-restraint circuit is recommended in addition to the percentage-differential relays (18). This circuit causes a differential relay to be self-desensitizing during magnetizing-inrush periods, but the relay is not desensitized if a short circuit occurs in the transformer during a magnetizing-inrush period. Only the fundamental component of the differential current is delivered to the operating coil. The harmonics are

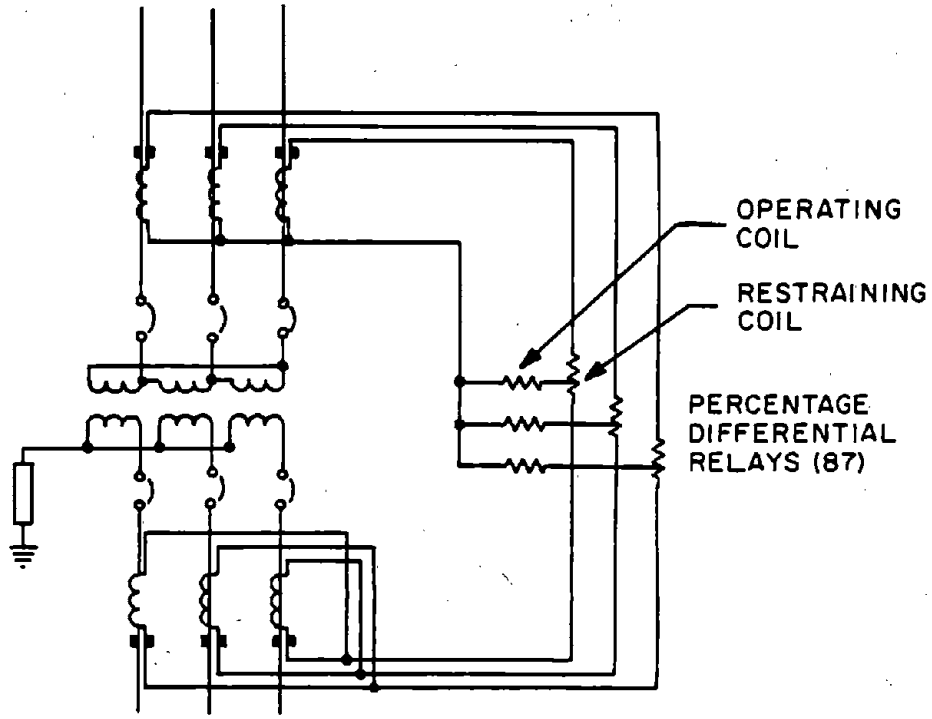


Figure 11.57. A Standard Percentage-Differential Relaying System for Transformer Protection.

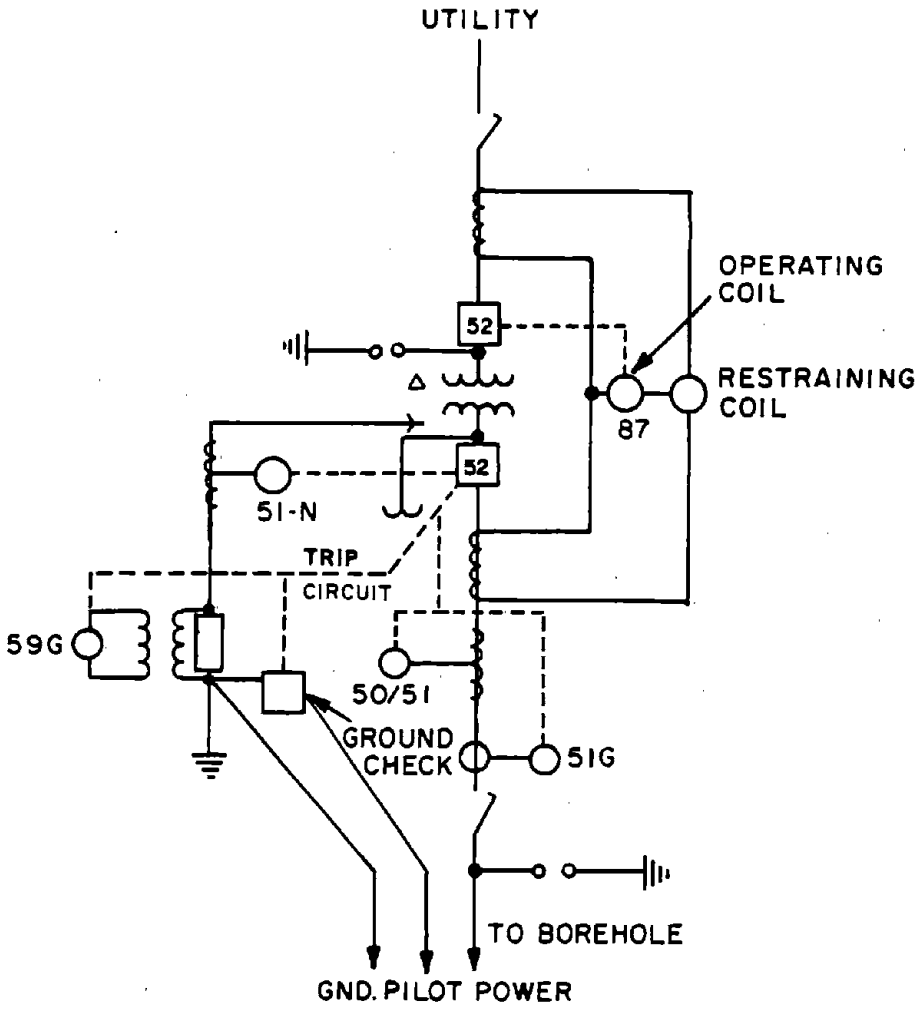


Figure 11.58. One-Line Diagram of a Substation with Percentage-Differential Relaying.

separated, rectified, and delivered to a restraining coil (15).

The pressure relays mentioned earlier can provide a valuable role as supplemental protection to differential relaying. In fact, with sensitive and reliable pressure relays, the sensitivity of the differential relays can be reduced to prevent undesirable operation due to inrush current (15,18). Thermal-overload protection should also be provided as a third means of transformer protection.

11.5-6 Lightning and Surge Protection

Since much of the equipment of the surface substation may be exposed, transient overvoltages due to lightning as well as switching must be protected against. Overhead static areas and shielding masts (see Section 10.5) are commonly used to protect substation equipment from direct lightning strokes. Two static wires are often positioned above and between the phase conductors to provide shielding for overhead distribution lines. In addition, surge arresters are mandatory to limit the transient overvoltages to safe levels.

The surge arresters on the incoming lines should be located as close as possible to the transformer terminals. Station-class valve-type arresters should be used. Again, arrester selection should be based on the primary voltage, the effectiveness of grounding, and insulation coordination between the arrester and the transformer BIL. With dry-type transformers, the BIL is practically constant with the width of applied impulse (see Figure 11.5). In that case, the margin of protection could be less for the arrester sparkover voltage than for the IR-discharge voltage. As shown in Figure 11.59, insulation withstand is not a linear function with impulse time for liquid-immersed transformers; the insulation-withstand level decreases from front-of-wave to chopped-wave to full-wave values (4). The last is the BIL rating, and standard values for oil-immersed transformers are listed in Table 11.7 (11). Values of insulation classes below that shown are provided in Chapter 10, Table 10.1. As evidenced in Figure 11.59, the BIL should be compared with the discharge voltage. Because the exposure available in substations can lead to worst-case surge conditions, the use of 20,000-A discharge current to establish the IR-discharge voltage is likely justified. The margin of protection should not be less than 0.20.

Surge arresters on the outgoing lines should be located as close to the point they leave the substation as practical. These can be station-class arresters but are commonly intermediate-class.

Since higher insulation levels are common on breakers and switches, protection with only arresters at more remote locations is sufficient. Breakers and disconnect switches are designed such that the impulse-withstand level over open switches is

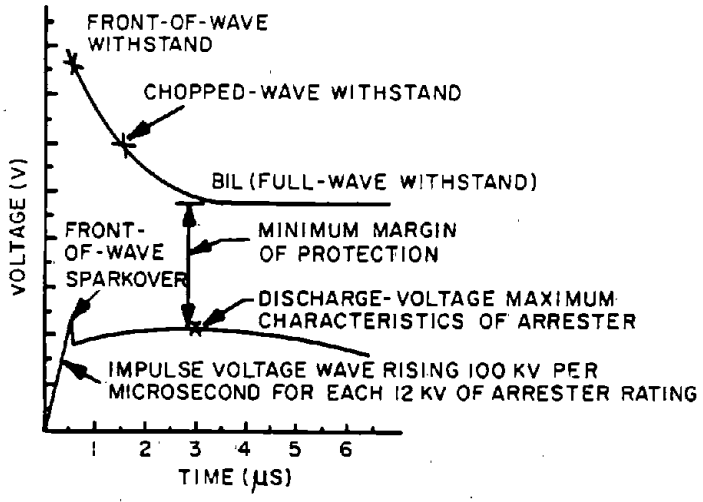


Figure 11.59. Liquid-Immersed-Transformer Insulation Characteristic Compared to a Valve-Type Surge-Arrester Characteristic.

Table 11.7. Standard Basic Impulse Insulation Levels for Oil-Immersed Power Transformers.

Primary Winding Phase-to-Phase Voltage (volts)	Insulation Class (kV)	BIL (kV)
22,900	25.0	150
23,000	25.0	150
26,400	34.5	200
34,500	34.5	200
43,800	46.0	250
46,000	46.0	250
67,000	69.0	350
69,000	69.0	350
92,000	92.0	450
115,000	115.0	550
		350*
		450*
138,000	138.0	650
		550*
		450*
161,000	161.0	750
		650*
		550*

*Reduced BIL's may be applied if proper coordination is maintained with surge arresters.

greater than that to ground, which reduces the possibility of flashover. As a result, a surge on these devices is likely to flash to ground and will not usually cause permanent damage (18).

Whenever current-limiting fuses are applied with surge arresters, the possibility exists that the arc voltage produced by fuse operation could result in arrester sparkover and damage (18). Station- and intermediate-class arresters are more susceptible to damage due to their lower protective characteristics. If fuses are located on the line side of the arresters, arrester sparkover will not occur.

11.5-7 Grounding

Extensive comments, including information about substation applications, have been presented in Chapter 6. However, there are specific concerns that could not be covered until now. Before discussing them, however, a short review should be helpful.

Two separated ground beds are required at the substation. Surge-arrester grounding conductors, static conductors, metallic frames and fencing are connected to the station bed, while only the distribution grounding conductors, including that of the grounding resistor, are tied to the safety ground bed. The two beds must be legally separated by 25 ft. Better separation is obtained by 50 ft or two times radial influence of either ground bed, whichever is greater. Separation is mandatory to prevent voltages produced across the station bed from being transferred to the safety bed. This is especially critical when portable or mobile equipment are involved, as all equipment frames can be assumed to be at the potential of the safety-bed (i.e., the voltage drop across the bed to infinite earth).

To limit the magnitude of voltage produced across a bed during current flow through it, "low resistance" for both ground beds is mandatory. The resistance value is generally defined as 5 Ω or less. In order that step-and-touch potentials are not hazardous in the grounding location, potential gradients during surging conditions must also be restricted.

For portable and mobile equipment being fed by the substation, a resistance-grounded system is mandatory. The ohmic value of the grounding resistor must be such that frame potentials of the high-voltage distribution are not greater than 100 V during ground-fault conditions. For practical purposes, this restricts the maximum ground-fault current to not more than 50 A. Most modern substations serving mines use a 25-A ground-current limit. However, it is important that the current limit selected be greater than three times the per-phase capacitive-charging current.

Ground-fault protection at the surface substation should be by:

1. zero-sequence relaying for each outgoing circuit;
2. potential relaying about the grounding resistor; and
3. (direct) neutral relaying between the grounding resistor and the neutral bushing of the power transformer or the grounding transformer.

Protective relaying to detect grounding-transformer failures is wise, but protection (such as fusing) should never be used that will remove the transformer from the line or the grounding resistor. Ground-check monitoring of circuits feeding portable and mobile equipment is a must, but it may be necessary on circuits feeding other loads as well.

A couple of comments relating to substations feeding underground mines are necessary. First, it is recommended that the mine ground bed be located as close as practical to the borehole or point where the power extends underground. This practice minimizes the possibility of damage to high-voltage circuits entering or extending underground which may lead to hazardous conditions, and the probability of lightning strokes hitting exposed high-voltage circuits extending underground. To further reduce these problems, federal regulations require that within 100 ft of extending underground, the circuits must have:

1. overload and short-circuit protection,
2. ground-fault protection,
3. surge protection, and
4. a visual disconnect.

As all of these can be contained within the substation area, it is logical to place the entire substation as close as practical to the underground power entry. This may also prevent unnecessary duplication of components.

11.5-8 Other Loads on a Mine Substation

When other loads are being supplied from a mine substation, such as fans, preparation plants and so forth, grounding problems can become complex. Three fundamental concepts must still be served:

1. provision of ground-fault protection,
2. the earth cannot be used as a grounding conductor circuit, and
3. isolation of the grounding system serving portable and mobile equipment.

Adhering to these criteria is mandatory where underground mines are connected with the substation, so the following discussion will be pointed directly at these applications. However, the comments are adaptable to any mine. Figure 11.60, illustrating

a substation feeding both surface and underground loads, will be used as a focal point.

At first glance, the circuits shown in Figure 11.60 would appear to be reasonably safe. The actual surface load is isolated from the main-substation secondary through the transformer windings of its unit substation. Both substations have separated ground beds with all appropriate connections. Each outgoing circuit from the main substation is separately protected for phase and ground overcurrents. However, consider the situation where a ground occurs in the unit substation, for instance, in the incoming circuitry or within the transformer. This can establish a ground-current path through the earth, the main-substation safety bed, and its grounding resistor. For the time that earth current flows, the mine grounding system is elevated by a potential equal to the mine-ground-bed resistance times that current. In other words, one forbidden grounding practice is being violated in the figure: the earth is being used as a grounding conductor. Furthermore, the ground-fault protection used in this system portion, zero-sequence (51G) and potential (59G) relaying, must have a specific level of ground current to pick up. Earth resistivity may be large enough so detection is not made and the current persists. Even if tests are made to ensure pickup, seasonal variations might destroy all intentions.

Figure 11.61 illustrates a solution to this perplexity. Here, the frames of all direct loads for the main substation are connected via grounding conductors to the safety ground bed. Ground-check monitoring of these conductors to the surface facilities is preferred, but equal safety may be available by establishing a low-resistance ground bed on the unit-substation end. The new bed must be considered as part of the mine ground bed.

Because of the increase in components connected to the safety bed, the probability of lightning strokes and other surging conditions elevating the bed is also raised. Surge protection, therefore, must be added. Static lines should protect overhead power, grounding, and ground-check lines extending to the surface loads. The static lines must not be connected to the mine ground bed. The unit-substation outgoing-circuit grounding should be separated from the mine ground bed by the same provisions as station ground beds.

The recommendations above do have exceptions. First, if the transformer used for the surface loads is in the same substation area as the main power transformer, a grounding conductor to the mine ground bed must not be used. This could easily tie the substation system and safety beds together. Isolation of the unit-substation secondary in some instances might not be practical or could create a personal hazard. An example is an unit substation mounted onto a preparation-plant metallic structure. An attempt at isolation could result in two proximate surfaces that can have dangerous potentials existing between them. In this situation, however, the grounding conductor to the mine bed is still mandatory. Yet, without the next exception,

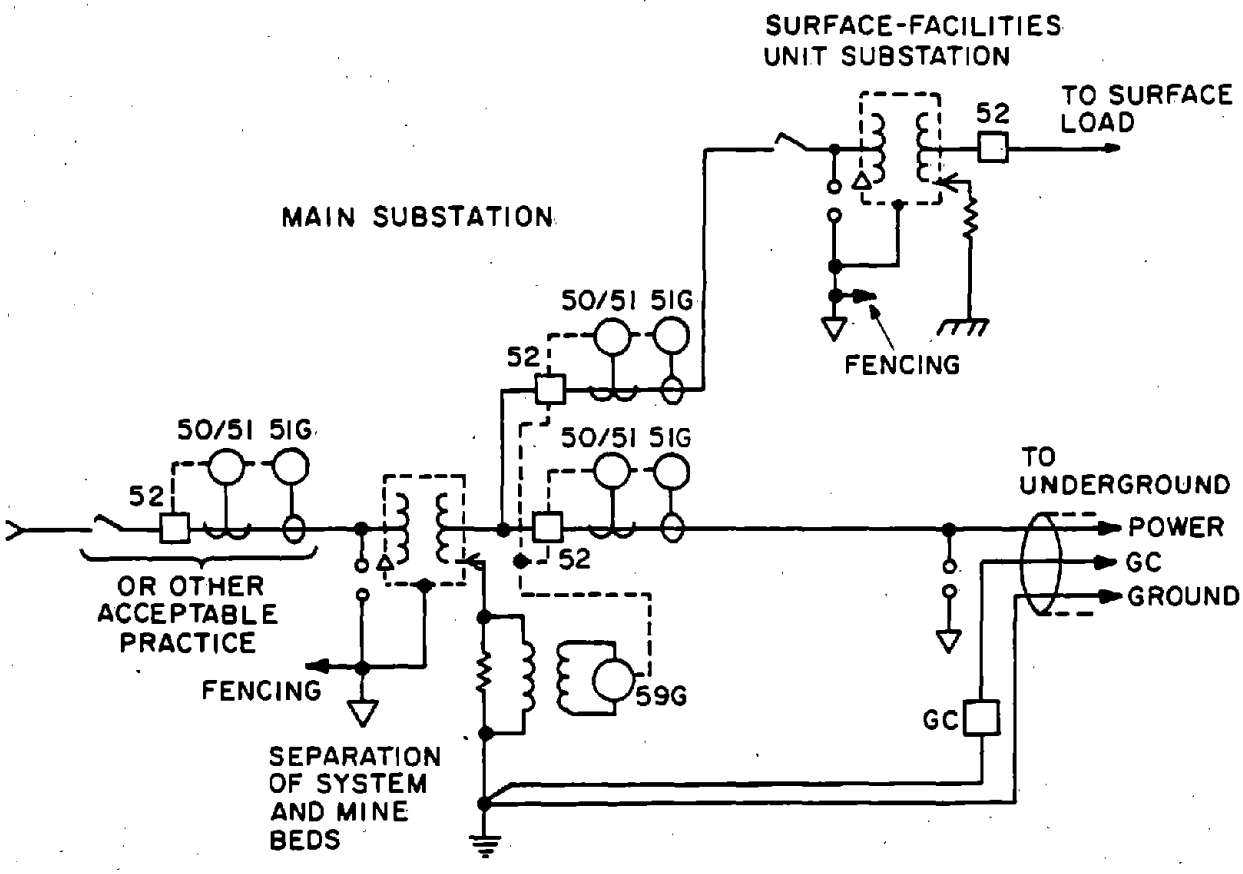


Figure 11.60. A Substation Feeding Both Surface and Underground Loads (No Grounding Conductor).

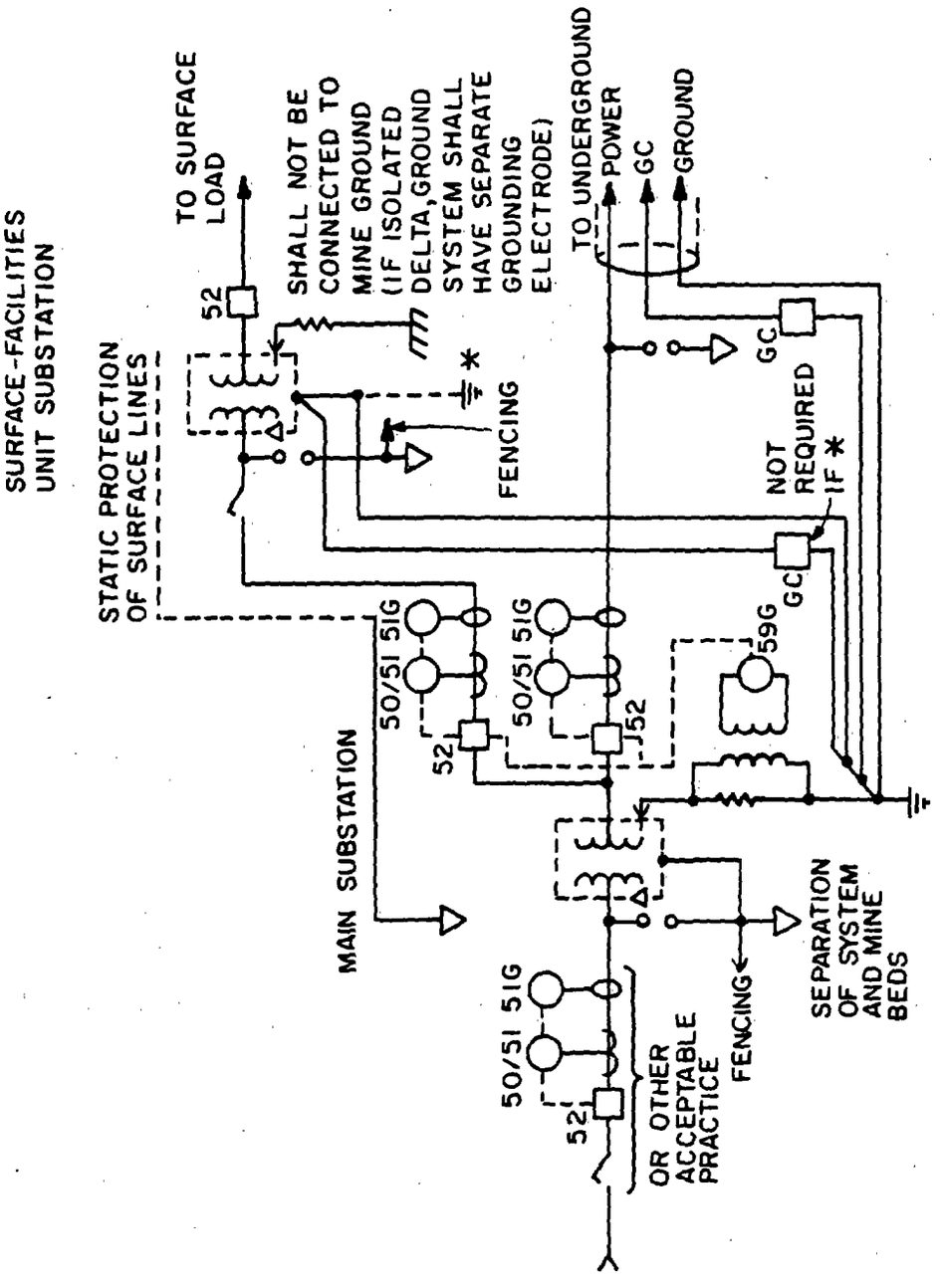


Figure 11.61. A Substation Feeding Both Surface and Underground Loads.

exposure of the mine bed to lightning-stroke surges would be substantially increased.

It can be shown that if a grounding conductor is approximately 250 ft in length, its typical impedance to a surge, such as an 1.2x50-μs impulse, is high enough to effectively stop the traveling wave. Thus, if a safety factor of two is applied, any protected (by static line or otherwise) grounding conductor of 500 ft or longer can be connected to the mine ground. This means that when isolation of the unit-substation is dangerous, the mandatory grounding conductor to the mine bed should be effectively 500-ft long. In addition, if a grounding conductor is static protected for 500 ft, it can be used for shielding the power conductor if properly grounded beyond that distance.

Although meeting these precautions should result in a safe substation grounding system, there exists a high chance that personnel safety could be compromised through human error. Accordingly, the most safety is achieved if a separate substation is used to supply mine power. Perhaps the best but the most expensive approach is to use subtransmission to feed a second substation for surface facilities. However, use of an isolation transformer between the main substation and the mine provides the same benefits. This is covered in Section 11.5-10.

11.5-9 Portable Substations

As mentioned earlier, portable surface substations have gained recent popularity for small-load situations. The entire substation is skid-mounted and can be transported as a unit by truck. Portable substations are custom built to meet the needs of the individual mines. For some small mines, the economics are such that the portable substation is used in conjunction with a diesel-powered generator. The output of the generator may be a low voltage, such as 480 V. For this case, the substation transformer may step up the voltage to 4160 V for distribution to the mine loads.

Figure 11.62 shows a situation where the utility company supplies a voltage of 12.47 kV. This particular substation is designed to operate a mine load of 750 kVA and surface loads of 150 kVA, including a conveyor belt and a ventilation fan. The surface and the mine circuits are paralleled with each other and supplied by the incoming feeder. The surface circuit can be isolated from the mine circuit by means of the load-break switch. The primaries of both the surface and mine circuits are protected by high-voltage fuses. The surface transformer steps down the incoming line voltage to 480 V for operating the belt and fan. Each of the surface loads is protected by molded-case circuit breaker. Each breaker contains an undervoltage release that is powered from the utility/control transformer. The utility/control transformer also supplies power to the 240-V and 120-V outlets.

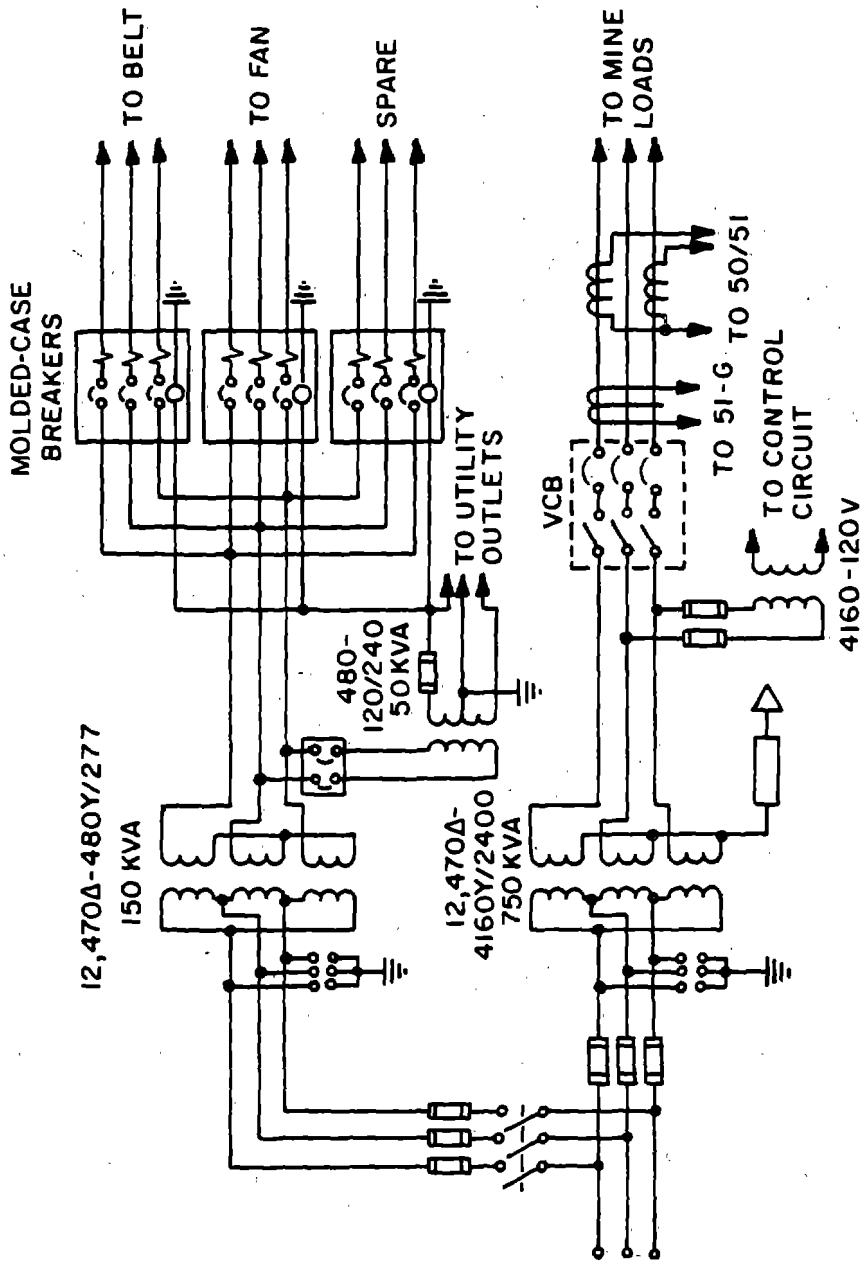


Figure 11.62. A Typical Portable Substation to Service a Small Mine.

The mine transformer steps down the incoming voltage to 4160 V for distribution to the mine loads. The transformer secondary wye is connected to permit resistance grounding. The secondary feeds the vacuum circuit breaker, which protects the distribution circuit. Current transformers at the breaker output supply inverse-time relays for phase-overcurrent protection and ground-fault protection. The control transformer on the line side of the vacuum circuit breaker supplies power for tripping the breaker.

As with the larger permanent surface substations, individual ground beds must be provided for the station ground and the safety ground. These connections are noted by the two ground symbols in the schematic.

11.5-10 Purchase at Mine Distribution

Either because of economics or a utility-company decision, some mines must purchase power at the same voltage as for mine distribution. The utility company often supplies power from an ungrounded-delta transformer secondary. The mine operator must supply basically the same substation components that have been discussed, but the main transformer may or may not be excluded. The omission is directly dependent upon the location of the utility transformer (which is the power source or "source transformer") and the location where a neutral must be derived to establish mine grounding. For surface mines, this location is often not critical. However, as mentioned earlier for underground mines, the mine ground bed should be as close as practical to the point where circuits extend underground. Regardless, the following rules apply to all ungrounded-delta sources supplying portable or mobile mining equipment, including situations where the mine owns the source transformer.

If the distance between the source transformer and the grounding location is 100 ft or less, the simple arrangement in Figure 11.63 can be used. A grounding transformer derives the neutral point, a grounding resistor is inserted to limit ground-fault current, and a safety ground bed is established. Load-break switches provide visual means of disconnect, and surge protection is afforded by arresters grounded to an arrester ground bed which is separated from the mine ground. Protective relaying is identical to any substation: phase-overcurrent, ground-fault, and ground-check monitoring. Further, it is imperative that the recommended zero-sequence relaying be located downstream of the grounding-transformer connection. Otherwise, it cannot detect downstream ground faults. Zero-sequence currents terminate at the grounding-transformer terminals. From switch to switch, the additional equipment becomes the mine substation.

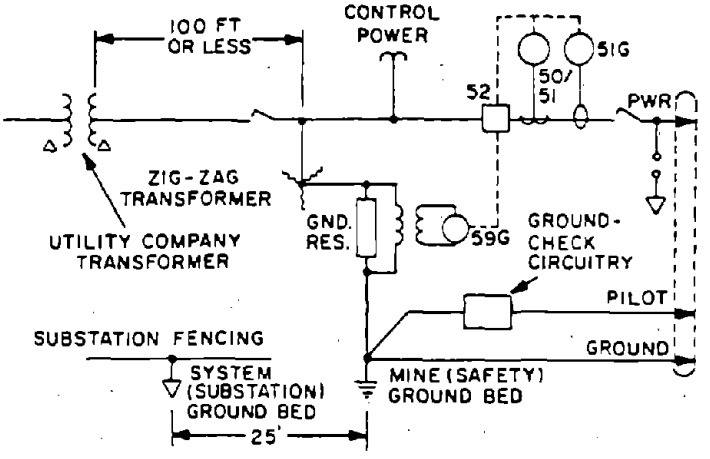


Figure 11.63. Providing a Mine Ground and Protective Relaying from a Utility Substation.

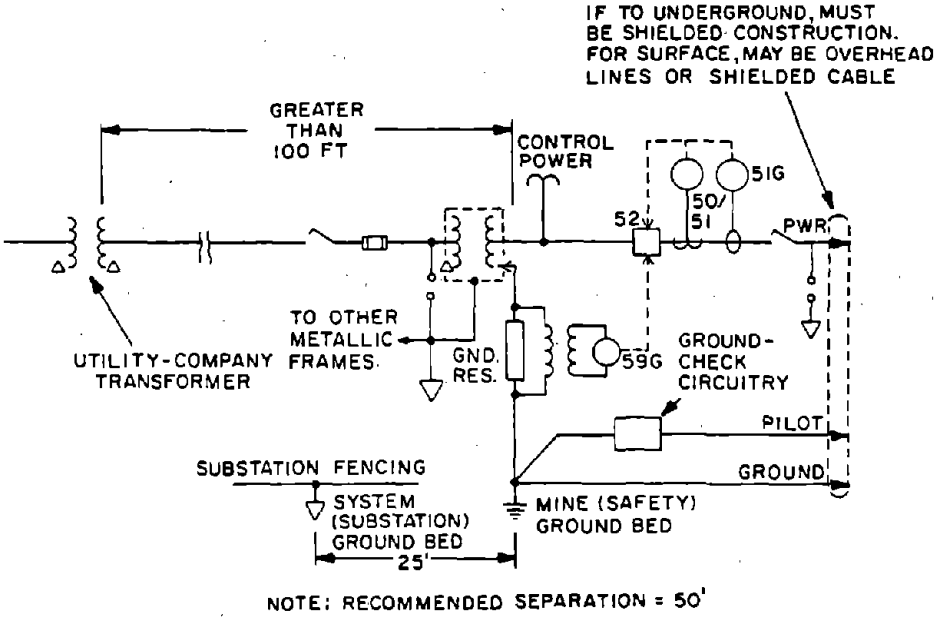


Figure 11.64. Use of an Isolation Transformer with a Utility Substation.

When the distance is greater than 100 ft, the one-line diagram of Figure 11.64 applies. An isolation transformer must be installed, and the required (unit) substation is practically identical to Figure 11.52. A delta-wye transformer is shown, but a delta-delta power transformer with a grounding transformer could also be used. The federal regulation behind this change is that the grounding resistor shall be located at the source transformer. To be consistent with other regulations, "at" is defined as 100 ft or less, and the logic for the requirement is very sound.

Utility companies commonly supply the ungrounded-delta power on overhead lines. The typical distance for one overhead span (pole-to-pole) is approximately 100 ft. Exposed power lines, beyond one span, do raise the probability of lightning strokes striking the mine power system but, equally important, the possibility of losing a phase conductor is significantly increased. One common example is a vandal shooting an insulator or power conductor with a rifle or hand gun. If one of the lines between source transformer and the grounding transformer is lost (say in Figure 11.63), the grounding transformer cannot find the system neutral, and its common terminal, which is connected to the grounding resistor, will rise to become near the same potential as a remaining phase conductor. With normal system operation, the problem presented here is small, as the resulting single phasing would be quickly detected by the overcurrent protective circuitry. Under no- or low-load conditions, however, this circuitry may not detect the unbalance, and all potentials in the mine could become elevated to near phase potential. Potential relays across each leg of the grounding transformer can be employed to detect the hazard and supply tripping to the main circuit breaker. An isolation power transformer provides this same protection but, along with surge arresters, prevents voltage surges from entering the mine.

11.5-11 Additional Design Considerations

Many additional design considerations and precautions have developed from experience with permanent substations for mining applications. The listing of some follow.

1. Substation conductor insulators may be of post or cap-and-pin types, and either standard strength or heavy-duty design may be used (18). "Extra-creepage" insulators and bushings (or one voltage class higher than required) are recommended (19). These extend the time between required clean-up and minimize flashover.
2. The high-voltage side should be located on the windward side of the substation (20,21). The prevailing winds will then help keep the substation insulators clean between regular cleanups.
3. The voltage drop on the distribution system should

be maintained within ± 5% to all load concentrations (19). This establishes the nominal voltage and necessary taps for the secondary of the substation, and corresponds to the taps stated earlier for power-center trans ormer primaries.

4. Permanent substations should be located outside the influence of the mine. This is very critical for surface mines.
5. Buses and bus supports should be designed to withstand the stress from the average asymmetrical short-circuit current during the first 10 cycles after a fault (18).
6. Line tensions within the substation area should be assumed to occur under maximum wind- and ice-loading conditions (18). Structure design should be also based on these specific line tensions and wind loading.
7. Substation primary voltages above 34.5 kV cannot be used for distribution-class equipment (i.e., cannot be transformed directly to low- and medium-voltage mine usage) (18). This could create problems in supplying certain surface loads.
8. The utility will meter the substation power consumption on the primary or secondary, depending on the primary voltage. The substation should also contain the mine's own metering, of equivalent precision to that of utility (19). Such is invaluable for maintenance checks and also as a double-check on the utility. Metering could include kilowatt, ammeters, voltmeters, and power-factor instrumentation for each outgoing feeder from the substation. Demand meters, for either 15- or 30-minute maximum demand, may also be needed.
9. The fence enclosing the substation area should be no less than 8 feet high (22). The fence should be provided with a door or gate, which should be locked at all times, except when authorized personnel are present. The fence should be grounded to the station ground bed. It should also extend to the ground so no one can crawl underneath. Danger signs should be posted on all sides of the substation area.
10. The substation area should be maintained free of weeds, trash, and combustible material that might create a hazard to personnel or the substation components (22).
11. All components containing liquid insulation should be mounted on pads to allow quick drainage and capture of any lost fluids. This is especially important when flammable or environmentally-hazardous liquids are involved.

11.6 Summary

This chapter has attempted to collate an enormous amount of information to provide a coherent presentation about the typical construction practices used for mine power equipment. Some designs, like mine power centers, are so dependent upon the application that standard units cannot exist. Yet the assembly of others, like switchhouses and substations, is rather uniform across the industry. However, the chapter subject is immense, and it is likely that some areas might be missing for specific needs. As can be seen in the Specification Section at the chapter beginning, anyone involved with this equipment should work very closely with the manufacturer.

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CHAPTER 12

SOLID-STATE CONTROL AND DEVICES

12.1 General

Except for a short introduction to electronics at the end of Chapter 3, the report has intentionally not covered electronic devices in mine power systems. The reason is that their use is a rather new aspect to the industry and, except for earlier experimental tries, their employment did not commence until the early 1970's. However, this impact has been substantial and, if one area of electrical engineering can be singled out as having the greatest probable influence on future mining operations, it is electronics. Evidence has already been seen with power electronics in belt-conveyor systems. This chapter will discuss solid-state applications in two important subjects: motor control and protective relaying.

12.2 Motor Control

12.2-1 Basics

Thyristors. Almost all activity and interest in solid-state control of industrial motors have centered around the use of the "silicon-controlled rectifier" (SCR) or "thyristor." This has been briefly covered in Section 3.11, but a model and circuit symbol are again shown in Figure 12.1. The outer two layers act as a p-n junction, and the inner layers serve as an element to control that junction. The device has three external terminals: anode, cathode, and gate (1,2).

If the anode is positive with respect to the cathode (forward biased) and, if the gate is reverse biased in reference to the cathode, there exists a balance of electrical charges in the four layers, and current flow is inhibited. This process is termed "forward blocking," and the SCR acts as a high resistance in both directions. However, when the gate is forward biased with respect to the cathode, gate current upsets the electrical-charge balance, and anode-to-cathode current can flow. When this condition starts, the gate loses all control; in other words, the gate can turn the SCR on but not off. Gate control (or turning the SCR off) can only be achieved by reverse-biasing the gate-cathode circuit and reducing the anode-cathode current to essentially zero.

A typical characteristic curve for a SCR is illustrated in Figure 12.2 and details the phenomenon just described. Voltages and currents are given with respect to the cathode. When the anode potential is positive and the gate is at cutoff (negative potential), the characteristics are similar to that when the anode is

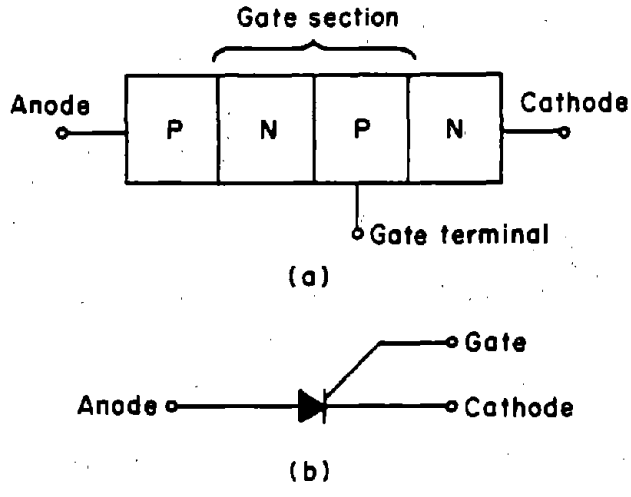

Figure 12.1. Model and Circuit Symbol for a Thyristor.

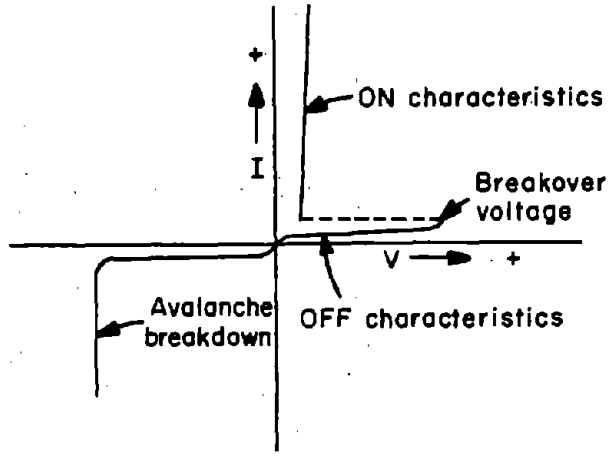

Figure 12.2. Typical Characteristic Curve for a Thyristor.

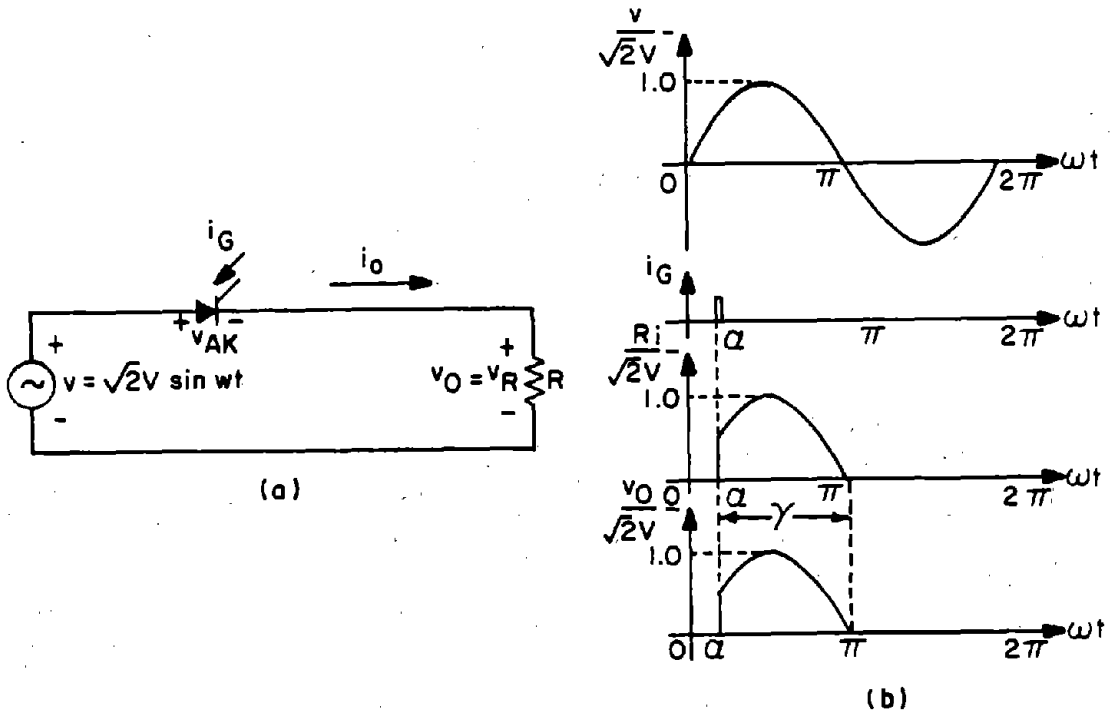

Figure 12.3. Thyristor Half-Wave Rectifier.

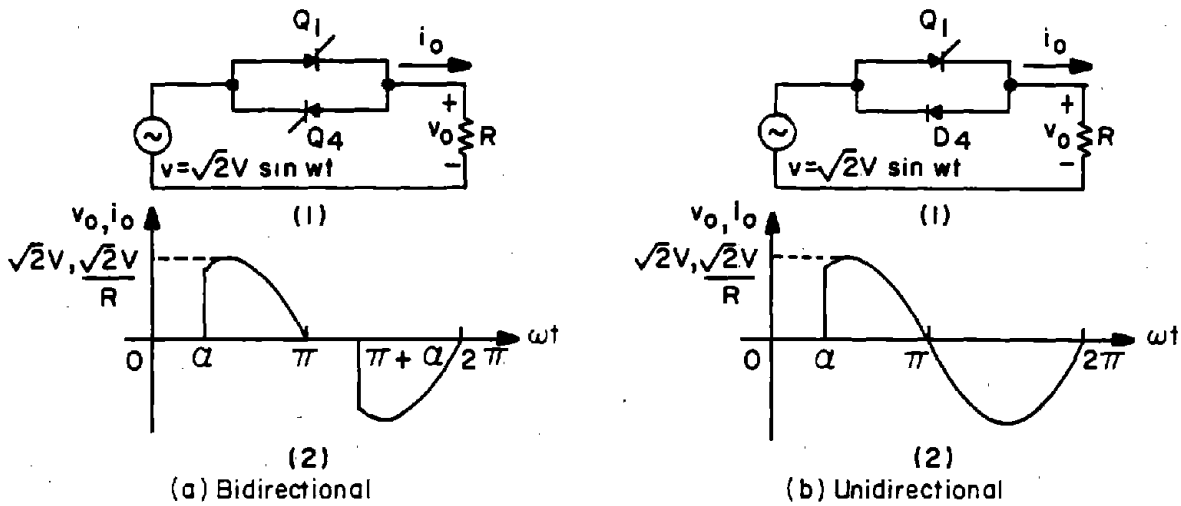

Figure 12.4. Alternating-Current Thyristor Control.

negative. At a specific positive potential, called the "breakover voltage," the SCR will turn itself on. Here, anode current increases substantially, and there is a large reduction of voltage drop across the device. The breakover point can be varied by varying the gate current. This characteristic is why the thyristor is so valuable in power-control applications.

The common technique for starting conduction is to apply a current pulse at the gate (3). The pulse alone neutralizes the thyristor blocking action at the desired breakover voltage. The most simple SCR application is in the half-wave rectifier circuit shown in Figure 12.3. Breakover is determined by the gate current and, thus, the average value of d-c through the load can be controlled by the gate control pulse (i_G). The process of starting the SCR is often referred to as "firing." The angular position (or timing) of each pulse with respect to the source waveform is called the "firing angle" (angle x). In order to control a-c, the load must receive both sides of the a-c waveform. Two single-phase circuits that can be used as a-c voltage controllers are shown in Figure 12.4. The bidirectional arrangement uses two thyristors (back to back) and gives a symmetrical output with appropriate firing-angle pulses for the two gates. The unidirectional circuit with one thyristor and one diode, however, presents an asymmetrical waveform to the load. The d-c component created is considered a major disadvantage because the source waveform must be ideal for the circuit to be of practical value (1).

Voltage control for three-phase loads employs three of the single-phase controllers as shown in Figure 12.5. Although the

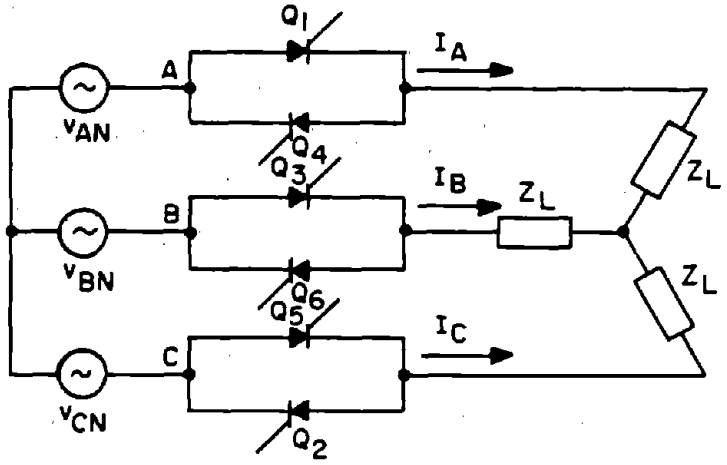

Figure 12.5. Three-Phase Control with Bidirectional Thyristor Arrangement.

bidirectional circuit is illustrated, unidirectional circuits can also be applied. Direct-current components are mostly negated with the three-phase waveform, but the unidirectional circuits introduce a higher harmonic content to the line currents (1).

Simple Motor Control. One method of speed control in d-c motors has already been covered, simply adjusting the d-c voltage to the machine. This would apply to loaded series-wound motors. Shunt and compound d-c motors also can be controlled by two direct means: armature voltage or field voltage. The field control is interesting because field excitation is usually considered constant, but motor speed can be adjusted inversely with field current. In any of these cases, the simple circuit in Figure 12.3 could be used when the source is a-c. However, the basic circuits of Figures 12.6 and 12.7 are commonly applied for single-phase and three-phase sources, respectively.

The commutation diode shown in Figure 12.7 serves an important purpose. "Commutation" is the transfer of current from one device to another as voltage relations change (4). The commutation diode conducts armature current so it will not be transferred to the thyristors and diodes of the bridge. Thus the thyristors can turn off at zero voltage. Without this diode, thyristor current might not reduce to zero; recovery then is not likely. Other commutation techniques are available (1).

A "chopper" or d-c to d-c converter is another method of variable-speed d-c motor control using thyristors; it is especially important because of operation between a d-c source and a load. As shown in Figure 12.8, the thyristors in the chopper circuitry switch the d-c source on and off, supplying unidirectional voltage pulses. This reduces the effective voltage (V_o) to the load.

Variable-speed control of a standard three-phase squirrel-cage motor is possible using thyristor voltage control (e.g., Figure 12.5). Motor speed varies because the motor allows a greater percentage slip at reduced voltage. As the controller increases the terminal voltage, the allowable slip is reduced, and the motor speed increases. However, three specific problems arise in this application. Reduced-voltage operation causes more heat to be generated in the motor. Motor torque is also reduced at slow speeds with reduced voltage. Finally, the waveform produced by the thyristors is rich in harmonics (frequencies other than line), and this creates even more motor heat. Regardless, if high-quality motors are used and reduced-voltage operation is restricted to a short time, the result can be effective controlled starting of straight induction motors.

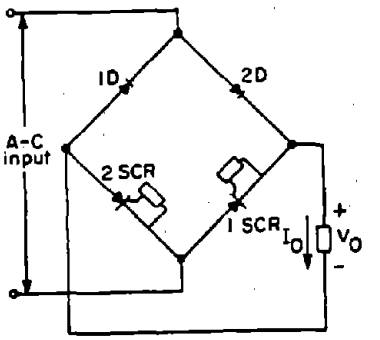

Figure 12.6. Full-Wave Thyristor Bridge Rectifier.

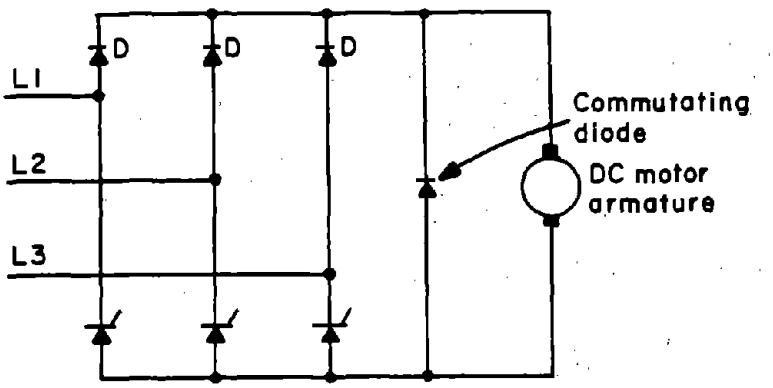

Figure 12.7. Three-Phase Thyristor-Controlled Rectifier.

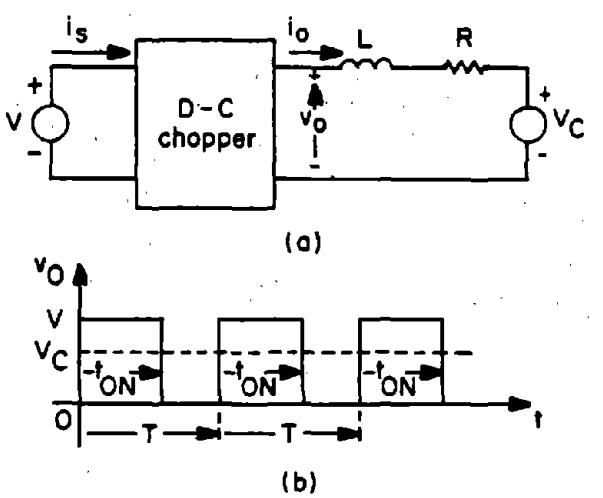

Figure 12.8. Simplified Chopper Control.

Control Systems. The foregoing has only discussed thyristors and their application to variable voltage control. Other than presenting how the device is fired, nothing has been stated about the control circuitry that supplies the gate signal.

Perhaps the best way to visualize power-control applications with thyristors is through control-system principles. The two basic types of control systems are open-loop and closed-loop (3,5). In "open-loop" systems, the controlling element is unaware of the effect it produces in the controlled element; whereas in "closed-loop" or "feedback" systems, information is delivered back to the controlling element so it can adjust control of the controlled element to produce a desired result. The feedback control systems of interest here are termed "regulators." Their purpose is to maintain a constant result. Feedback systems inherently provide more precise control than open-loop.

Operation of these systems can be described with the assistance of the basic "block diagram" in Figure 12.9. The lines in the diagram represent system variables. A block represents "transfer function," the quantity which must be multiplied times the input to obtain the output. A summation or comparison point is a position where two or more system variables are summed, the output being the algebraic sum of the entering variables.

The variable to be controlled, C, may be voltage, speed, or any other quantity. The reference variable, R, which is usually adjusted manually by an operator, determines the desired value of C. The feedback element, H, supplies information about the output to the summation point. The function of the summation point is to compare the input and feedback signal; the difference or error, E, drives the controller, G. In the simplest system, the controller might contain the device that needs to be controlled. (Note: G usually represents the transfer functions from input to output. H denotes transfer functions in a feedback path.) A feedback system contains all these elements and variables; whereas open-loop systems only have the controller respond to the reference signal.

Elaboration of these statements can be seen in the block diagram of Figure 12.10, which illustrates the main parts of a motor controller (1). The power circuits, which primarily contain thyristors, provide variable direct or alternating voltage output to the controlled system. The controlled system can be a rotating machine or any other driven load. Appropriate feedback is supplied back to the controlling system. The feedback, for example, could represent current, voltage, temperature, speed, and so forth. The controlling system responds to the

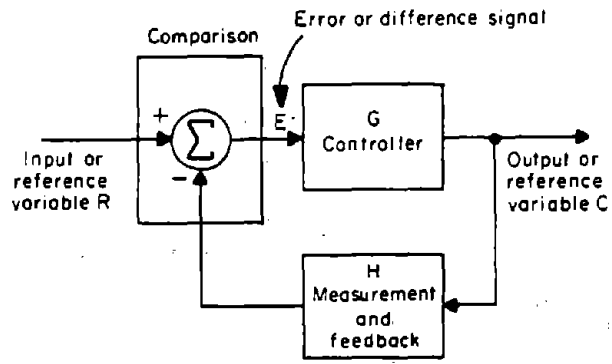

Figure 12.9. Basic Control-System Block Diagram.

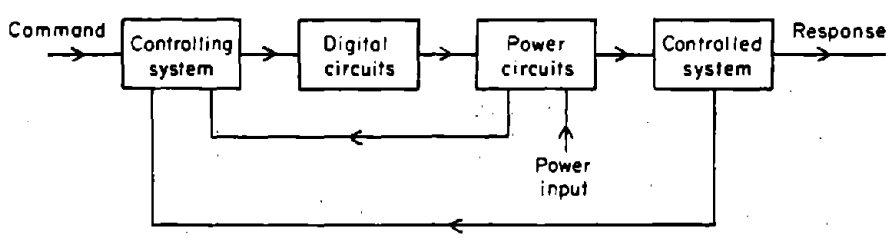

Figure 12.10. Simplified Block Diagram of a Motor Controller.

feedback and input information and supplies control signals to the digital circuits. Finally, the digital circuits, acting as an additional transfer function, simply switch the thyristors in the power circuit off and on at appropriate times.

Thyristor Physical Characteristics. The two common thyristor configurations used in industrial applications are illustrated in Figure 12.11. Stud types are intended for smaller loads and have average forward current ratings up to around 150 A. Heat sinking is like that shown for diodes in Figure 3.91 and, because thyristors have p-n junctions, the same heat-dissipation theory given in Chapter 3 applies to these devices also. The large thyristors were introduced in the late 1960's and are termed "hockey pucks," "press packs," or "disks"(6). These have the ability to transfer junction heat on both sides, being clamped between two heat sinks (see Figure 12.12). Heat-sink cooling can be either by air or water. Single disk thyristors presently have average forward-current ratings up to 7500 A. Their cost has made solid-state motor control competitive in areas where before 1970 only electromechanical arrangements were thought applicable.

12.2-2 Mining Applications

Direct-Current Equipment. There has been excellent success applying solid-state (or "static") control to many d-c equipment, especially under 100 connected horsepower (7,8,9,10). Examples include battery on-track and off-track vehicles as well as underground face equipment. Most systems have applied feedback control of chopper circuitry. In all these, two important advantages have been achieved: increased motor life and significantly reduced drive-train maintenance. Limiting armature current during acceleration, thereby reducing brush and commutator problems, account for the first. General mechanical problems are reduced because motors have controlled acceleration. Even during the worst shock-loading instance, plugging, the motors have controlled deceleration, reversal, then acceleration. For battery-powered vehicles, battery life is increased. Here, peak current demand is reduced, and power is generally used more efficiently. (Note: Applications in battery chargers is given in Chapter 13.)

Other instances of static control of d-c motors involve surface excavators, hoists, and conveyor belts. A variable-speed requirement and substantial demand fluctuations are still the typical reasons to use d-c motors (8). (Power to surface excavators can swing from 200% demand to 120% regeneration in one cycle.) Control should soon be available for applications up to 1500 hp.

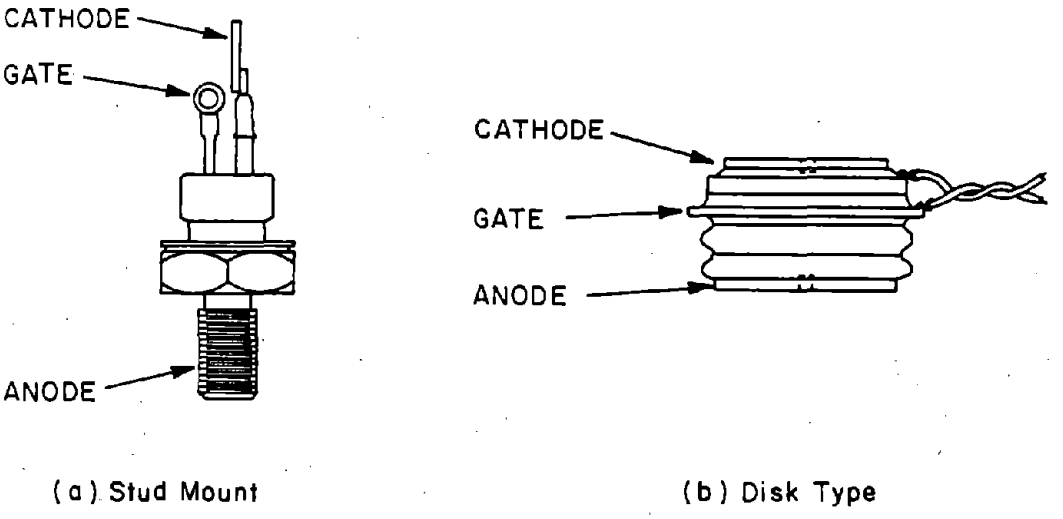

Figure 12.11. Common Thyristor Configurations.

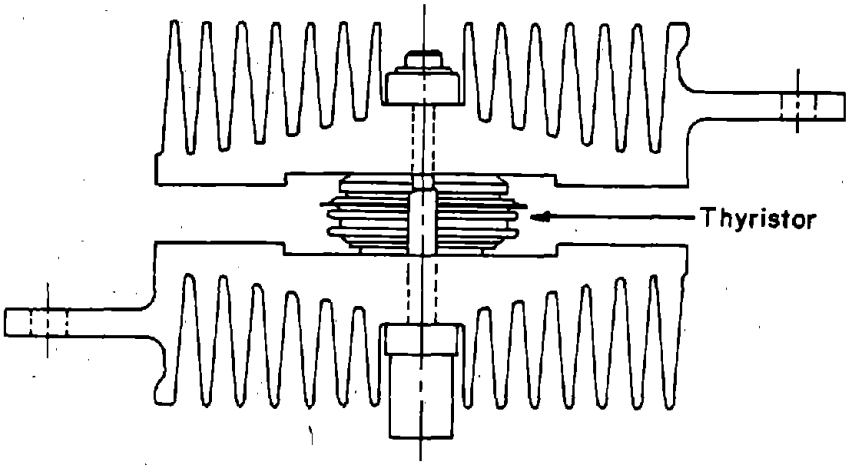

Figure 12.12. Heat Sinking of Disk-Type Thyristors.

The surface excavators that have available static control are usually limited to 20 cubic yards or less, most often they have a similar form to the conventional Ward-Leonard system (8,11). The motor-generator set is replaced by thyristors in a bridge configuration with feedback control. The change does improve operational performance, but it has a detrimental effect on the a-c distribution system to the machine (12).

High-amplitude voltage transients and the common high electrical-noise environment found on mine trolley systems have seriously hampered the adaptation of this technology to trolley locomotives (8). However, there has been some limited success with chopper control (10). It is interesting to note that the problems have been encountered on practically all solid-state equipment receiving trolley power.

AC-DC Equipment. An outstanding success of static control has been in underground a-c face equipment. Termed the "a-c/d-c drive," the design maximizes power-distribution efficiency, uses the traction advantages of d-c series-wound motors, and has the improved performance available from thyristor control (7). Diagrams for systems used on shuttle cars and continuous miners are given in Figures 12.13 and 12.14. In both, a-c power is supplied through the trailing cable. After the main circuit breaker, a-c is supplied through conventional contactors to the pump-conveyor (hydraulic) motor, the cutting motors, and an on-board three-phase transformer. The transformer secondary supplies a-c for the d-c system, involving thyristor control to motor.

Alternating-Current Equipment. It has already been mentioned that full variable speed cannot be accomplished with straight current or voltage control on a-c induction motors. However, as motor speed is a function of the applied power frequency, speed control can be obtained by varying this frequency (3). A simple representation for one type of variable-frequency a-c drive is shown in Figure 12.15. The incoming a-c is rectified then filtered by capacitance to provide a high-quality d-c. An inverter then converts the d-c back to a-c. (An elementary inverter circuit is illustrated in Figure 12.16.) By controlled switching of the thyristors, an alternating square-wave signal of the desired frequency can result. This can be directly used, or filtered (e.g., the transformer in Figure 12.16) to provide a sinusoid. Three-phase a-c output can be obtained by employing three inverters and firing the inverters so 120° timing is available.

A direct adaptation of this technique has been used on production mining shovels; Figure 12.17 is a block diagram (11). Better performance is reportedly obtained over Ward-Leonard d-c

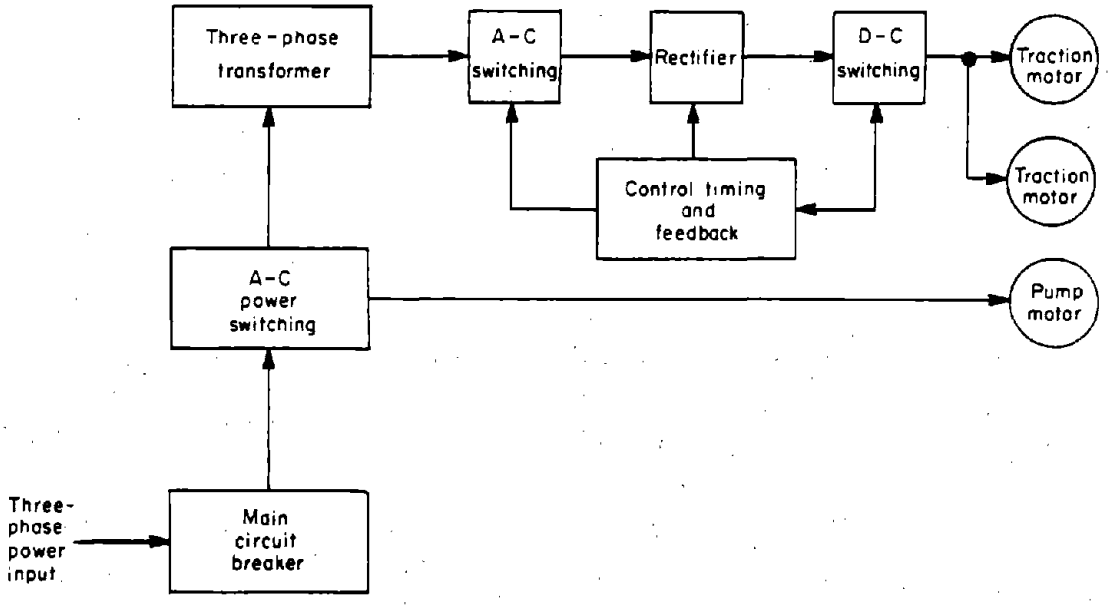

Figure 12.13. Block Diagram of AC-DC Shuttle Car.

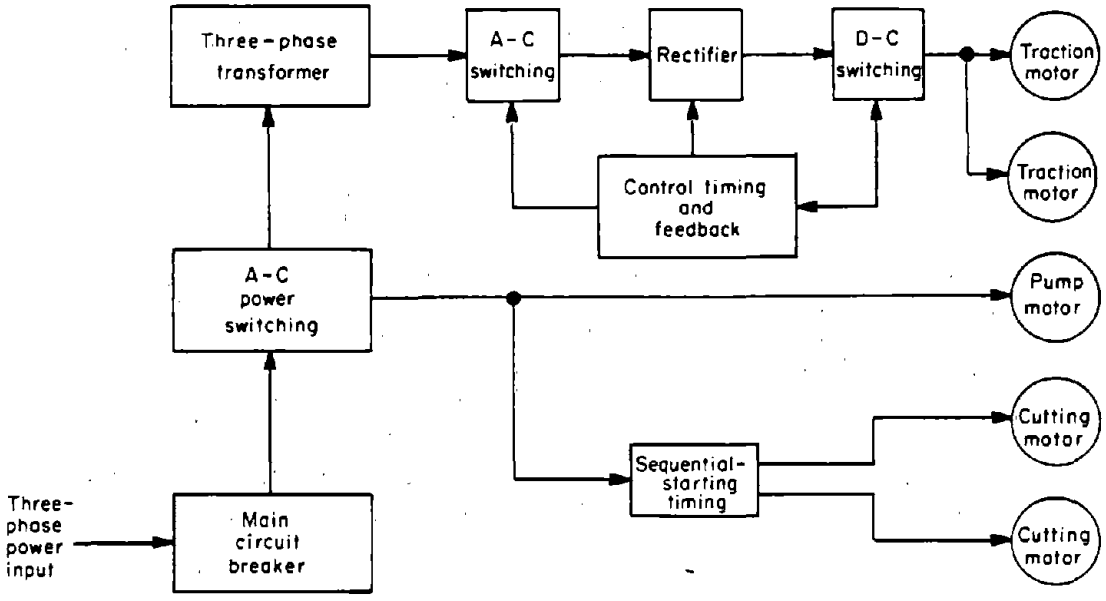

Figure 12.14. Block Diagram of AC-DC Continuous Miner.

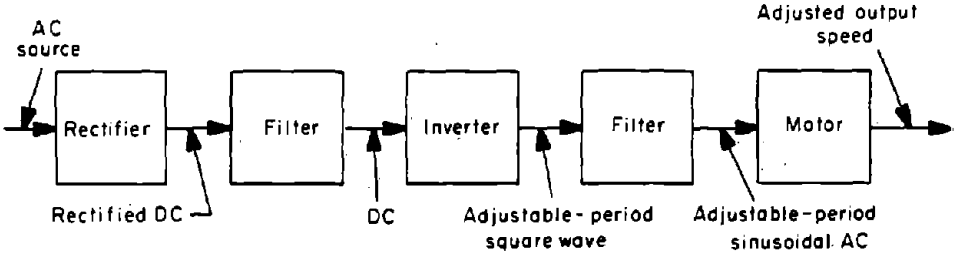

Figure 12.15. A Simple Variable-Frequency Control.

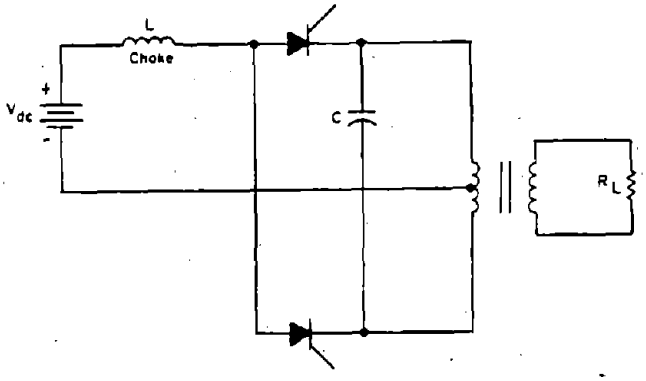

Figure 12.16. An Elementary Inverter Circuit.

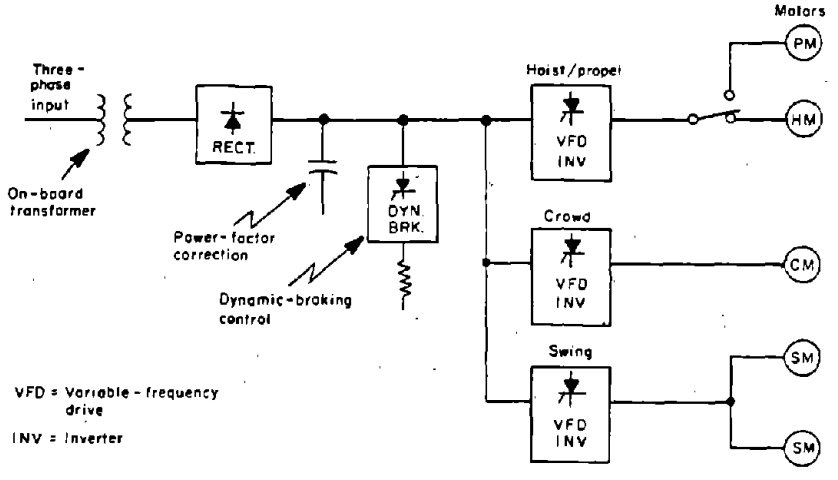

Figure 12.17. Use of Variable-Frequency Drive on a Production Mining Shovel.

motor control, as machine characteristics are a function of the power electronics and not the motor.

Another application of thyristor control of a-c induction motors is in conveyor starters. This, however, deserves a separate chapter section.

12.2-3 Belt-Convevor Static Starters

General. In the past, the principal drive motor used for belt conveyors has been the wound-rotor induction. For this, the belt starter is essentially a bank of resistors, which are switched in when the belt is started (see Chapter 5). The resistors are then switched out to allow the belt to come up to speed. The resulting acceleration is thus in a series of steps, corresponding to each selected torque-speed characteristic of the motor.

On the other hand, solid-state-started squirrel-cage induction motors provide controlled motor acceleration. As the steps are eliminated, the following advantages are gained:

1. reduced belt and spliced tears;
2. decreased stress on mechanical power-transmission components, resulting in increased life;
3. elimination of some mechanical components, such as extensive gear cranes, clutches, and so on;
4. elimination of belt slippage, thereby reducing belt burns and removing impulse stresses;
5. custom design for special applications; and
6. increased motor life and reduced maintenance.

All these have been validated by experience.

Control Systems. All three-phase solid-state belt starters in common use today employ reduced-voltage motor starting. The technique is coupled to the principle that torque developed at the motor shaft is proportional to both the rotor current and the square of the terminal voltage. Therefore, if the terminal voltage is reduced to a given level to correspond with a desired torque value, then motor current is limited. From this concept comes the term, "current-limited" starter, which is often used in place of static or solid-state.

Thyristors are used to control power turn-on to the a-c motor. Firing control is by one of two means: straight current or tachometer (6,12,13).

In basic current-regulated types (See Figure 12.18), feedback control is used to compare an adjustable reference signal (the "current-limit" setting) with a signal that represents motor current. Motor current is monitored by current transformers, preferably in all three phases (6). The torque being developed

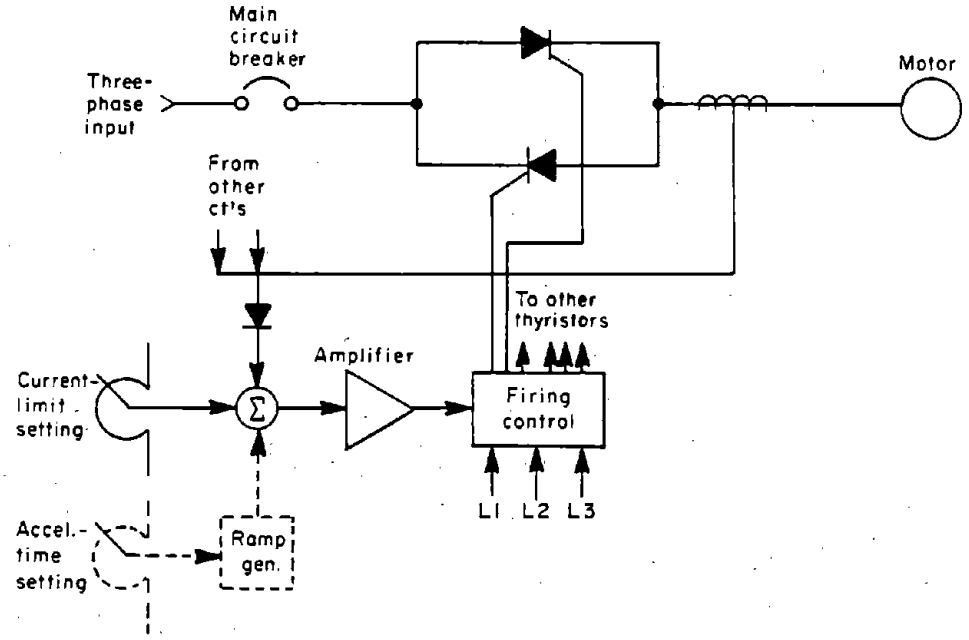

Figure 12.18. Simplified Diagram of Current-Regulated Static Belt Starter.

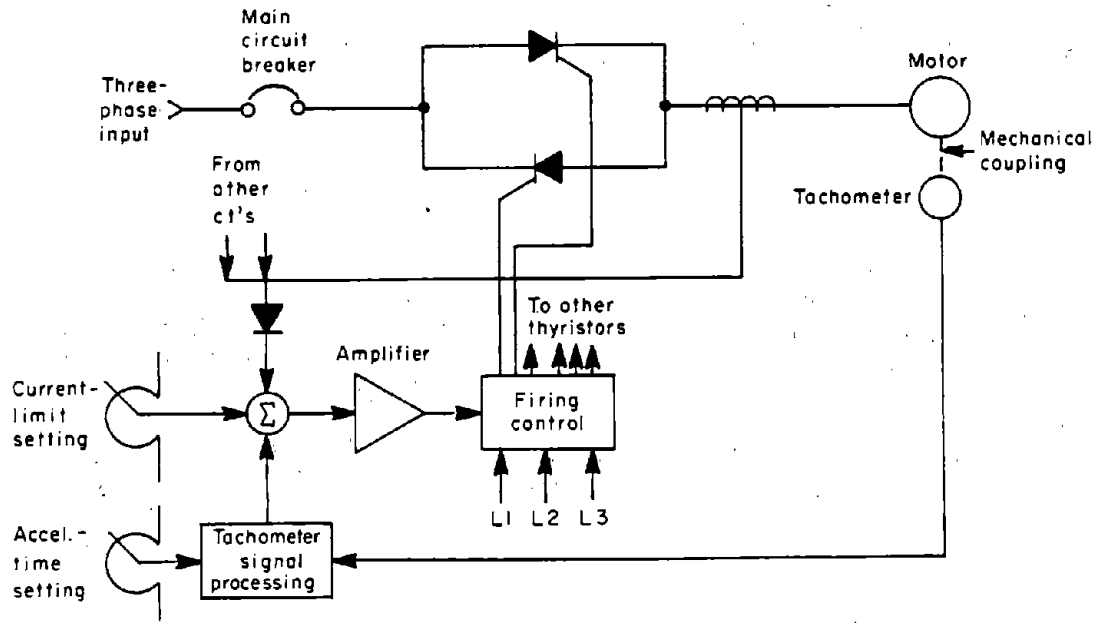

Figure 12.19. Simplified Diagram of Tachometer-Controlled Static Belt Starter.

at the motor shaft is then computed by the starter circuitry from the current being used. The current is thus limited to a preset value by the thyristors. The resulting belt acceleration is nonlinear (almost logarithmic) and is a function of belt load. When the belt is empty, a full-voltage start can occur.

The full-voltage-start problem can be removed with the addition of a second reference supplied to the control-system summing point. Providing an adjustable ramped-reference signal (usually a linearly increasing voltage with time), the starter circuitry now restricts motor current to rise over a preselected time period ("acceleration-time setting") to the current-limit setting. However, motor acceleration is still non-linear.

With tachometer control, a tachometer is placed on the motor shaft, and its output either substitutes or augments the current-transformer signals. (See Figure 12.19.) The shaft speed is now directly compared with the adjustable ramped reference. Motor voltage is adjusted to limit current, such that a specified rate of acceleration is obtained. As a result, belt acceleration is linear and rather constant regardless of load (belt empty or full). In some starters, controlled deceleration is also available, but the deceleration time must be longer than that for the drive mechanical inertia.

Either control system gives the same basic static-starter advantages given previously. Tachometer types have a special advantage with installations where belt length is constantly changed, such as for panel belts. Here, little or no adjustment of the starter circuitry is necessary. With current-regulator control only, adjustment is required for any conveyor change, but these types have an advantage of simplicity. Interestingly, most manufacturers are presently providing both options in their equipment.

The start-stop circuitry is often relay controlled. (This is not shown in Figures 12.18 and 12.19.) When off, relay contacts clamp the thyristor gates and the input of the control-system amplifier. Under a start command, the relay contacts sequentially unclamp the gates then the amplifier, allowing the control system to start the acceleration cycle (6). Because the thyristors do not physically disconnect the load, a circuit breaker is also provided on the incoming line for this purpose as well as for short-circuit protection.

Thyristor Configurations. Both thyristor configurations, unidirectional and bidirectional, are available depending upon the starter manufacturer. There are difficulties with unidirectional control.

A disadvantage of unidirectional control is the higher harmonic content that it adds to line current when in the control mode (see Figure 12.4b). When applied to static induction-motor starters, this does create excess heating but mainly during acceleration. If sufficient cooling time is allowed between starts and acceleration times are minimized, the heating problem is reduced considerably but not eliminated (13).

Three-phase application of the unidirectional system does negate most of the d-c component problems but, through slight phase unbalances, some d-c can still remain. Some high-power-factor, high-efficiency motors do have difficulty with any d-c components (8). The main problem with unidirectional control, however, is allowing d-c to flow in the motor (13). During a motor ground fault, the diodes can rectify current, and d-c can flow through the grounding resistor and grounding conductor, not being detected by the zero-sequence ground-fault relaying. Thyristor failures are rare but are always in the shorted mode. If thyristor fusing is not available, there exists a low-impedance path for d-c through the motor windings and the other two diodes. Both these cases are problems whether the starter is on or off.

With the harmonic and d-c difficulties presented by the alternative, it appears that bidirectional control is better even with its additional cost. Some other advantages are gained (8).

1. Two thyristors are always in series from phase to phase. Less stress is given per thyristor by transient and long-term overvoltages.
2. Because of symmetry, smoother control is provided under varying conditions.
3. Motor windings and cable power conductors are near neutral potential when the thyristors are off.

Firing Control. When discussing the basics of thyristors, a single gate pulse was shown to fire the device (e.g., Figure 12.3). However, a single gate pulse may not fire the thyristor for many reasons, including low ambient temperature, low line voltage, or old devices (8). Two firing systems overcome this problem: "multi-pulse" and "sustained-pulse" firing (8,13). Often, a pulse transformer is used in the multi-pulse system for isolation between the power circuit and control circuit. Numerous pulses, each capable of turning the thyristor on, are applied to the gate to keep the device on during its intended conduction period. The other technique, also termed the "d-c firing system," is considered the best firing circuit (also the most expensive). Here, a high-level initial pulse is followed by a sustained lower value of direct current (above the minimum gate-current value) through the conduction period. Isolation between control and power circuits is obtained with standard transformers and photo-isolators. The advantages of the sustained-pulse are

two-fold. First, the high initial gate current floods the conduction region of the thyristor and turns it on completely. Thus, the firing circuit gives the largest margin of turn-on signal. Second, after the device is conducting, the sustained pulse keeps it on even if the anode-to-cathode current approaches zero. This prevents thyristor turn off during the critical end of the conduction cycle. These two advantages allow the use of "off-the-shelf" thyristors, even under the most adverse turn-on conditions.

Motors. Both NEMA B and C designs are recommended by manufacturers with their static starters. The worries of selecting a suitable motor and motor characteristics are four fold: to provide sufficient starting torque, to draw symmetrical line current with minimum disturbance to other equipment, to optimize the thyristor characteristics, and to provide an acceptable stress level on motor insulation under any condition (8). In terms of characteristics, NEMA B appears to be a good match for tachometer (or linear-acceleration) control because of its greater locked-rotor time, and NEMA C seems best suited for current-regulated applications from its greater starting torque at a given current (12). However, the main consideration is thermal because the motor must accelerate to full speed for normal operation. Energy continues to be stored in the motor until the internal-fan velocity can dissipate the heat faster than it is generated. Accordingly, NEMA C motors are often recommended for both control schemes because less energy output is needed to provide the same output starting torque (8).

Some motor manufacturers are producing squirrel-cage machines specifically designed for solid-state starting. They have higher quality insulation, larger fans, and are built on a larger frame per given horsepower. These motors can have energy-in/heat-out balance at 75% of full speed, where the standard motor can be as high as 90% of full speed (8).

Experience has shown that conventional thermal-overload relays do not provide adequate protection during the long starting times caused by static control (6,14). Overtemperature-detection devices installed in the motor are the best way to afford thermal protection. Of these, solid-state temperature sensors, internally installed in the motor windings, with a load-current-detection backup appear to provide the best technique to use (6).

Thyristor Ratings. Standard practice is to select a thyristor voltage rating at 2.5 times the nominal phase-to-phase system voltage. For bidirectional control, this is quite adequate considering the 5-pu utilization transients discussed in Chapter 10. However, the thyristors are a source of abnormal transient overvoltages by themselves, and some engineers prefer to use a device voltage rating no less than 3 or 3.5 times the system voltage (8,13).

Calculation of the required thyristor continuous-current rating from the load current should be easy if the thermal properties of the heat sink are known. Yet, during starting, which is the worst-stress case, the device is called upon to deliver much more current. The conventional approach for overload protection of the thyristor is a 30-s (overload) rating of 300% continuous current. Several engineers, however, do not believe this adequate because the induction-motor starting currents may be as high as 6 to 8 times the running current. Accordingly, certain manufacturers have selected thyristors with 300% of the continuous-current requirements and a 30-s overload rating at 500%. Others feel that it is better to have an overload rating based on horse-power or 25 s at 600% or 100 s at 300% of continuous current (8). Thus the thyristor current-rating selection is not a straightforward matter, and special attention is sometimes required for individual cases (13).

Special Thyristor Protection. Special attention must be paid to four protection areas in order to ensure thyristor life: short-circuit or current-surge, dv/dt, transient overvoltage, and di/dt. A typical protection arrangement is given in Figure 12.20.

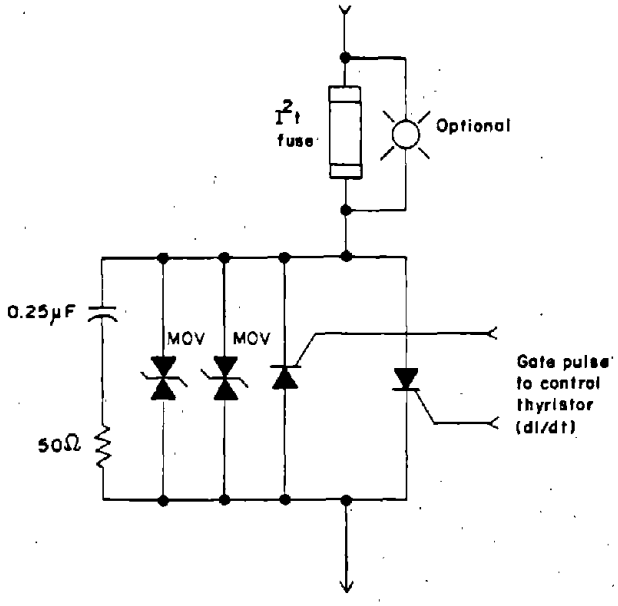

Figure 12.20. Thyristor Protection for Static Belt Starters.

Some short-circuit protection is afforded by oversizing (300%) the continuous-current rating. However, experience has shown that additional protection with semiconductor-protection or I^2t fuses is necessary with one fuse in series with each device. The fuse continuous-current rating is matched to that of the thyristor, but the I^2t (let-through energy) rating must be less than the thyristor I^2t capability. Even though these fuses are expensive, the replacement costs for thyristors are even more so. (There are instances where the thyristor continuous-current rating is set at 150% of needed, then the I^2t fuse is matched (8). However, this closeness can lead to nuisance fuse activations, especially during acceleration.)

A high rate of forward-voltage increase can turn a thyristor on, even with a zero gate current (1). Inductive loads, such as induction-motor belt drives, can present dv/dt problems (13). The common solution is RC snubber networks across each pair of devices as in Figure 12.20. Typical values for R_s and C_s are 50 Ω and 0.25 μF, but values must be selected so the dv/dt allowed is less than the minimum specific by the device (typically around 100 V/μs).

To assure the transient overvoltage does not destroy a thyristor, metal-oxide varistors (MOV) across each device are at times specified. The maximum crest allowed by the MOV is coordinated with the maximum voltage rating of the thyristor, allowing the usual 20% safety factor.

A large rate of rise of anode current (di/dt), during device turn-on, can cause only a small portion of the thyristor to conduct. Due to the high current density, a local hot spot can occur in the vicinity of the gate connection with sufficient heating to cause thyristor failure (1). A method of causing a rapid spread of the conduction area, and thus minimizing pinpoint conduction, is applying a fast-rising gate-pulse current with a crest higher than the minimum value specified for turn-on (1,13).

12.2-4 Motor-Control Summary

The preceding paragraphs have not only had the purpose of exposing the reader to the basics of solid-state motor control but also to the special worries of applying static-starter concepts to mine belt conveyors. This is one firm example of where technology has benefited the industry. Even with the increased internal complexity, the end result is an overall increase of the belt-conveyor system reliability.

12.3 Static Protective Relaying[1]

12.3-1 General

The definition that most engineers ascribe to the term "relay" may be expressed as (15):

> "an electrically-controlled, usually two-state, device that opens and closes electrical contacts to effect the operation of other devices in the same or another electric circuit."

Historically, one important relay use has been the protection of electric circuits and people from electrical hazards. The operation of an electromagnetic protective relay has been presented in Chapter 8 but is again illustrated in Figure 12.21 (16). This particular relay uses two actuating quantities (voltage and current) which directly effect the status of the relay contacts. Whenever current and/or voltage exceed a predetermined level, the current sensor and/or voltage sensor (i.e., current transformer and/or potential transformer, respectively) outputs cause the relay to close its contacts through electromagnetic attraction or electromagnetic induction. These closed contacts permit current to flow through the trip coil, tripping the circuit breaker. Electromagnetic-attraction relays in common use are the solenoid, clapper, and polar types (17). The typical electromagnetic-induction relay is the induction disk (17).

The basic idea in the design of solid-state relays (again also called "static" relays) is to replace the mechanical contact device with a solid-state device. The solid-state device is inserted in the trip-coil circuit and controlled by the sensor circuit. When unactuated, the solid-state device acts as a very large resistance in the trip-coil circuit, limiting the current through the trip coil to a very small value (known as leakage current) which is incapable of tripping the associated circuit breaker. When actuated, the solid-state device acts as a very small resistance which allows ample trip-coil current, thus tripping the circuit breaker. The solid-state devices which are commonly used are the transistor, thyristor, and triac.

12.3-2 Operation of Simplified Solid-State and Hybrid Relays

Transistor. The electromagnetic relay of Figure 12.21 is represented schematically in Figure 12.22, where the current and voltage input have been replaced with a manual push button,

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[1] This chapter section was written for the report by D.J. Tylavsky, Instructor of Electrical Engineering, The Pennsylvania State University, and has been edited by the author.

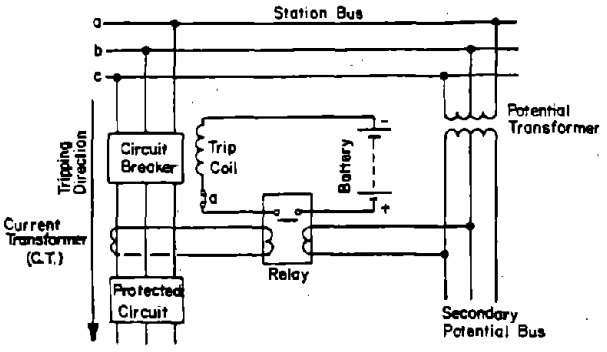

Figure 12.21. Protective-Relay Connection.

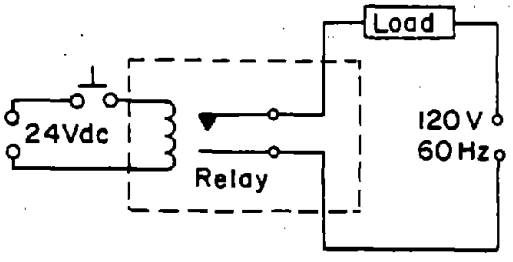

Figure 12.22. A Simple Electromagnetic Relay.

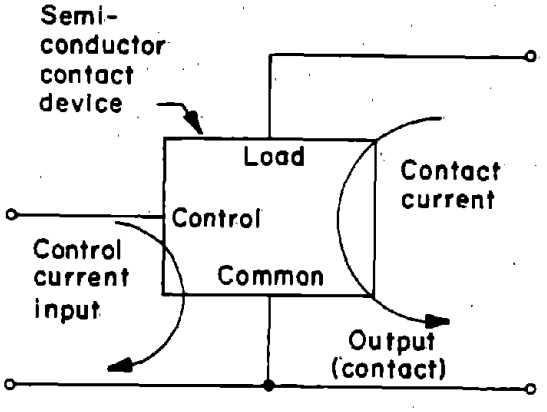

Figure 12.23. A Simple Transistor Relay.

and the trip coil (i.e., load) circuit is supplied with an 120-V, 60-Hz power source. The static relay differs from this by replacing the contents of the dashed box of Figure 12.22 with the semiconductor device schematically shown in Figure 12.23 (18). The load current now flows through the common terminal of the semiconductor device which is common to the trip (contact) and sensor (control) circuits.

If the static device is a npn transistor, the circuit of Figure 12.24a results. As the transistor is a current-controlled device, if zero input (control) voltage is applied to the transistor base, no current will flow into the base. Since base current is required for current flow from collector to emitter, no current will pass through the load. Hence, the contact-circuit voltage supply will not be dropped across the load. The voltage must therefore be across the collector-emitter terminals of the transistor. A positive input voltage applied to the transistor base causes a positive current to flow into the base. This base current is the controlling factor which permits a large collector-to-emitter current to flow through the transistor. When sufficient base (control) current is supplied, the collector current will increase until essentially all contact-circuit voltage is across the trip coil (load). Thus the switching characteristics of Figure 12.24b are obtained.

A drawback to the circuit in Figure 12.24a is the lack of electrical isolation between the control and trip circuits. One isolation method is to use the photon-coupler circuit shown in Figure 12.25 (18). The transistor performs the same function as that of Figure 12.24a except that it is light-controlled with a high-intensity light (from the LED) acting as a large base current. This light impinges on the phototransistor base region, allowing current to flow from collector-to-emitter. Without an input to the LED, no light is produced and consequently no collector-to-emitter current flows.

Thyristor. Replacing the transistor with a thyristor results in the circuit of Figure 12.26 (18). The operation of this device has been described earlier in the chapter; thus the operation here should be clear.

Triac. The triac, which is a contraction for triode a-c semiconductor, is a bidirectional solid-state device that acts like two thyristors connected back-to-back, as shown in Figure 12.4a. The triac accomplishes this operation in one solid-state structure with only one gate control, as shown in Figure 12.27a. The load-voltage characteristics shown in Figure 12.27b are very much like those exhibited by the thyristor. The single structure has heat-dissipation limitations, restricting the triac to small-current applications (1).

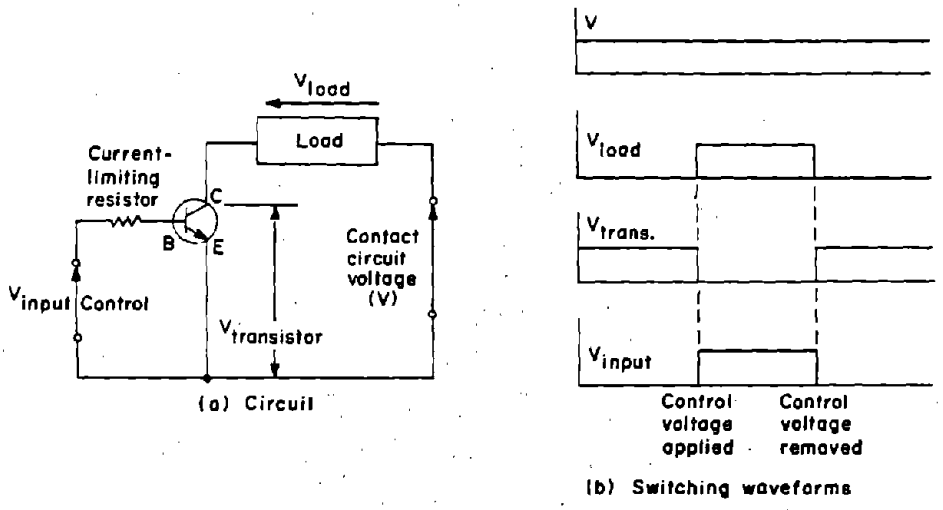

Figure 12.24. A Transistor Used as a Relay.

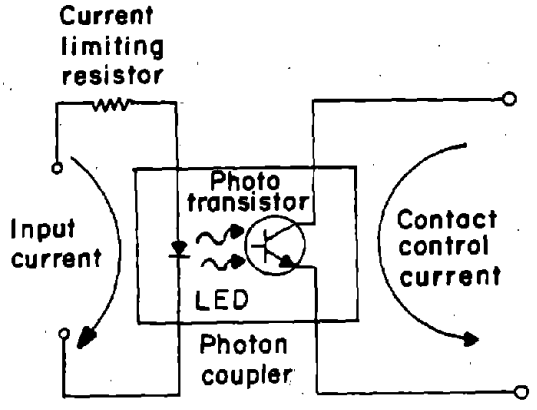

Figure 12.25. Optical Transistor as a Relay.

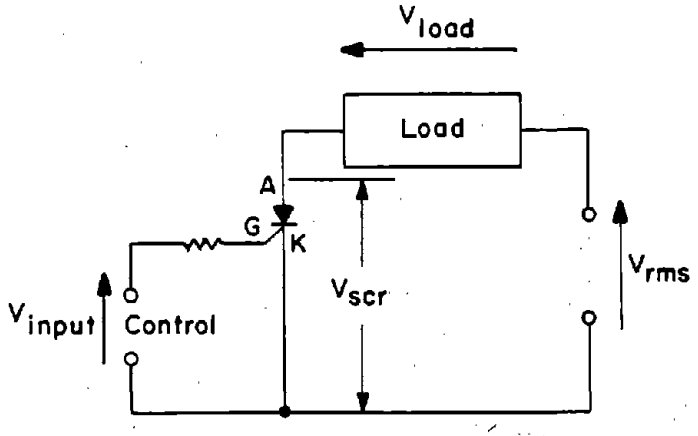

Figure 12.26. A Thyristor Used as a Relay.

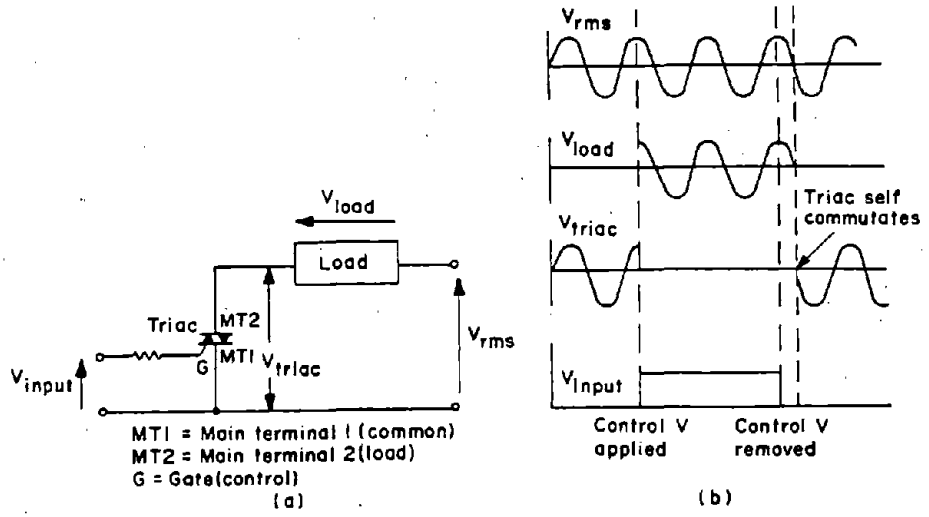

Figure 12.27. A Triac Used as a Relay.

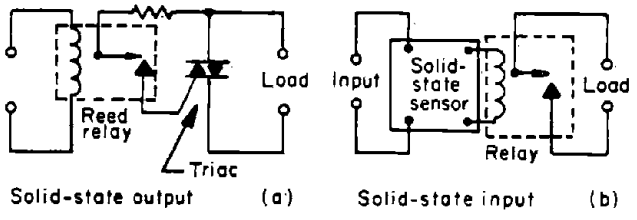

Figure 12.28. Hybrid Static Relays.

Hybrid. The output and input circuits of the triac and thyristor relays again have a common terminal between them. Where input-output isolation is required but a solid-state relay is also desired, hybrid relays are commonly used. Hybrid relays employ a reed relay in either the input or output stage, with a solid-state device functioning in the other stage. The hybrid relay shown in Figure 12.28a has the reed relay in the input stage (19). Switching the reed relay activates the gate-control input which fires the triac. The hybrid circuit of Figure 12.28b uses a solid-state input stage that can react to the power-network conditions. When a predetermined threshold is reached, the solid-state stage sends a current through the relay coil which will pick up the relay contacts.

Reed relays alone, when compared with static devices, have the advantages of simplicity, low cost, high reliability, and low maintenance. The best reed contacts are mercury wetted and provide bounce-free operation. Dry reed relays with heavy-duty silver contacts will carry 2 kW with a maximum of 30 A. They can withstand 5 G (50 m/s^2) when mounted correctly (6). The characteristics of electromagnetic (attraction and induction types), reed, transistor, and thyristor (including triac) relays are summarized in Table 12.1 to allow a quick comparison (20). This table shows that static relays out-perform electromagnetic relays in almost every row of comparison.

Before a detailed comparison of static and electromechanical relays can be made, it is necessary to determine whether static relays are capable of performing the same functions as electromechanical. The latter are usually classified according to the actuating quantity (see Chapter 8). The most common types used in mining are overcurrent, overvoltage, and undervoltage. The overcurrent or overvoltage relay is designed to trip when a predetermined current or voltage threshold value has been exceeded. The undervoltage relay is designed to trip whenever the measured voltage falls short of a predetermined level. Static relays can be designed to respond to these actuating quantities as well as many others (20).

Static-Relay Operation. As an example of static operation, consider the overcurrent relay shown in Figure 12.29. Alternating current from the current transformer (CT) is forced through a resistor which produces an alternating voltage across the input rectifier bridge. This voltage is rectified by the bridge and applied to the series-RC elements in the base-emitter circuit. When the capacitor voltage exceeds the battery voltage in the base-emitter circuit by a sufficient amount, the transistor begins to conduct current. Thus, current picks up the trip coil, tripping the circuit breaker. A time delay is achieved in this circuit by virtue of the series-RC time constant associated with the base-emitter circuit. The other actuating-quantity operations can be described in a similar manner.

Table 12.1. Typical Electromagnetic and Static Relay Characteristics.

PARAMETER	ELECTRO-MAGNETIC	REED	TRANSISTOR	THYRISTOR
Input	1 - 3 W	0.1 - 3 W	10 mW	40 mW
Switching Capacity	30 W	to 20 W	50 W	1200 W
Power Gain	10-30	7-200	5000	30,000
Cont. carrying current	5 A	1.0 A	1 A	5 A
Delay	10 ms	1-2 ms	20 μs	50 μs
No. of Contacts	to 6	to 6	one	one
Max. Operations	10^7	10^7	no limit	no limit
Ambient-temp. range	-5° - 70°C	-5° to 55°C	-20° to 100°C	-20° to 100°C
Affected by Vibration	yes	little	no	no
Affected by Corrosive Atmosphere	yes	no	no	no

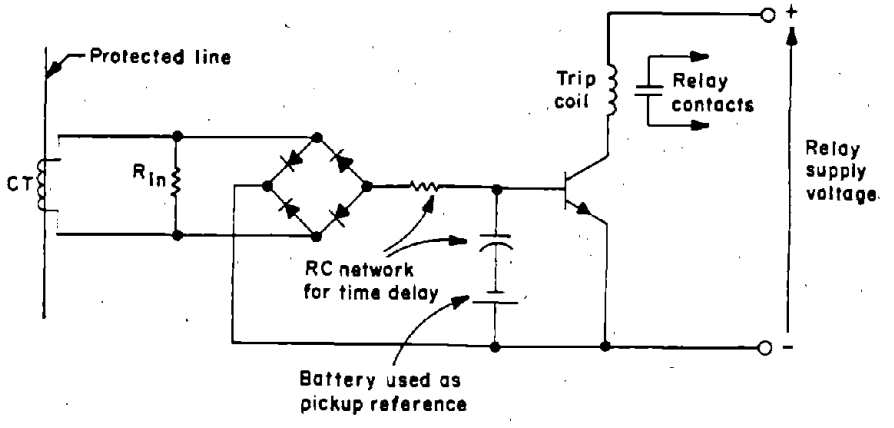

Figure 12.29. A Simple Overcurrent Static Relay.

12.3-3 Static and Electromechanical Relay Comparison

A large amount of literature has been devoted to the advantages and disadvantages of static relays. A detailed comparison which summarizes this literature can be made by discussing the advantages and disadvantages associated with static and electromechanical differences. These fall into the following categories. A listing of the references used follows each subject.

Speed. Table 12.1 shows that static relays are more than two orders of magnitude faster than electromechanical. This speed difference results from no mechanical motion in solid-state devices. High speed is advantageous because it gives the static relay the capability to turn on at zero-voltage crossing. This eliminates much radio-frequency interference (RFI) caused by capacitance switching or prestrike which is found with mechanical opening or closing of circuits with large capacitance values. Controlling RFI is important because digital circuits are easily affected by such interference. RFI is not present when static devices open since, for example, the thyristor and triac always turn off at zero current. The variability in closing and opening time precludes this type of control in electromechanical relays. Reset times are also much shorter for static. An extremely-inverse electromechanical relay may require 15 to 25 s to reset while a static relay resets in a few cycles (19-23,25).

Power Requirements. As evidenced by Table 12.1, static relays require far less input power than electromechanical. Input power delivered to any one static device may come from a wide range of voltages, including a-c and d-c. Electromechanical relays are normally limited in the voltage range they can accept for proper operation and require different coils for a-c and d-c operation. Static relays are capable of using a range of a-c and d-c power supplies in their tripping circuit (22,24).

Heat production in the solid-state relays results from the 1.0 to 1.5 V drop across the device in the on state. Thus, power consumption is limited by current required for tripping operation. Static relays used for protective-relaying applications usually require only 5 A, which is insufficient to produce enough heat for concern. Relays carrying between 5 and 25 A, usually referred to as power relays, may require auxiliary heat-sinks or special mounting arrangements. Above 25 A, a relay becomes a contactor, even though its function does not change. Thus, a static relay above 25 A is considered a solid-state contactor. Electromechanical relays require no heat sinking since, in an underrated condition, their contact resistance measures in the milliohm range (19,22,23).

Temperature. Typically, the maximum allowable continuous junction temperature for thyristors and triacs is 120°C, while electromechanical relays may be used in ambient temperatures that exceed this value. Temperature has little effect on the electromechanical characteristics; however, solid-state devices exhibit different characteristics at elevated temperatures. If subjected to these temperatures for long periods, their characteristics may even change permanently. Short-range thermal compensation can be accomplished by the use of thermistors in the design or, more commonly, differential-stage construction. The long-range effects of elevated temperature are guarded against by pre- and post-assembly heat soaking and testing (20,22,23).

Power Transient Response. Power transients refer to both transients on the power system being monitored and transients on the trip-circuit control power. Static relays are fast responding devices, and they rarely trip on power-system transients unless set to do so. Electromechanical relays, however, may trip erroneously due to either ratchetting or overtravel. As was discussed in Chapter 9, mechanical inertia causes overtravel of the induction-disk or induction-cup relay even after the actuating quantity has been removed. If the relay is not set properly, overtravel may cause the undesired tripping of a back-up relay, thus isolating a sound part of the power system being protected. Static relays have negligible overtravel, which precludes this type of error and makes possible the closer time settings of back-up relays for faster protection. Table 12.2 shows a comparison of the time-margin calculations for a back-up time-overcurrent relay. These calculations assume that the circuit breaker operates within three to eight cycles after pickup has been exceeded in the primary relay. A tolerance margin is allowed for the normal variation in the time-current curves. The smaller tolerance margin used in the minimum time calculation corresponds to setting the trip time by testing, while the larger margin assumes a time selected using the time-dial settings on the relay. For practical purposes, a 0.3-s margin is used for the electromechanical and a 0.2-s setting for the static relay, the difference being due to the negligible overtravel of the static device (25,26). "Ratchetting" is the accumulation of overtravel due to successive faults or sequential starting of motors. Static relays do not exhibit ratchetting due to their negligible overtravel and short resetting time (25).

Table 12.2. Time-Margin Comparison Between Electromechanical and Static Relays.

OPERATION	ELECTRO-MECHANICAL		SOLID-STATE	
	Min. (3 cy.)	Max. (8 cy.)	Min. (3 cy.)	Max. (8 cy.)
Breaker Time	0.05^5	to 0.13^5	0.05^5	to 0.13^5
Overtravel	0.10^5	to 0.10^5	0.01^5	to 0.01^5
Tolerance Margin	0.07^5	to 0.17^5	0.07^5	to 0.17^5
Total Time	0.22^5	to 0.40^5	0.13^5	to 0.31^5

Trip-circuit control-power transients may cause false operation of an electromechanical relay, if that device relies on the control power to keep it closed under normal circuit conditions. Voltage spikes on the control-power circuit also can cause unwanted tripping of static relays from two separate situations. If the transient is of sufficient magnitude, the solid-state device may break down, permitting conduction. This problem has, to a large extent, been overcome by triacs with blocking voltages of 800 to 1000 V and higher. However, if the voltage spike has a large rate of rise, the inherent capacitance of the thyristor or triac will allow a momentary current to flow (i.e., $i = Cdv/dt$). With sufficient magnitude this current will act as a gate current and turn on the device. Similar to that discussed for static belt-conveyor starters, this dv/dt problem is being overcome by including filters which are capable of absorbing the energy contained in these transients. On the other hand, dv/dt current is not a problem with electromechanical relays. Breakdown voltages of these relays are normally many times their operating voltage due to the air gap between the mechanical contacts (21-23,27).

Mechanical Nature. Electromechanical units have contacts that close mechanically and electrically, while static units only close electrically. The differences between these two relay types, due to the mechanical nature of electromechanical relays, can be described by comparing the relays when the contacts are open or closed, and when the contacts are in the act of opening and closing.

When electromechanical contacts are open, they are subject to the surrounding atmospheric conditions. Settling dust can act as an abrasive agent and cause premature contact failure. Chemical contaminants promote oxide-layer protection which also can increase the contact resistance. Static relays are not subject to environmental conditions since they are usually encapsulated in an epoxy for protection. However, the physical separation of the open contacts provides a very large resistance in the trip-coil circuit which cannot be matched by a solid-state device.

The leakage current that flows through the solid-state device when in a high-impedance state is on the order of 10 to 20 mA. Static relays should not be used where this current magnitude cannot be tolerated (18,21,22,27).

When electromechanical contacts are closed, they normally have only a few milliohms of resistance to control-power current, while thyristors or triacs provide a 1.0 to 1.5 V voltage drop. If the contacts become so degraded that contact resistance causes excessive heat generation, the contacts may weld closed. Moderate overloads, however, are tolerated for short periods. Solid-state relays, on the other hand, which are underrated for a particular application, will catastrophically fail. Where more than one contact closure is necessary, additional contacts are easy and inexpensive to add on electromechanical relays. Additional contacts can be added to static units only by a costly duplication of solid-state-circuitry portions. Similarly, interlocks and remote indicators are also more expensive. These features may be performed more economically by using digital logic on the control side of the static relay (19,21,22,27).

The input-output coupling of electromechanical relays provides a large isolation resistance between input and output. Hybrid relays can match this resistance, while straight static devices can approach a value of between 10^{10} and 10^{11} Ω if the photon-coupler isolator shown in Figure 12.25 is used.

Contacts are in the act of closing or opening for a small portion of their life. This movement, however, is the essense of the difference between static and electromechanical relays and ladens the latter with several drawbacks. High-inductive circuits will usually cause contact arcing during separation, and arcing will pit the contact surfaces, giving a higher value of contact resistance. Arcing is particularly unwanted in explosive environments. Closing contacts are subject to contact bounce which can also cause arcing. Arcing does not occur in static relays due to the nature of the solid-state contact (18,19,21, 22,27).

Testing relays by listening for contact closure is a simple method of inspection. Thus, early static units had no equivalent test procedure. More modern static relays have push-button testing that uses a target (flag) to signal proper operation (19,21,28).

Both moving and stationary mechanical contacts are subject to nuisance tripping due to external vibrations. This is especially bothersome with portable power equipment in mining. The mechanical nature and the large number of mechanical configurations makes electromechanical relay response difficult and costly to predict. The epoxy-resin covering, physical structure,

and structural arrangement of static relays make them much less susceptible to seismic disturbances (15,27).

Versatility. If there is any one characteristic, other than reliability, which should ensure an ever increasing role for static relays in the future, it is versatility. Time-current characteristics of the electromechanical relays shown in Chapter 8 can be duplicated. Further, static relays are providing functions which heretofore have been impossible with electromechanical. For instance, static directional-overcurrent relays are feasible to provide unique characteristics for improved operation (29). New static negative-sequence relays are capable of tripping at only 10% negative-sequence component content, where electromechanical relays have been limited to tripping levels of 18% negative-sequence component (25,30). Many static relays are compatible with digital logic (19). The capability and versatility of digital logic will push static relaying in directions not even considered. More will be said about this when the future of static relaying is discussed.

Current-Transformer Burden. Current-transformer burden has been defined as the external load applied to the secondary of a current transformer. As noted in Chapter 9, high CT burdens may cause core saturation due to the magnitude of the voltage developed at the CT secondary terminals. Saturation causes a burden reduction since, under deep saturation, the burden approaches its d-c resistive value. This burden change modifies the relay characteristics thus leaving the switching characteristics in question (16).

The possibility of CT saturation is of particular importance when low-ratio current transformers cause large secondary currents (i.e., large secondary voltages) and when large burdens from additional secondary loads cause large secondary voltages from even moderate secondary currents. Therefore, relays presenting lower burdens are clearly advantageous. Table 12.3 compares the burdens presented by a typical electromagnetic-induction overcurrent relay with its static counterpart when set on the minimum tap setting. The static-relay burden includes that of the relay current-measuring portion and the power-supply portion because the relay receives its operating power from the CT. The burden of the current-measuring portion of the static relay is actually much less than that for the electromechanical. It can be noted that the burden is greater than the electromechanical burden at pickup. Thus, the lower static burden has the advantages of allowing:

1. more relays to be connected in series,
2. the lowest tap of a multi-ratio CT to be used,
3. a step-up auxiliary CT to be used for greater sensitivity, and
4. more auxiliary burdens to be connected without CT saturation.

Table 12.3. Comparison of Induction-disk and Static Time-Overcurrent Relay Burdens to a Current Transformer.

Relay	Time-Overcurrent Relay Burdens (Magnitude of Impedance in Ohms)							
	(0.5–4) Range				(1.5–12) Range			
	1X	3X	10X	20X	1X	3X	10X	20X
Inverse Electromechanical*	22.0	10.80	5.00	3.66	1.45	0.65	0.32	0.24
Inverse Static	6.42	1.5	0.42	0.31	0.72	0.174	0.046	0.033
Very Inverse Electromechanical	4.15	4.15	2.90	2.20	0.59	0.58	0.40	0.25
Very Inverse Static	6.42	1.5	0.42	0.31	0.72	0.174	0.046	0.033
Extremely Inverse Electromechanical	1.60	1.60	1.60	1.60	0.17	0.17	0.17	0.17
Extremely Inverse Static	6.42	1.5	0.42	0.31	0.72	0.174	0.046	0.033

*The inverse induction-disk relay was not available with a range of 1.5 to 12 A. The burdens given in that column are for relay range of 2 to 16 A on the 2.0-A tap. Comparison is still possible because the static-relay burden is constant regardless of the tap setting.

Another advantage is that the low CT burden will permit the use, without saturation, of a less expensive CT which has no relay classification (26,28).

Accuracy. In general, static relays are more precise than their counterparts for reasons other than already mentioned. Common induction-disk relays are adjustable in 11 discrete tap settings in one range only. A typical static time-overcurrent relay can have an additional tap-block arrangement which permits numerous tap settings in more than one range. At low multiples of pickup, typically below 1.5 times pickup, induction-disk relays produce very low torque levels which can make time settings unpredictable, whereas static relays reportedly work reliably down to 1.1 multiples of pickup. The frequency content of the signal applied to a relay is another source of error. Static-relay response in the band of interest is uniform, while the induction-disk relays show a distinct variation of response with frequency. The uniformity of static-relay frequency response should make their performance more predictable (25,26).

Size. Static relays typically require about one-third the panel space required by electromechanical units.

Reliability. Perhaps the most important concern in deciding whether to use static relays over electromechanical is cost, since cost must include the overall price of owning and operating a relay. The biggest component of the ultimate cost of relay operation is that paid if relay failure causes lost production or destruction of distribution or utilization equipment. Thus, reliability is a major factor in the relay comparison. Total reliability relies on the combined reliability of each component, their assembly, and their electrical and mechanical operation when subjected to accidental electrical and environmental abuse. Electromechanical units have a very high reliability, less than 1.5% wrong operations due to relay failure or inaccuracies. It is believed that the overall static-relay reliability will eventually result in 0.5% wrong operations (20). The life expectancy of 10^7 operations is commonly claimed for electromechanical devices. The absence of moving parts in static units gives them a life expectancy that is theoretically unlimited (22,27,31).

Cost. Cost is the ultimate characteristic that will determine whether static relays can capture a major portion of the protective-relay market. Any cost analysis must at least take into account the cost of the maintenance, replacement, elimination of RFI, explosion and corrosion resistances, power-system down-time, accessibility of location, safety, reliability, and unit price. Only when all of these factors have been considered can a valid comparison be made between static and electromechanical relays (19).

The unit cost of static units is currently higher. Maintenance and replacement cost is also higher since boards covered with epoxy resin are not usually repairable and must be replaced. This cost, however, is only one factor in an overall cost analysis.

12.3-4 Mining Applications.

The most outstanding application of solid-state relaying to mining has been in ground-check monitoring, especially when connected to portable or mobile face equipment. As the success of these devices has been covered in Chapter 8, nothing more will be said here.

Static protection relays have been applied successfully in U.S. mines for the following common a-c distribution areas (32,33):

1. phase short circuit and overload (device 50/51),
2. undervoltage (device 27),
3. phase loss and phase sequence (device 47)
4. zero-sequence ground fault (devices 50G and 51G), and
5. grounding-resistor overvoltage (device 59G).

As was anticipated, these applications had improvements over the use of electromechanical devices: greater environmental resistance, easier adjustment and testing, more sensitive ground-fault protection, and lower maintenance (33).

Of all the kinds of protection that can be provided by static devices, the use of zero-sequence relaying in high-voltage resistance-grounded systems is likely to give the most benefit to the mining industry. The increased sensitivity and decreased burden should remove many of the problems that were covered in Chapters 8 and 9. The other major distribution protective-relaying concern is short circuit and overload, but induction-disk relays have been proven as effective and reliable here. Thus, any questions of cost and reliability must be answered before industry acceptance is possible.

A protection-relaying problem area that has plagued the mining industry for several years is faults on d-c trolley circuits. The situation can be divided into two main subjects (34).

1. For short-circuit protection, the d-c overcurrent relay (device 76) often works off a shunt. When using large locomotives, its pickup setting is on the order of 3000 to 4000 A. Testing with such large values to trip electromechanical relays can be dangerous and the resulting accuracy questionable.
2. Because normal load current can exceed 3000 A, conventional electromechanical relaying cannot detect arcing or high-impedance faults that can lead to a mine fire.

The best avenue to solve these problems appears to be through solid-state relaying. Static overcurrent relays afford safe, fast testing as required by federal regulations (36), with inexpensive hand-held devices (32,34). For item 2 above, many techniques are under demonstration at this writing (see Chapter 8).

When conventional molded-case circuit breakers are used for trailing-cable protection, the precision of short-circuit settings can always be questioned due to the mechanical nature of the trip elements. Overload adjustment is not available and requires (if possible) an exchange of thermal elements. Mining-duty molded-case circuit breakers are available with static trip elements for both short circuit and overload. Here, the conventional thermal-magnetic trip elements are replaced with current transformers and solid-state circuitry. The CT's proportionately reduce the line currents to a level that can be used as input to the solid-state circuitry. Breaker tripping is initiated when a low-power, flux-transfer shunt trip or UVR is energized from the output of the solid-state circuitry. The overload rating can be changed simply be changing a small rating plug on the front of the breaker. The instantaneous-trip range is specified as a multiple of the overload-current setting. Operation of the static trip elements has resulted in increased accuracy, reliability, and repeatability over their mechanical counterparts.

It is interesting to note that static relays are used extensively in the United Kingdom for overload, short-circuit, and ground-fault protection of distribution and utilization equipment in their mines (37). Two of their techniques deserve presentation: the sensitive earth-leakage system and the phase-sensitive short-circuit system.

Sensitive Earth-Leakage System. In an attempt to reduce the dangers of incentive arcing from damaged trailing cables, the National Coal Board of the United Kingdom developed the "Sensitive Earth-Leakage System" (SEL) for ground-fault protection (38). The system also substantially reduces the chance of an electrocution by limiting ground-fault currents to extremely low values (39).

A simplified diagram of the SEL system is shown in Figure 12.30. The neutral-grounding impedance limits the maximum ground-fault current to 750 mA. Fault detection is by the zero-sequence scheme (see Chapter 8), but a solid-state amplifier increases sensitivity to as low as 90 mA (versus 4 to 6 A with electromechanical). Currents below 90 mA are allowed to flow continuously, but currents up to 750 mA are permitted for about 0.02 s. To provide selectivity, a 0.4-s time delay is introduced at the main circuit breaker. The power factor of the neutral-grounding (earthing) impedance is normally specified from 0.65 to 0.75 to prevent limiting the current to a level that cannot be detected due to system capacitance. The circuit is simply a solid-state-amplified zero-sequence relay. Because of the high sensitivity, a grounded shield is placed over the CT to reduce electromagnetic interference that can cause nuisance tripping.

To prohibit the circuit from being reset until a ground-fault is cleared, the SEL system has an auxiliary circuit connected to a second winding on the CT. Upon ground-fault pickup, an auxiliary contact is closed by the relay and causes the auxiliary CT winding to be energized. This induces a voltage on the other CT winding which creates a lockout.

The other ground-fault method in use in the United Kingdom is the "multi-point" SEL. Here a "false-neutral transformer," which is impedance grounded, replaces the zero-sequence transformer. The source-transformer secondary is isolated from ground across a spark gap (see Figure 12.31). When a ground-fault occurs, a potential is developed across the wye-connected impedances (false-neutral transformer), and current flows through the grounding impedance. The voltage developed across the impedance is amplified, causing the relay to pick up. As with the preceding system, an auxiliary "change-over" contact provides lockout until the fault is cleared.

The multi-point system, however, has several disadvantages. The technique is indiscriminate and limits the number of units which can be utilized at a gate-box end (utilization center). For a 550-V system, the maximum number of units is 37 and for 1100-V systems, 18 units. Ground-fault current is again limited to 750 mA, but this time all relays see the fault current produced and will pick up. This is a definite drawback, even though the unfaulted units may be reset at once. The faulted unit will be locked out. In the United Kingdom, automatic circuit-breaker resetting is allowed on this system to restore operation to the unaffected portion.

The sensitivity of the multi-point system is excellent. Pickup is about 3 mA and 6 mA on 550-V and 1100-V systems, respectively. The high sensitivity is desirable for the case of the two simultaneous ground-faults on separate phases (39).

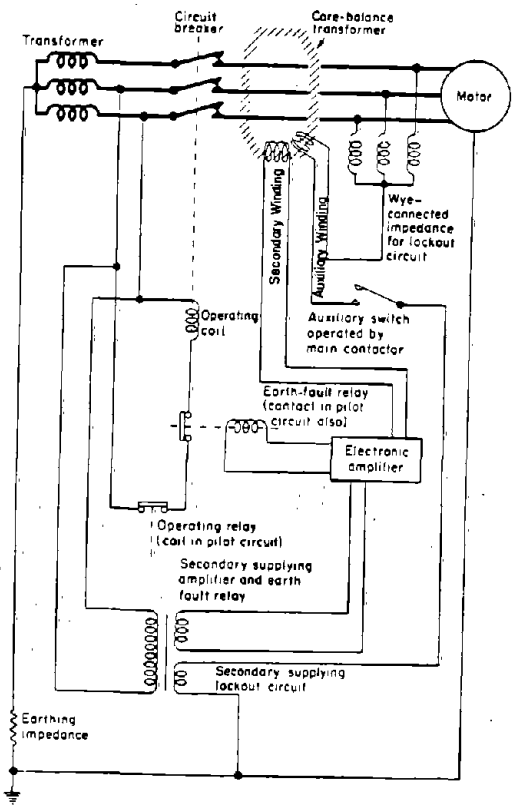

Figure 12.30. Simplified Sketch of the SEL System.

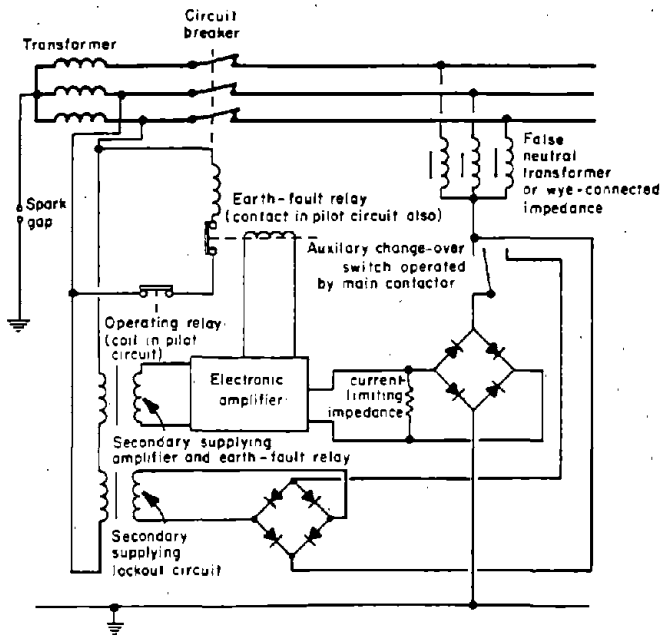

Figure 12.31. Simplified Sketch of the Multi-point SEL System.

In this case, with a motor at full load, only 50% of system voltage is available to drive the ground-fault current.

Phase-Sensitive Short-Circuit Protection. Because both motor starting and fault conditions result in large current flows of comparable magnitude, it is often difficult to adjust standard relays to differentiate between the two and provide interruption only when a fault occurs. "Phase-sensitive" relaying is able to distinguish between these two conditions by sensing the phase angle between the current and voltage. It utilizes the fact that the induction-motor power factor at starting is approximately 0.5, while typical faults have about 0.9 (40). Actual in-mine use of the method has been very promising, revealing that nuisance tripping on motor starting can be eliminated while short-circuit trip settings can be reduced to half the value of those required for standard instantaneous relays (37). Two techniques can be used to provide the protection: diode bridge and an electronic comparator.

The circuit shown in Figure 12.32 is a simplified diagram of one phase of a three-phase phase-sensitive system employing a switching diode bridge. In this circuit, the current transformer and diodes act as a standard full-wave bridge-rectifier circuit to create the voltage across the bridge (V_b). The potential-transformer secondary may be modeled as the secondary of an ideal transformer in series with a resistor, as shown in Figure 12.33. The voltage in the secondary of the potential transformer, V_v, will be a sinusoid, and the resultant voltage across the transformer-secondary resistances V_r, is $V_b + V_v$. Current flow in this resistance will be proportional to V_r, as will the resultant current flowing through the current transformer and the load resistance R_L. The trip signal will then be the voltage appearing across R_L due to the current flowing through it. Thus, the trip signal ultimately is proportional to $V_v + V_b$.

If the voltage and current are in the phase, V_v and V_b are in phase, and they add in phase to produce V_{trip}. If V_b increases due to an increase in current flow, the peak value of V_{trip} will increase. The instantaneous-relay unit connected across R_L could be adjusted so tripping would occur when V_{trip} reaches a certain magnitude which corresponds to a short-circuit condition on the system. If the voltage and current are out of phase by 60° (0.5 power factor) relating to motor starting, V_{trip} is less than for the in-phase situation. Even if the current were increased significantly (as in motor starting), V_{trip} would still be lower than that produced by a system fault, and the instantaneous unit would not trip.

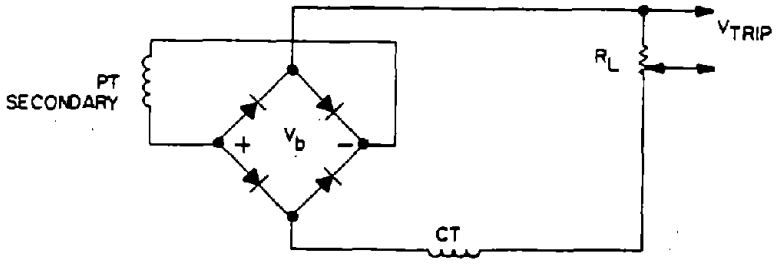

Figure 12.32. Diode-Bridge Phase-Sensitive Protection.

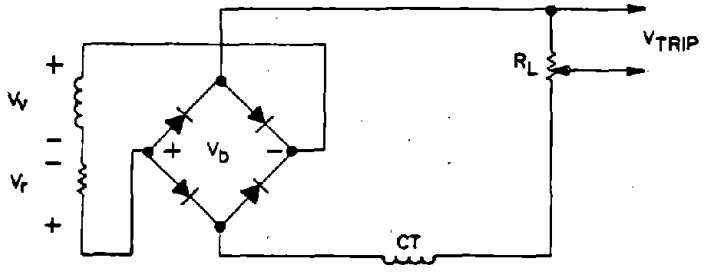

Figure 12.33. Equivalent Model of Figure 12.32.

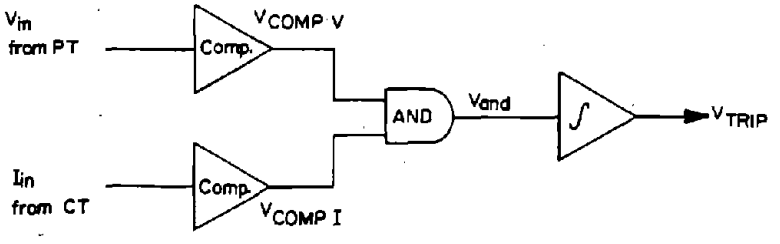

Figure 12.34. Electronic-Comparator Method of Phase-Sensitive Protection.

A block-diagram-comparator circuit, which could also be used to provide this protection, is shown in Figure 12.34. The voltage and current comparators will each output a "1" (high logic level) when their respective inputs are above a specific threshold level. The AND gate will then output a "1" as long as the outputs of both the current and voltage comparators remain high. This AND-gate output signal is then integrated by the integrator circuit as shown, causing V_{trip} to reach a level that would operate a circuit-interrupting device if the AND-gate output remained too high too long. The integrator can be designed with enough leakage so V_{trip} will not reach the tripping level during short-time intermittent overvoltages or overcurrents.

If the voltage and current are in phase and a high-current magnitude exists (a fault condition), both V and I are above the comparator threshold levels, causing the comparator outputs to be high during the voltage and current peaks. Moreover, the voltage and current are in phase so the AND-gate output is high during these peaks as well. The AND-gate output is integrated, and V_{trip} increases to the level where tripping occurs. It can be seen that normal current levels, even if they are in phase with the voltage, would not cause tripping because they would never cause the current-comparator output to reach a high state.

During motor starting, I and V are still above the comparator threshold levels, but they are out of phase, resulting in a narrower pulse at the output of the AND gate. Although the AND-gate output is integrated, the narrow pulse width allows the integrator to return V_{trip} to zero before the next pulse occurs. This prevents short-circuit tripping for a motor-starting condition on the system. (Indeed, a separate relaying circuit would still be necessary for overload protection.)

This new system-protection scheme, which can be implemented either electromechanically or electronically, promises to contribute in meeting both conflicting objectives of coordination: protection and selectivity. Tests have shown that electronic phase-sensitive protection tripped at much lower levels and in shorter times than standard short-circuit devices. While typical instantaneous relays may need a pickup setting of seven to ten times normal full-load current to prevent nuisance tripping on a motor start, it has been found that phase-sensitive relaying eliminates spurious tripping during motor start, even when the pick-up is as low as three times full-load current (40).

12.3-5 Solid-State Relays in the Future

The future development of static relays is indicated by many theoretical papers on the subject. Basically, new devices can be roughly grouped into three groups: continuous, digital-controlled continuous, and digital. Continuous relays are the present types in which the power system is sensed continuously and relaying activates from the continued existence of a malfunction. A digital-controlled continuous technique has been illustrated in Figure 12.34, but Figure 12.35 relates its use in timed-overcurrent relaying. The full-wave rectifier and CT continuously sense power-system operation. The particular relaying characteristics are provided by the function generator with time delay provided by the linear-ramp generator. The pickup-level and ramp-level detectors essentially function as digital control devices since they operate in a go or no-go manner (26).

Digital relays rely on discrete sampling of current and/or voltage waveforms, pushing this data through an algorithm and decision process which ultimately decides whether a relay is to be actuated. Perhaps the ultimate in digital relays of the future will use microprocessors distributed throughout the power system to analyze circuit conditions on a real-time basis. Each microprocessor could be responsible for making decisions for its system portion with control relinquished when demanded by a larger computer or when power-system conditions exist which are beyond the analytical capability of the particular microprocessor in question.

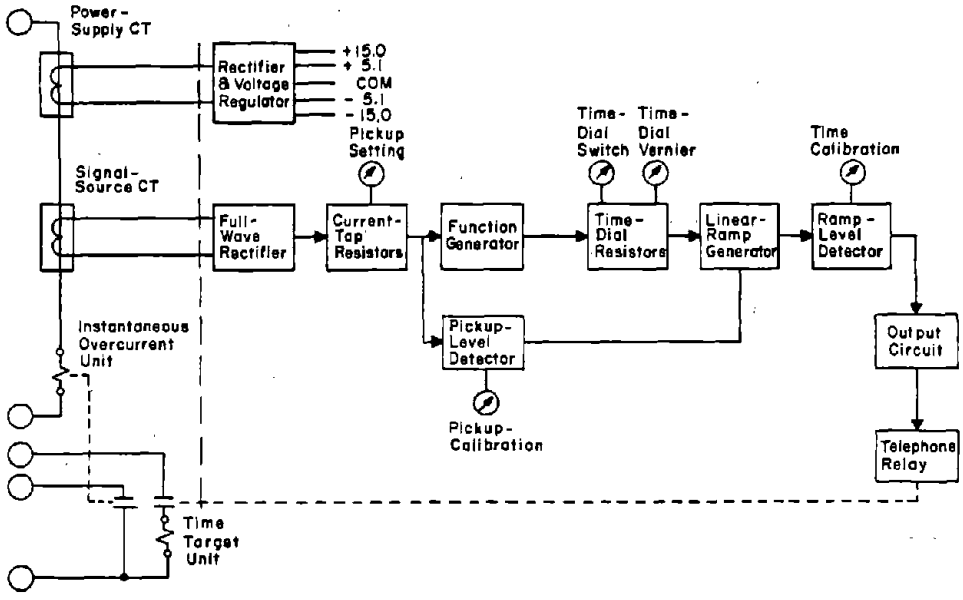

Figure 12.35. A Digital-Controlled-Continuous Static Relay Used for Timed Overcurrent.

12.4 Summary

The solid-state applications discussed here are a viable alternative to their electromechanical counterparts. Indeed with most features they are decidedly superior in performing conventional functions and unmatched in their capability to perform functions and exhibit characteristics which are, in some cases, otherwise impossible. A major drawback for static belt starters and relays is their cost, and the major factor in the cost breakdown is reliability. Belt starters have proved their desirability through a half decade of in-mine experience. However, the reliability for static relays is questionable because it has not been well documented to date, especially in mining. This problem is due to their recent introduction and the replacement of older with newer designs before life-test data could be compiled (20). Static relays presently occupy only a small portion of the protective-relaying market. Their main benefit to the mining industry today is decreased burden problems and increased sensitivity for zero-sequence relaying in resistance-grounded systems. Another contribution appears in solid-state tripping elements in molded-case circuit breakers. As the reliability becomes more fully documented and as reliability is increased to be competitive in terms of cost, static relays may take on a bigger role including overload and short-circuit protection.

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Chapter 13

BATTERIES AND BATTERY CHARGING

13.1 General

Although the storage battery had a variety of applications in the 1800's, successful use of the battery for traction purposes was not achieved until the turn of the twentieth century. Early mining batteries were used to power gathering locomotives and replaced mules to a certain extent in nongassy mines where open lights were used. From this start, the battery-powered vehicle has become an important part of many underground coal mines, both for rail and off-track haulage.

The first haulage applications had little concern for safety, but the storage-battery locomotive was soon recognized as having some important inherent safety advantages over trolley locomotives and cable-reel locomotives. As an advantage of batteries, Appleton (1) reported that one advantage of batteries is that the danger of starting a fire from a short circuit or an arc in a cable is removed. L. C. Ilsley (2) said of the battery locomotive:

> That its energy is self-contained and limited to the immediate zone of the locomotive is a safety factor of great importance. In the trolley type of equipment one necessarily uses the track return, and the danger zone from the return current may extend through the mine. Poor bonding or no bonding may force the return current back toward the face. A storage battery locomotive does not use or need the dangerous overhead trolley with its constant shock menace and fire hazard, and with the possibility of trolley or feeder circuits becoming a factor in the ignition of gas of coal-dust.

Storage batteries have had a relatively good underground safety record.

However, early battery locomotives had open controllers, open motors, weak battery covers, battery jars that were prone to breakage, and crude exposed wiring. To help correct these problems, the U.S. Bureau of Mines in 1919 issued Schedule 15, which set standards for permissible battery-locomotive equipment (3). (Chapter 14 covers the subject of permissible mining equipment.)

Even with this regulation in force, several incidents involving battery locomotives raised further questions concerning battery safety underground. For instance, a major mine explosion occurred in 1927 at Federal Number Three mine, Everettville, West Virginia, claiming the lives of 97 miners, and the resulting investigation traced the ignition to a battery locomotive (4). A report by

C.W. Owings (5) contained the following description of another incident:

> The only gathering locomotive approved by the Bureau of Mines is the storage-battery locomotive. The motormen at the _____ mine, referred to in my paper, have used both the storage-battery and this type (cable-reel) of locomotive; and their experiences in that gaseous mine is that the cable-reel locomotive is much safer than the storage-battery machine. The general superintendent of the mine told me of an occurrence that happened recently to one of their Government approved storage-battery locomotives, in its regular operation. One of the covers of the battery box, in some manner, had become dislodged, causing a short-circuit and flame in the battery box. The machine was then operating in a rib section giving off gas. The battery box, as we all know, cannot be enclosed and there is no way of shutting off the current. For that reason, the men were much alarmed, until one of the cable-reel locomotives was run up into the section and the other machine pulled it out into the intake air. The cable-reel permits the current to be instantly shut off in case of need from any cause. They feel that three years of comparative operation of these two types of equipment demonstrates that the cable-reel locomotive is much the safer machine in gas.

Owings examined the facts pertaining to both incidents and concluded that battery locomotives were relatively safer than the other available gathering-locomotive types. The Everettville explosion was created by a nonpermissible locomotive and could as easily have occurred from the use of other nonpermissible equipment. The second incident was later discovered to have resulted from a faulty cell that had accidentally been reversed. This caused the cell to emit hydrogen, which exploded and dislodged the box cover. Owings concluded that the occurrence was very rare, and that the risk of fire was greater when trailing cables were involved.

The shuttle car, introduced in 1938, was initially battery-powered. Cable-reel shuttle cars soon became much more popular than the battery cars, probably due to the low-capacity per unit weight of the batteries then available. In the United Kingdom, trackless battery-powered vehicles were widely felt to be unsafe. Explosions at Weetslade Colliery and Eppleton Colliery were the result of storage batteries (6). A consequence of these occurrences was twofold: battery-powered trackless vehicles were prohibited from nearly all British mines and the use of battery locomotives was restricted to types approved by the Minister.

In the United States, however, permissible battery-powered equipment is allowed inby the last open crosscut. Although not currently used to power shuttle cars, batteries have a variety of

other uses in coal mines and, because of several factors, there has been a recent increase in popularity of battery-powered vehicles. Some reasons follow.

The efficiency of batteries has been greatly improved in recent years. One prominent manufacturer reports a 70% increase in ampere-hours per cubic foot (Ah/ft^3) and a 39% increase in watt-hours/pound (Wh/lb) over earlier models (7). In addition, improvements in plate and grid design have increased the average service life of motive power batteries.

The trend in underground mining today is toward conveyor belts for coal transport, and rail systems for personnel and supply movement. Mines which have a-c face equipment and d-c tolley lines can be subject to problems such as nuisance tripping of a-c circuit breakers from stray d-c ground currents, which often result from poor track bonding, ineffective trolley-line insulators, or inadequate d-c to a-c ground-system isolation, are eliminated when batteries are used to power locomotives.

Regardless of the intermediate and main-line haulage methods, many operations have found it profitable to utilize articulated ram-dump haulers (Ramcars), tractor-trailer units, or scoops (front-end-loader tractor units). When employed for face haulage, they eliminate the headaches involved with shuttle-car trailing cables. In small conventional mines, the operator can be spared the cost of a loading machine and a separate machine for clean-up and supply haulage. For moderate-to-large production operations, the extreme mobility of the tractor-trailers and scoops has made them invaluable ancillary equipment for clean-up and supply in practically all longwall and many continuous operations.

Coupled with the earlier concerns just mentioned, there are, however, inherent hazards in battery use. These fall into three broad categories:

1. batteries emit hydrogen, an explosive gas, while charging;
2. batteries and battery chargers are capable of delivering a fatal electric shock; and
3. batteries are a potential fire hazard.

In addition, a number of less catastrophic hazards may be encountered, including acid burns from spilled electrolyte, pinched fingers from careless handling, and so forth.

Because of the connection with mine power systems, this chapter will discuss only vehicle batteries currently in use. Nevertheless, it should be mentioned that there are other important battery applications in mining. The most outstanding is for cap-lamp power.

13.2 Basic Battery and Battery-Charging Theory

Terms. A "storage battery" can be defined as a battery in which the electrochemical action is reversible (8). That is, after an output of electrical current ("discharge"), the battery can be returned to the original state ("recharged") by passing current through it in the opposite direction. The basic unit of the battery is the "cell," simply consisting of positive plates, negative plates, and electrolyte. One or more cells are connected together to form the battery, and the connection is usually in series (parallel and series-parallel combinations are also used). The battery voltage, often given as an open-circuit value, is the sum of the series cell voltages. The capacity, commonly expressed as ampere-hours (Ah) or kilowatt hours (kWh), is mainly dependent upon the plate size (surface area and voltage).

Types. Two types of storage batteries have been employed in underground traction applications. The "nickel-iron" or "Edison cell" is an "alkaline-type" cell because of the electrolyte used. The plates for this battery are constructed of nickel oxide and iron, immersed in an electrolyte of potassium hydroxide and lithium hydroxide. Having high-reliability and minimum-maintenance characteristics, Edison batteries were once popular in the mining industry. However, lead-acid batteries have replaced the Edison type as a result of their high-energy per unit volume and high-power capability.

The basic lead-acid cell utilizes a lead peroxide (PbO_2) positive plate and a sponge lead (Pb) negative plate. These plates are suspended in a solution of dilute sulphuric acid (H_2SO_4), see Figure 13.1 (9). When a circuit is completed between the positive and negative plates, the following reaction occurs:

$$PbO_2 + Pb + H_2SO_4 \underset{\text{charge}}{\overset{\text{discharge}}{\rightleftharpoons}} 2PbSO_4 + 2H_2O + 2e^- . \qquad (13.1)$$

When a large portion of the PbO_2 and Pb is in the form of $PbSO_4$ and H_2O, the battery is in need of charge. Charging a battery consists of supplying electricity to drive the reaction as shown. Fully charged, the positive-plate active material is all lead peroxide, that for the negative plate is pure sponge lead, and the specific gravity of the electrolyte is at a maximum (8).

Discharging and Charging: The lead-acid cell has the highest voltage of any commercial battery cell; the nominal voltage is generally referred to as 2.0 V. However, the actual value varies depending upon the electrolyte specific gravity and if the cell is being charged or dicharged. With a full-charge specific gravity of about 1.280 (a common level for motive storage batteries), the open-circuit voltage is around 2.12-V per cell (8,9). However, due to the effective internal resistance, the cell voltage decreases

as soon as discharge commences. As shown in Figure 13.2, the voltage continues to decrease with discharge, the rate-of-voltage decrease being connected to the discharge-current rate (8). The "final" voltage is the point where the battery is no longer effective for its application. Because this value also changes with the discharge rate, a typical final voltage of 1.75 V is often assumed (the standard discharge time is taken as eight hours). When the discharged battery is placed on charge, cell voltage immediately increases and continues to rise as the charging progresses (see Figure 13.3) (9).

The number of times a lead-acid battery can be recharged is a function of:

1. the discharge level of the battery during its working cycle,
2. the method used to charge the battery, and
3. the quality of battery maintenance.

Each parameter is independent of the others.

The effect of the discharge level on N, the number of times a battery can be recharged, is illustrated by:

$$N = \frac{k}{D^x}, \tag{13.2}$$

where k and x are constants of the particular battery, and D is the percent of total battery energy removed during a typical discharge. The equation states that the theoretical number of times a battery can be recharged is inversely proportional to the discharge level raised to the power x. Battery manufacturers recommend that lead-acid batteries not be discharged below 80% of their capacity. Because it is difficult to determine the extent of battery discharge until the battery is dead, it suffices to say that a battery should be recharged when the machine it is powering begins to show signs of sluggishness, if not before. In other words, the discharge should not be beyond the point of cell exhaustion or where voltage drops below a useful value (8).

Of the ampere-hours discharged, about 110% must be returned to fully charge a lead-acid battery. The rate at which charge is restored is an important consideration in getting the maximum number of charge cycles and maximum life out of the battery. Generally, any current level is acceptable, as long as temperatures above 115°F (125°F for short periods) or excessive gassing is not produced (9). Commonly, manufacturers publish a "normal" or "finish" rate; at this current level, the battery can be safely charged anytime charging is required. The charge cycle (i.e., returning discharged battery to full charge) is usually based on an eight-hour duration.

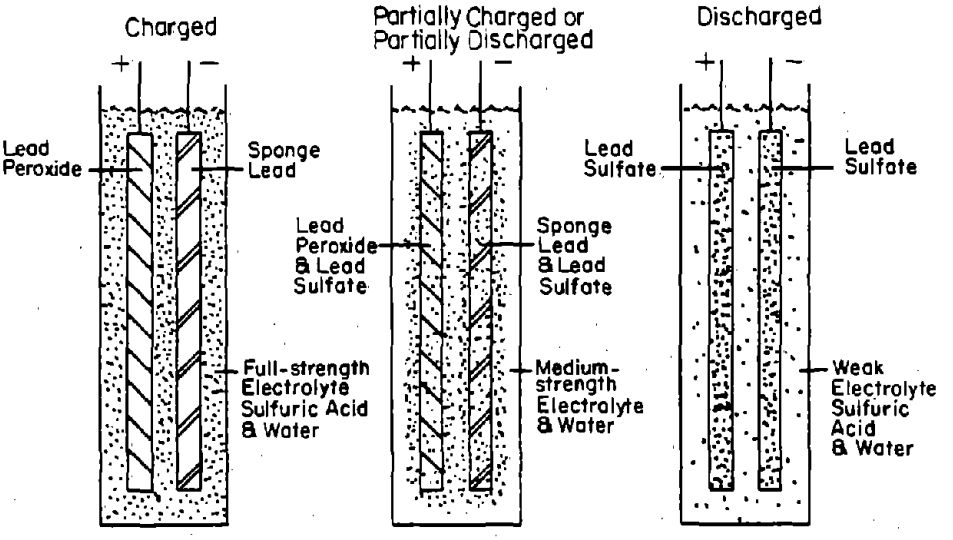

Figure 13.1. The Composition of a Lead-Acid Storage Battery in Various States of Charge.

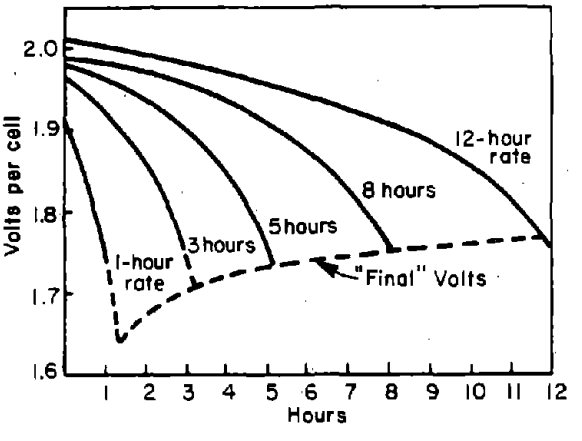

Figure 13.2. Voltage Per Cell of a Typical Lead-Acid Battery with Varying Continuous Rates of Discharge.

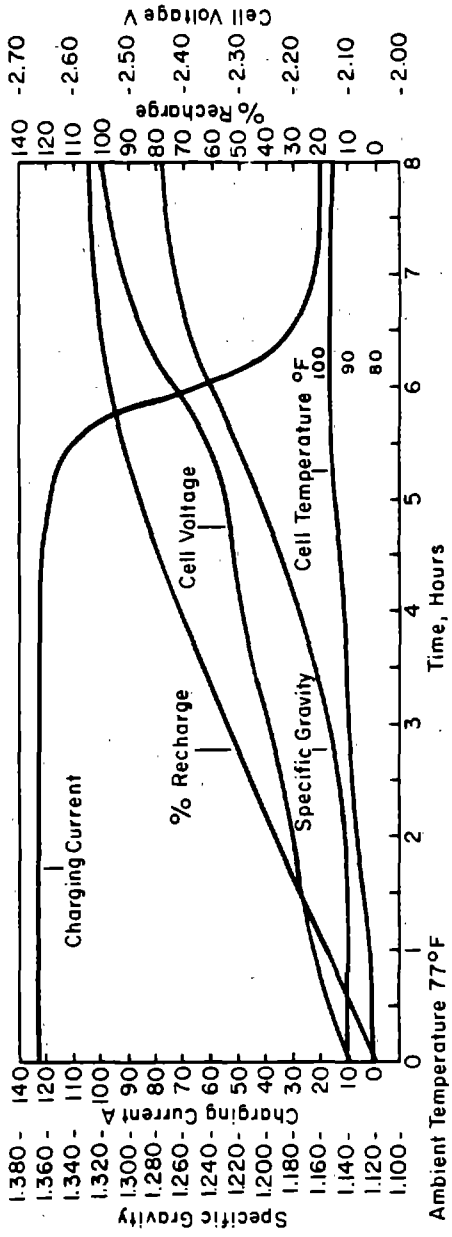

Figure 13.3. A Typical Charging Process of a Cell from an 18-cell, 725-Ah Battery.

Most of the electricity supplied to a cell being charged is actually used to transform water and lead sulfate into sulphuric acid, lead, and lead peroxide. However, some of the current breaks the water down into its constituents,

$$2H_2O \rightarrow 2H_2 + O_2 \qquad (13.3)$$

which is called "gassing." The rate of gassing increases dramatically at a cell voltage of 2.37 V. It is at this level that increasing quantities of current become available for electrolysis because of the higher state of charge in the cell.

A certain amount of gassing is a necessary consequence of a good charge, which explains why water must periodically be added to batteries. However, excessive gassing (or "overcharging") causes damage to the plates, excessive water consumption, and excessive hydrogen evolution. For this reason, the amount of charging current must be regulated as the battery charges. Large amounts of H_2 and O_2 released during excessive gassing cannot be detected by mine personnel. However, this condition is sometimes accompanied by amounts of H_2SO_4 released into the mine atmosphere which is easily identified.

Undercharging a battery is also harmful, even if it is only occasionally practiced. Insufficient charging leads to a gradual "sulfation" of the negative plates, eventually causing a reduction in battery capacity and life (8). The same situation can occur when batteries are left standing in an uncharged state for long periods (9).

Maintenance. Proper battery maintenance is a very significant consideration in the determination of battery life. Battery manufacturers normally provide a maintenance program with their batteries that includes the following information.

1. Specific Gravity Levels. One characteristic of the lead-acid battery is that electrolyte specific gravity is a function of the state of battery charge. Consequently, a plot of electrolyte specific gravity versus discharge depth for a particular battery is important.
2. Equalizing Schedules. "Equalizing" is the process by which all the cells in a battery are brought to the same voltage. All lead-acid batteries require periodic equalization; however, excessive equalization causes unnecessary battery deterioration.

Representing a good battery-maintenance program, the following discussion can be used as a guideline (9) (references 10 through 15 can also be consulted). The technique involves three groups of activities: those which should be performed during each charge period (daily): those that should be performed weekly: and those to be performed approximately once every three months.

Accurate records should be kept of all maintenance activities for each battery. Records provide a convenient way to monitor individual battery performance, thus exposing deteriorating battery conditions before the battery becomes a safety hazard or the source of costly downtime.

Daily battery-maintenance activities should include the monitoring of one of the battery cells (called the pilot cell), and any battery cell can be used as the pilot. The following cell characteristics should be recorded during each charge: specific gravity before and after charging, electrolyte temperature before and after charging, and the water level in the cell. If any of the pilot parameters fall outside those specified as acceptable by the manufacturer, all of the cells should be checked and corrective action should be taken. Other daily maintenance activities should include checking the battery for physical defects such as cracked cell plugs and ensuring that the charger output voltage is correct.

The weekly maintenance program includes checking all battery cells for proper water level and cleaning the battery tops if corrosion is present. It should be noted that the water consumption of a good battery is generally equally distributed among the individual cells.

At every three months, it is a good practice to take a complete set of cell-voltage and specific-gravity readings at the end of an equalizing charge. These parameters should meet manufacturer specifications; if not, corrective action should be taken.

13.3 Chargers

The current supplied to a cell must be d-c, which could be obtained from a trolley-distribution system. However, this source has one serious drawback: it is difficult to obtain the precise voltage requirements for charging.

Accordingly, most mining batteries today are charged underground from the a-c distribution system, using a transformer-rectifier combination. Mercury-arc rectifiers were once used (16),but selenium or silicon rectifiers are universally employed today. Silicon diodes are generally considered to be the industry standard. Transformers generally have isolated secondaries and are most often three phase, although single phase can be used. Rectifiers are usually in a full-wave bridge.

There are several methods which are commonly used to control the rate of charge. The majority are designed to initiate the charge at a fairly high current or "starting rate," commonly 20 to 25 A per 100-Ah capacity. The level is then "tapered" off to

the finish rate as the battery charge is restored, for example 4 to 5A per 100 Ah as shown in Figure 13.3. Some chargers reduce the starting rate to the finish rate in one step when the charge is about 80% complete, but this type is not common in mining. Taper charge-rate control devices can be divided into two basic groups, either active or passive. Whatever the method, the charge is usually stopped automatically when full charge is reached (8).

The most popular passive system for taper charging uses some value of "ballast" resistance placed in series with the battery (17). This resistance limits initial charge current and gives a relatively flat current-versus-time curve throughout the charging cycle. The advantage of this method (sometimes termed "modified constant potential") is its simplicity. Its disadvantages include the fact that the ballast resistor dissipates a rather large amount of energy and the charge rate does not coincide with what is considered optimal for lead-acid batteries. A variation of the above system uses a timer to switch additional resistance in series with the battery, thereby reducing the rate of charge at some point in the charge cycle.

A characteristic common to all active systems is that information concerning the battery-charge level is employed to control the charging current. This information is obtained through the use of a voltage-sampling feedback system.

The simplest active system (again, for the taper method) consists of a voltage-controlled relay, switching additional resistance in series with the battery at a cell voltage of 2.37 V. This system, as with all active systems, must have different voltage thresholds for batteries with different numbers of cells

Another active method utilizes a saturable-reactor type of voltage transformer to feed the rectifier. The saturation level of the transformer core is controlled by a d-c current supplied to a winding on the core. The secondary voltage is, therefore, regulated by voltage-controlled current feedback from the battery. Output regulation usually begins at a battery voltage of 2.37 V per cell and is varied to zero current at the end of the charge cycle (14). Figure 13.4 provides a simplified schematic of a saturable-reactor type of charger.

A relatively new method uses thyristors in place of the silicon diodes. The thyristors usually replace half of the silicon diodes in the full-wave bridge as shown in Figure 13.4, and the firing angle is determined by a feedback circuit that senses battery voltage (18). The circuit given is for a single-phase charger. Three-phase chargers would have three SCR's in the full-wave bridge with three firing boards, but the control circuitry would be much like that for single phase. (One disadvantage of SCR systems is that, in some designs, a phase reference for firing

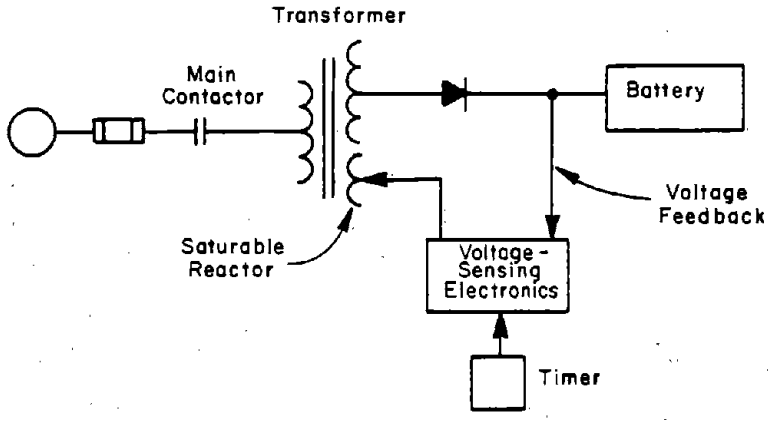

Figure 13.4. A Simplified Schematic of a Saturable-Reactor Charger.

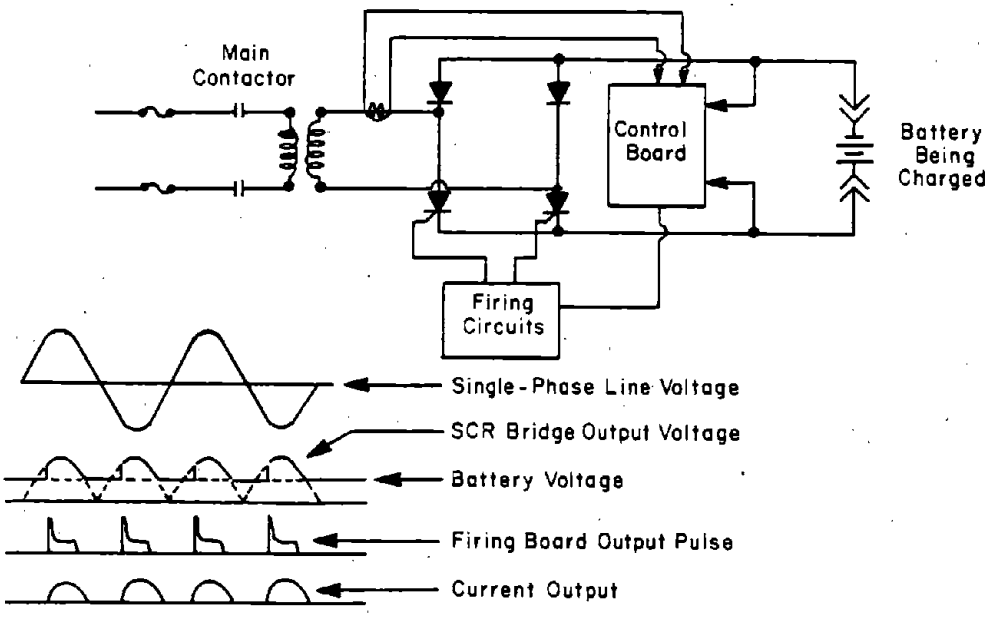

Figure 13.5. A Simplified Schematic of a Single-Phase Thyristor Charger.

the SCR's cannot be obtained with a full-wave rectifier due to negligible ripple, and a half-wave must be used. This results in less efficient rectification and, in some designs, in a chopped waveform which is not entirely suitable for battery charging. However, many manufacturers and users find success with full-wave rectifier configurations.

The last active method employs a ferroresonant transformer and bucking coils (19). For the conventional transformer, as modeled in Figure 13.6, any change in primary voltage produces a corresponding change in secondary voltage. Such will occur until saturation commences, or the "knee" shown in the transformer-magnetization curve of Figure 13.7. This is advantageous for most power applications as transformer operation approaches ideal when used in the linear portion of the curve (to the left of the knee). However, there are many instances where fluctuation in the secondary voltage due to normal primary-voltage changes are unwanted. In other words, the secondary voltage must be "regulated," or remain reasonably constant under a specific load condition. As evidenced by the two preceding methods, regulation is desirable in battery chargers.

A more constant but distorted secondary voltage could be obtained by driving the transformer into the saturation region (to the right of the knee in Figure 13.7). Any change in the primary-voltage magnitude would only cause a small change in the core flux, and thus a small change of induction in the secondary winding. This operation is unwise because primary current becomes excessive. However, regulation could be obtained with normal primary current, if the transformer is modified so the secondary winding is exposed to a saturated core portion while the primary operates under unsaturated conditions. This is the basic principle behind a ferroresonant transformer.

A model of a ferroresonant transformer is shown in Figure 13.8 (19). The leakage block provides a shunt path to bypass part of the flux produced by the primary winding, with the air gaps limiting the amount of flux bypass. The flux not bypassed causes induction in the resonant winding. The inductance of this winding and the capacitance (C) are selected so additional flux is produced which is in phase with the primary flux when no load is on the secondary winding. The resultant flux in that core portion is thus increased to about the knee of the magnetization curve. Therefore, the right transformer portion will operate under saturated-core conditions while the primary sees an unsaturated core.

With the basic ferroresonant transformer, an increase in primary voltage will still produce a slight increase in secondary and resonant winding voltages. To offset any increase in secondary voltage, a "compensating" or "bucking" coil can be connected in series with the secondary winding but with opposing polarity (see Figure 13.9). Consisting of a few turns wound directly over

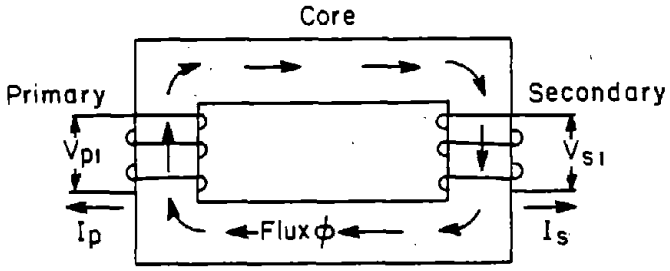

Figure 13.6. A Two-Winding Transformer Model.

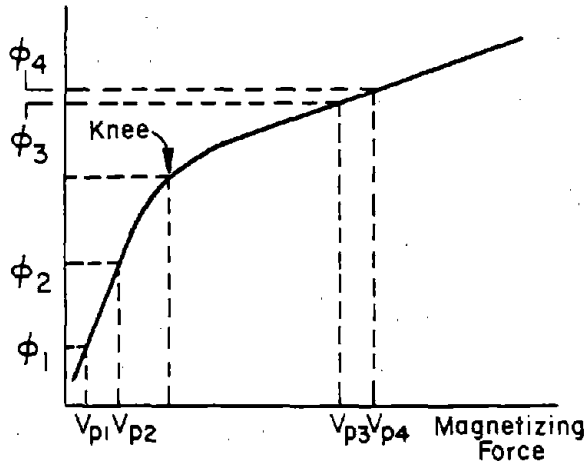

Figure 13.7. A Representative Transformer-Magmetization Curve.

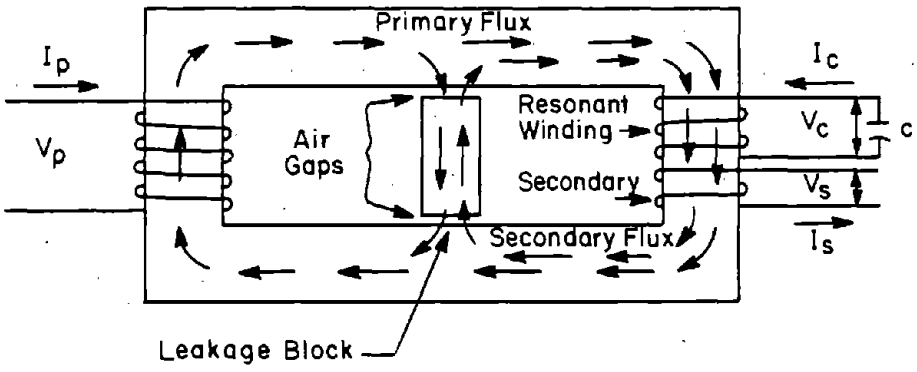

Figure 13.8. A Ferroresonant-Transformer Model.

the primary, any increase in primary voltage will produce a proportional change in V_b. This will offset any increase in secondary voltage and produce a rather constant output voltage over a specified range of primary voltages.

Figure 13.10 shows the adaptation of a ferroresonant transformer to a battery charger. A single-phase unit is illustrated, but the technique is also available in three-phase units. Some chargers do not use the bucking coils for reasons that will be discussed later in the chapter.

Active charging systems have the advantage over passive systems in that the charge rate can be more accurately controlled using feedback principles. The saturable-reactor, thyristor, and ferroresonant types are the most popular techniques in mine-vehicle battery chargers.

Charge termination is achieved by several methods. Passive chargers generally use a timer, as do some active systems. The cell voltage or its rate of change can also be used to determine when the battery is fully charged.

The success or failure of a battery-powered mine-transportation system is largely a function of the operator's ability to get maximum life from the batteries. It is also a function of the relative safety factor involved in battery usage. The following sections provide a discussion of elements related to battery safety such as ventilation of the charging station and charger design.

13.4 Charging Stations

Requirements. In order to charge vehicle batteries, charging stations must be established. For these, there are specific requirements in terms of maximum hydrogen concentration, air coursing, and construction. Because mining methods and plans vary widely, it is extremely difficult to establish a rigorous of guidelines to meet the demands. Accordingly, only general information will be given in regard to underground mining operations.

As was mentioned previously, a consequence of battery charging is the liberation of hydrogen gas near the charge-cycle end. Modern battery chargers, however, are designed to prevent excessive gassing in the latter phases of charge, by automatically dropping the charge rate to a very low value when a certain cell voltage is reached. Although much of the gassing is eliminated, it is not possible to properly charge a battery without producing some gas.

For this reason, a method is required to dilute the explosive gas and render it harmless. The traditional method is by forced ventilation of the charging room. The concern is to

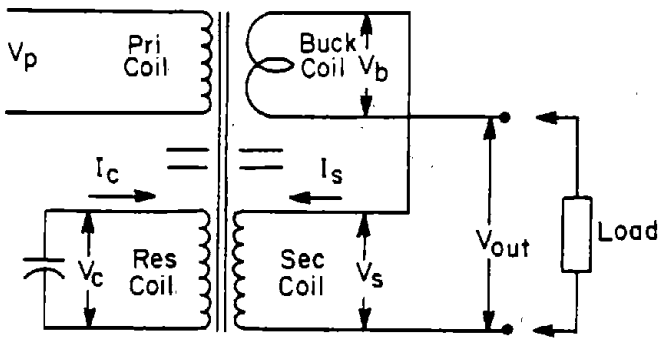

Figure 13.9. A Ferroresonant Transformer.

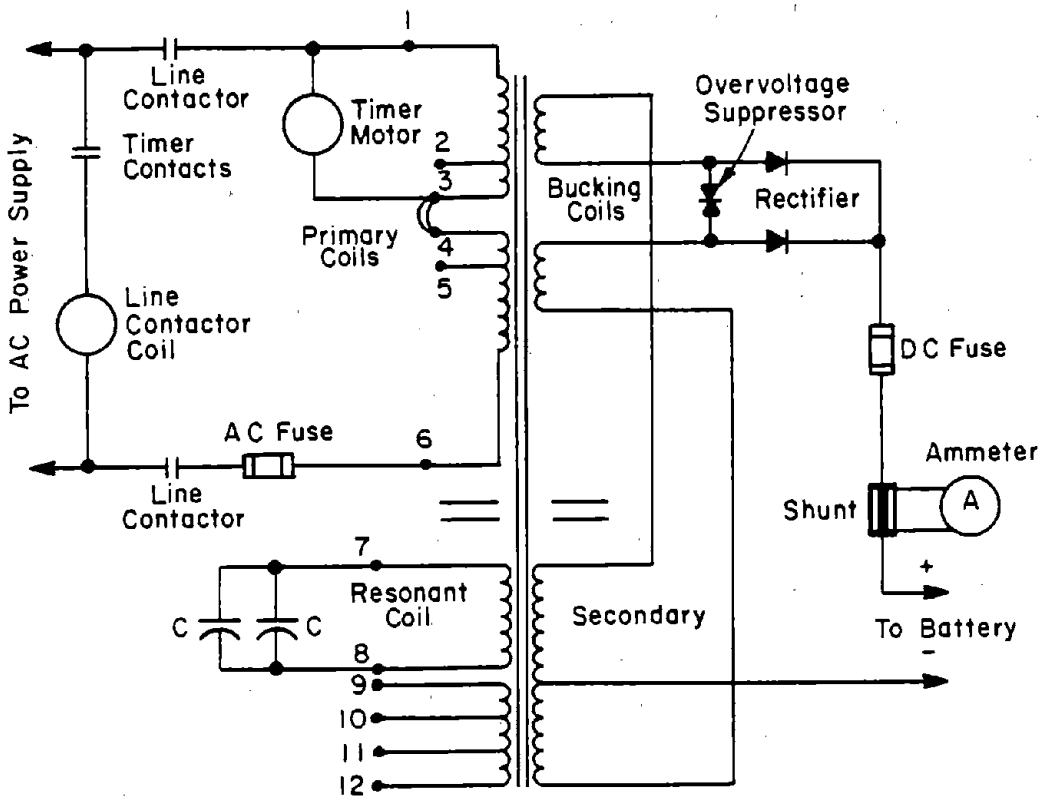

Figure 13.10. A Ferroresonant Battery Charger.

always keep the concentration of hydrogen below its lower explosive level of 4%. Because of the catastrophic nature of underground explosions, federal regulations limit the permissible concentration of H_2 in coal-mine atmospheres to 0.8% (by volume), which provides a safety factor of five.[1] This is analogous to a maximum allowable concentration of one-fifth the lower explosive level of methane.

By assuming typical charge characteristics, manufacturers have made it possible to estimate hydrogen evolution from the number of cells and rated ampere-hour capacity. Table 13.1 lists such formulas from three different manufacturers. As shown in the table, the H_2 evolution calculated from these equations is fairly consistent, ranging from 0.0024 to 0.0028 ft^3/cell-Ah. These figures are applicable to the latter stages of the charge cycle (at cell voltages of 2.37 V and greater). An in-mine survey has compared actual concentrations and charging-room air-flow rates with calculations using the Table-13.1 formulas and dilution requirements (20). The results correspond favorably.

Beyond maximum hydrogen concentration, federal regulations stipulate two additional charging-station requirements:

> Underground . . . battery charging stations . . . shall be housed in fireproof structures or areas. Air currents used to ventilate structures or areas enclosing electrical installations shall be coursed directly into the return. Other underground structures installed in a coal mine as the secretary may prescribe shall be of fireproof construction.

To render the station fireproof, common practice is to line the charging area with corrugated metal siding, covering all exposed (but rock-dusted) coal. In some instances, concrete block is used. The balance of the above statement basically stipulates that the charging station must have a separate split of fresh air. To comply, mines often place stations in unused crosscuts immediately next to return entries (air courses). A small opening is provided in the ventilation blocking so fresh air passes over the station and dumps into the return. Figure 13.11 shows an example of a charging station meeting these regulations. It should be noted that many other configurations are possible.

Minimum Air-Flow Quantities. For each charging-station design, it must be verified that the hydrogen concentration is below the maximum allowed. A simple but effective approach would be to establish a worst-case air-flow quantity per battery on charge. Then the safe condition could be easily substantiated by an actual air-flow measurement of the charging station (e.g., with an anemometer).

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[1] Title 30, Code of Federal Regulations, Part 75, Paragraph 75.301-5.

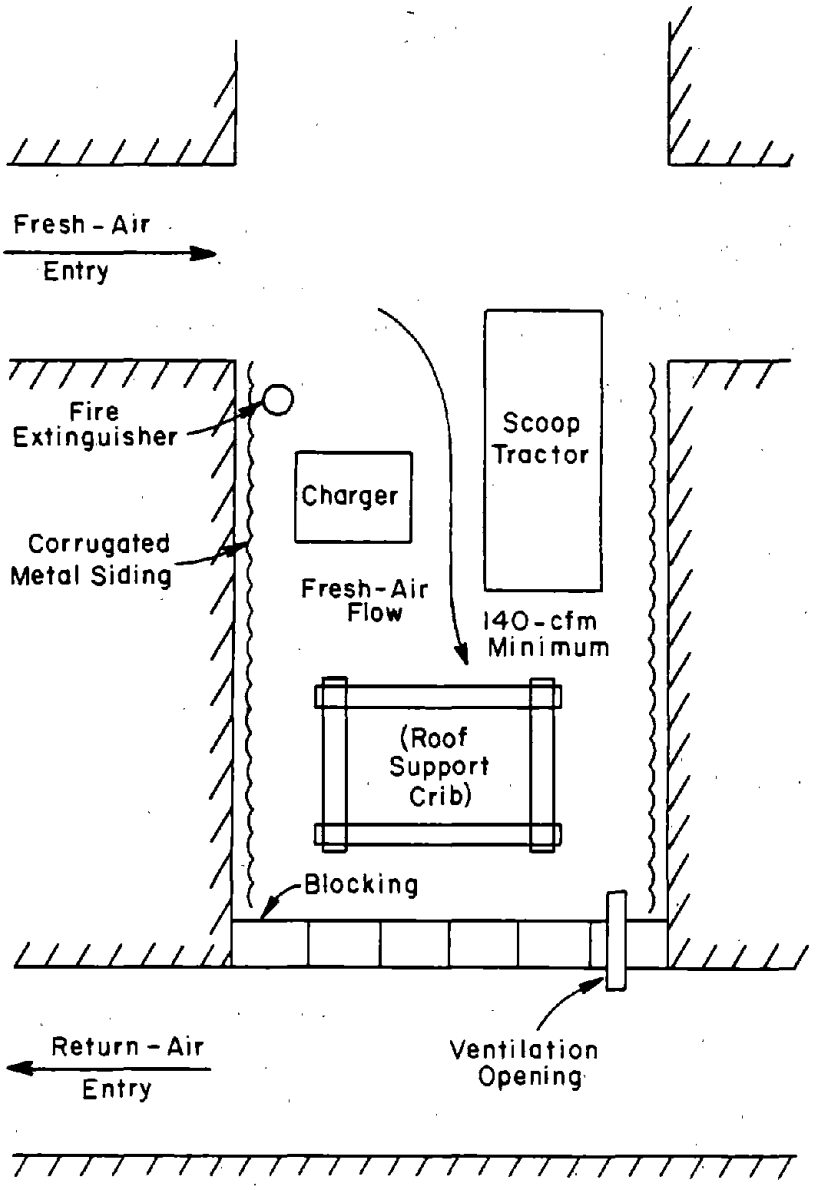

Figure 13.11. Sketch of Underground Charging Station (Plan View).

Table 13.1. Formulas to Estimate Hydrogen Evolution.

Formula Number (Manufacturer)	Formula	Rate of H_2 Evolution Per Cell Ah
1 (C & D)	(# of cells)(Rated Ah capacity) (0.0024) = ft^3 of H_2 liberated in last 3 hours of charge	0.0008 ft^3/hr
2 (EXIDE)	(5) $(\frac{Ah}{100})$ (# of cells)(0.016) = ft^3 of H_2 liberated in last 3 hours of charge	0.0008 ft^3/hr
3 (KW)	(# of cells)(Ah)(0.002948) = ft^3 of H_2 liberated in last 4 hours of charge	0.0007 ft^3/hr

From Table 13.1, batteries in the final states of charge evolve hydrogen approximately to the following:

$$(5)(\frac{Ah}{100})(\#\ cells)(0.016) = feet^3\ H_2/hr.$$

Accordingly, dilution requirements can be calculated by:

$$Q(cfm) = \frac{(5)(\frac{Ah}{100})(\#\ cells)(0.016)}{(0.008)(60)} - \frac{(5)(\frac{Ah}{100})(\#\ cells)(0.016)}{60} \qquad (13.4)$$

where Q(cfm) is the minimum quantity of air necessary to dilute the H_2 produced to 0.8%, not allowing for dilution by room volume. To approach a worst case, it could be assumed that all batteries are 120-cell, 700 Ah (the present upper limit in battery size). Thus each battery in a charging station requires about 140 cfm of air for good ventilation.

The foregoing ventilation quantity assumes that the battery lids remain open (or removed) during charging. This is mandatory practice which is sometimes neglected, especially in low coal. Vehicle storage batteries are placed in strong enclosures ("trays") with removable lids. Due to the small volume above the battery top when the lid is closed, dangerous accumulations of hydrogen are likely to accumulate there during charging. A charging battery can be expected to liberate 60 ft^3/hr per 25,000 cell-Ah. The result is explosive concentrations, unless forced ventilation is applied, or the venting slots are so large as to

considerably weaken the battery box. Forced ventilation is considered not practical by many.

13.5 Battery-Box Ventilation

The ventilation of a traction-battery enclosure is not only important while charging but also during discharge. Following the charge cycle, the covers are closed, and the vehicle is placed in service. From chemical reactions and entrapped gas within the cells, lead-acid batteries continue to emit gas for several hours after receiving a charge, be they open circuited or on discharge (21). Considering the ignitability of hydrogen, there is a possibility of a dangerous air mixture accumulating. Hence, the safety worry here is adequate ventilation for the evolved hydrogen in a closed box while the battery is not on charge.

Prior to 1945, there was little mention in the literature of possible gas emissions from lead-acid batteries during discharge. In fact, many early publications stated that there were no emissions under normal conditions (22). This thinking was also extended to early battery applications in U.S. underground mines (23).

As reported by Robinson (21), this gas-generation question, however, received much attention from authorities responsible for high-capacity battery installations in confined spaces, such as on submarines. He related a report stating that lead-acid batteries in these locations are always able to emit considerable quantities of hydrogen and oxygen for the first few hours after charge (24). Although actual quantities varied greatly from battery to battery, an 80-Ah cell standing idle at 80°F (26.7°C) with 1.26 specific-gravity electrolyte would probably emit 5 to 20 ml of hydrogen per hour for about 12 hours after charge. The approximate rate was found to be:

1. directly proportional to the battery capacity,
2. doubled for each 15°F (9.5°C) rise in temperature, and
3. doubled for each 0.050 unit increase in electrolyte density.

As a result of antimony contamination of the negative plates, the open-circuit emission also increased with cell age. Upon discharge, additional hydrogen was evolved from the negative plates (thought to be a release of entrapped gas during charging). Combining the open-circuit and discharge emissions on a worst-case basis, it was postulated that a lead-acid battery cell, at the end of its useful life, could release up to 500 ml (about 0.2 ft^3) of hydrogen per hour.

An advisory committee on coal mining was formed in the United Kingdom during the mid 1940's, and part of its effort was to investigate underground battery vehicles (25). Realizing the hydrogen-generation problem on discharge, the committee

recommended that traction-battery enclosures be properly ventilated to prevent a hazardous accumulation. Accordingly, a regulation was promulgated in 1949 (26). For the U.S., Bureau of Mines Schedule 2G contains a similar requirement stating that "battery boxes shall be adequately ventilated" (27).

Corresponding to the regulations, a test procedure was made statutory for the United Kingdom in 1949 by the then Ministry of Fuel and Power (now the Department of Energy) (21,28). The salient test conditions were as follows:

1. Hydrogen generation was calculated at 3.0 ft^3/hr per 25,000 cell-Ah.
2. Tests were made in still air.
3. Maximum hydrogen concentration within the box under these conditions must not exceed 2.0% with tolerance.

The emission calculations assumed that all factors which contribute to the hydrogen-emission rate (i.e., cell temperature, acid specific gravity, and discharge rate) were simultaneously at worst case. Still air was selected to simulate the vehicle traveling at the same velocity as mine ventilation, thereby the container natural ventilation received no assistance. The maximum concentration provided a safety factor of 2.0 from the lower flammable level of hydrogen (4.0%).

Robinson (21) researched simple arrangements of container vents that would provide sufficient natural ventilation to meet these ventilation requirements. He used the fact that hydrogen has the highest coefficient of diffusion into air of any gas and, from its extreme mobility, it is very difficult to retain within a leaky enclosure. The investigation used a simulated battery box, containing a dummy 56-cell, 288-Ah lead-acid traction battery. Hydrogen liberation for discharge was calculated at 2.0 ft^3/hr (by the foregoing relationship). While hydrogen was pumped in at this steady rate, hydrogen concentrations were measured in the space between the battery top and cover (volume of 6.1 ft^3). Eleven different venting arrangements in the enclosure top were used, ranging from 40 to 140 in^2, and sealed top vents were also investigated. End-plate venting was available in all tests.

Robinson's findings were as follows.

1. Equilibrium between the battery rate of hydrogen emission and rate of hydrogen escape through the vents was established within one hour after each test commenced. Afterwards, the hydrogen concentration remained almost constant.
2. Maximum concentrations with natural top venting ranged from 1.3% to 2.8%, inversely with vent area, following a near logarithmic curve.
3. When the top vents were sealed and the side vents open, hydrogen concentration rose sharply to 5.3% obtaining 4.2% in 8.0 minutes. However, with 31 cfm of forced

ventilation through the side vents, the 5.3% maximum dropped to 1.7% hydrogen. He hypothesized that normal speeds and mine-ventilation flow rates would create a high factor of safety.

Robinson's overall conclusion was that a battery box could be readily vented to meet the United-Kingdom requirements. Forced ventilation was not needed.

Titman (29) studied lead-acid-battery gas emissions for the period of 45 minutes after charging (he earlier did a similar study for alkaline cells). The impetus behind the work was a knowledge that gas-emission rates from a battery immediately after charge might be greater than that later emitted after a standing period. Titman also investigated the parameters causing emission variations, mainly acid strength, discharge rate, and increased cell temperature. The experiments employed a new 6-V, 309-Ah traction battery. The research conclusions follow.

1. Total gas emission for similar cells varied as much as 15%.
2. Hydrogen emission rate doubled for an increase of 0.050 in acid specific gravity (1.260 to 1.360). Note this increase could easily happen if a battery electrolyte is not topped up (20).)
3. The rate doubled for a 12.5°C increase in electrolyte temperature.
4. Overall rates were on the same order as for alkaline cells.
5. Immediately after charging, hydrogen rates up to 5.0 l/hr per cell were observed (corresponding to 14.30 ft^3/hr per 25,000 cell-Ah).
6. After 45 minutes, the cells were found to liberate as much as 1.3 l/hr per cell (3.72 ft^3/hr per 25,000 cell-Ah).
7. The minimum emission rate was always reached within 5.0 to 8.0 minutes standing after charging.

As can be seen, the findings for specific gravity were similar to that previously stated. However, hydrogen emission rates were considerably in excess of the 3.0 ft^3/hr testing standard: 376% higher immediately after charging, and 24% higher after a brief standing period.

Using these emission rates as a basis, Titman (30) further investigated the effect of high hydrogen rates in relation to typical battery-box ventilation. The enclosure was basically the same as used by Robinson (21). Findings included the following.

1. A 2.0% hydrogen concentration was not exceeded until the emission rate was ten times the 3.0 ft^3/hr standard rate.

2. After one-half hour, the hydrogen became uniformly distributed with no tendency to accumulate at a specific place.
3. For hydrogen concentrations of 2.0% or less, the enclosure concentration varied as the 2/3 power of the emission rate. (This was also verified theoretically.)
4. With the high emission rates, acid-drainage holes assisted enclosure ventilation.

The foregoing has been presented to provide the reasoning behind battery-box venting requirements. A direct comparison of hydrogen emission rates versus the top venting area of the enclosure would be advantageous. Yet, no direct relationship has been found. In practice, however, it has been discovered that about 25 in^2 of top vent area will allow 1.0 ft^3 of hydrogen to escape per hour, while meeting the United Kingdom testing requirements (31,32). An alternative, the use of catalytic battery caps, appears to be an excellent solution for difficult venting situations.

Catalyst Battery Caps. A "catalyst battery cap" converts any emitted hydrogen and oxygen back into water (33). The caps have the dual function of preventing the escape of any hydrogen from the cells and restraining the loss of any water from the cells.

The safety advantages of this scheme are considerable. No additional ventilation is required, either of the tray or of the charging station itself. The battery lids do not have to be opened for charging, a big factor in low coal. The explosion hazard associated with batteries is practically eliminated. Since watering of the cells would not be required, no electrolyte would be spilled on top, and the possibility of surface leakage (explained later) would be greatly minimized. Tray corrosion by spilled electrolyte would also be greatly reduced.

Catalyst caps have been in use for quite some time in various applications ranging from torpedo batteries to batteries for salt-mine personnel carriers. They have proved to be reliable and effective. A problem with these caps, however, is that the palladium catalyst may be destroyed if the cap is turned over, say during maintenance.

13.6 Battery Surface Leakage and Faults

A battery is designed to be an electrically floating system, insulated from its tray, which is at ground potential. Yet three situations can occur which can connect the battery with its tray.

1. Current may leak across the battery surface to the steel tray; this is referred to as "surface leakage."

2. A poorly insulated or damaged cable, bushing, and so forth may contact the tray causing a fault condition.
3. A rock fall or collison may force the battery box cover down onto the battery terminals, possibly shorting one or more to ground.

Batteries could be solidly connected at one end to the tray with a conductor, as is done with the automobile starting battery. However, this would greatly aggravate any surface leakage problems that might occur and could allow a very large current to flow in the case of a single ground fault of type 2 or 3 above.

Surface Leakage. Since lead-acid traction batteries are quite heavy, often weighing several thousand pounds, the only presently-available material which is suitable for tray construction is heavy-gauge steel. Steel is a good conductor of electricity, a disadvantage when used to support an isolated system such as a battery. After a battery has been in operation, coal dust mixed with spilled electrolyte can form a conducting path across the battery top, from the cell terminals to the tray. If these paths are permitted to accumulate, a number of low-resistance paths may form between the various cell terminals and the tray. Since the terminals are at different potentials, currents tend to circulate across the battery top and through the tray, and may cause three problems.

1. Currents circulating in resistive loops cause heating. This heating is proportional to I^2R, where I is the leakage current and R is resistance of leakage path. When R is low enough to permit a substantial current to flow, a smoldering fire may ensue. This hazard is compounded by the often explosive hydrogen concentrations which occur in the battery above the electrolyte level.
2. The presence of paths from the cell terminals to the tray cause a shock hazard for mining personnel. A miner leaning against a battery box and touching an exposed terminal could be shocked. Terminal-to-tray conducting paths present an especially serious hazard when the battery is charging and the charger design or a fault within the charger permits d-c to flow in the ground. This condition, when combined with poor grounding practices, was the cause of a recent fatal electrocution (see Section 13.7).
3. Circulating currents represent wasted battery power and may reduce the amount of time a battery can be used before recharging is necessary. They also tend to increase tray corrosion.

Faults. Another potentially hazardous situation, which may occur in batteries, is the low-resistance ground fault. A damaged cable in contact with the tray would typify this type of situation. Since the battery is theoretically a floating system, a single such fault would cause no current flow. The effect of surface-leakage paths would cause a certain level of current, depending

upon their resistance. However, two simultaneous low-resistance-ground faults would permit extremely high currents to flow. Because of the low internal resistance of lead-acid batteries, currents on the order of 10,000 A may exist for a short duration, depending on the contact resistance of the fault. A very hazardous situation could result because batteries cannot be de-energized: a fire caused by faults would be difficult to extinguish until the battery was discharged.

Hazard Reduction. The surface-leakage problem has been recognized by battery manufacturers for some time. The virtues of keeping battery tops clean have repeatedly been emphasized. An example is the following excerpt taken from a typical maintenance article (34):

> If the battery tops become wet and dirty, or if tray corrosion is visible, give the battery a soda wash. Mix a handful of bicarbonate of soda (baking soda) in a bucket of water. Pour this solution over the top of the battery, using one full bucket per tray. Be sure vent caps are in place. Water will dry, leaving some dry soda on the battery top. It is good practice to give batteries a soda wash once a month. If a battery is accidentally flooded (acid spilled on cell tops) due to overfilling cells, give soda wash as soon as possible.

If mine batteries were always kept clean and dry, the surface leakage problems would be greatly reduced. However, cleaning can be neglected in the mining industry, especially in low coal, simply because the batteries are difficult to access. Some alternative way of reducing this problem would be advisable.

Most batteries now in use underground have a thick coating of paint on their trays. This reduces leakage somewhat, but is prone to deterioration by chipping, abrasion, and attack by battery acid. Recently, however, some manufacturers have begun coating their battery boxes inside and out with a tough vinyl compound. This product, known as "plastisol," is readily available and can be sprayed onto any properly-prepared steel surface. A significant reduction in surface-leakage problems results.

To further increase the safety of batteries, exposed intercell connectors must be insulated in some manner. While this sounds simple, any insulating coating applied to the connectors reduces their heat-transfer capabilities. Since batteries lose about 80% of their heat through the intercell connectors, this can be a serious problem.

Leading battery manufacturers have recently been producing a "dead-top battery," with totally insulated intercell connectors as an option on their mining batteries. The system should greatly reduce the possibility of surface leakage and also remove the possibility of dangerous arcing caused by a tool dropped across the battery top.

Statham and Littlewood (135) realized the need for detection and isolation of surface leakage and ground faults in batteries. They developed a fault-detection system designed to be fitted to the battery or battery charger. The circuit shown in Figure 13.12 provides a simple method for detecting ground faults that might occur between the battery and its load. One problem with the circuit is that a large portion of the battery itself cannot be protected. For instance, a fault occurring at point A in Figure 13.12 would produce no current flow through the current relay. Figure 13.13 is a plot of relay current versus fault position on the battery; it is assumed that the current relay shunt is set at 1000 Ω and that a 200-V traction battery is used.

In order to increase the sensitivity of their current to battery surface leakage faults, Stratham and Littlewood proposed installing switches at points X and Y (of Figure 13.12). These switches would be alternately opened and closed by a mechanical or solid-state device. The upper line in Figure 13.13 shows the new position sensitivity curve resulting from the modified circuit. The entire battery could be protected in this manner, although sensitivity still varies with fault position for surface leakage faults.

Virr and Pearson (36) devised an electronic a-c injection system which would provide protection sensitivity independent of fault location. They utilized a system of red and green lamps to indicate a "not safe" or "safe" condition. Although Virr and Pearson recommended mounting the device on each battery, this would not be necessary for trackless battery-powered vehicles, since a device on the charger would be sufficient to prevent an unsafe battery from being charged. Since the development of surface leakage presumably takes place gradually with accumulation of conducting material on the battery top, continual monitoring of each individual battery is probably unnecessary.

Although not yet mentioned directly, there is an ever present hazard when using lead-acid batteries in any environment: an explosive hydrogen-air mixture can always be available inside the cell. This is true even with catalytic caps. If ignition energy is sufficient within the cells, or even close to the vent cap, the internal mixture can explode, possibly spraying acid and blowing bits of the cover towards personnel in the vicinity. Internal faults can produce this kind of explosion. Virr and Pearson relate that a common source of such events also occurs when electrolyte leaks from a cracked cell, producing a spark when the acid level falls below the bottom of the plates. There is no known method of preventing or suppressing these internally initiated cell explosions. However, ground-fault protection will detect electrolyte leakage.

Low-resistance faults to the tray or vehicle frame caused by damage to cables, and so on, represent a different problem. As previously mentioned, no provision is currently available for

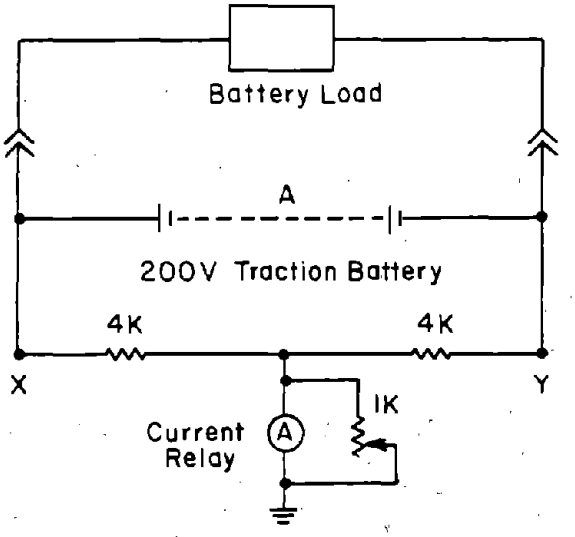

Figure 13.12. Circuit for Detecting Faults in Batteries.

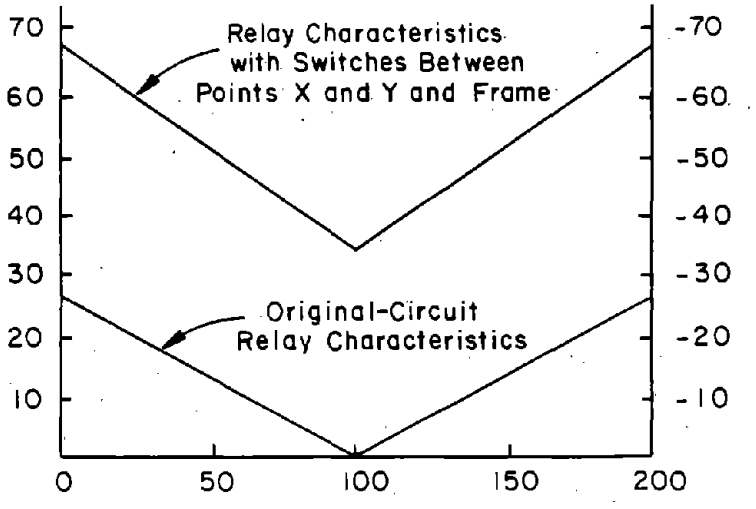

Figure 13.13. Curve of Relay Current for Various Fault Positions on Battery.

de-energizing a faulted battery, which would continue to discharge until its stored energy was dissipated. Some form of circuit breaker between the cells of the battery would provide a way to sectionalize the battery in the event of a fault. In conditions of excessive current flow the intercell connectors might themselves act as protective fuses, melting down when their current-carrying capacity was exceeded.

Proper isolation of the battery electrical system from the mine ground system is a prerequisite to safe battery use. The reliability of battery isolation can be greatly enhanced by following the maintenance and design suggestions given in this chapter. Total electrical safety for any battery installation is, however, a function of charger characteristics as well as battery isolation. Battery chargers will be considered in the next section.

13.7 Battery-Charging Hazards

Electrocutions. A brief review of four representative battery-charging accidents will shed some light on the associated hazards (37).

1. A scoop operator was electrocuted when his body came in contact with the frame of a scoop tractor that was being discharged. During the subsequent investigation, it was found that a potential difference of 260 V existed between the tractor frame and mine floor when the charger was energized. The cause of this was a low-resistance surface-leakage fault current between the battery and battery tray, which caused the tray and the tractor frame on which it was resting to become energized. Faulty insulation between the primary and secondary windings on one arm of the three-phase transformer permitted secondary current to flow in the ground. The glaring error here was the failure of mine personnel to properly ground the steel frame of the tractor while it was being charged.
2. A utility man received a fatal electric shock when his body contacted the frame of a battery charger. A fault existed within the charger which caused 210 Vdc and 114 Vac to exist between the charger frame and earth. Despite the fact that the primary cause of the electrocution was a worn bushing which failed to insulate the timer circuit from the charger frame, a proper frame ground again could have prevented the fatality.
3. An electrician was fatally injured when he came in contact with a bare conductor on the charging leads of a battery charger while connecting the charger to the vehicle. The electrician was standing in water while attempting to connect the battery. Although the charger switch was in the off position, a primary-to-secondary fault in the charger

transformer circumvented the switch (which interrupted only one primary conductor) and caused the charger leads to become energized.

4. A surveyor was electrocuted when he contacted the battery ground clamp, which was attached to the charger frame. The charger frame was energized due to a fault within the charger. The investigation showed the accident to be due to inadequate safety grounds on the frames of all the electrical equipment in the mine.

These accidents occurred using chargers containing the basic circuitry as was discussed earlier in this chapter and, perhaps except for the enclosure, not much different than those used by other industries. The implication here is that additional design concepts or components must be included in battery chargers in order to ensure safety in the mine environment.

The two most notorious contributions to mine-charger accidents and electrocutions have been poor grounding and component failure (most seriously the power transformer), causing the a-c source power to be impressed on the d-c charging circuit. For instance, the charging circuit must be isolated from ground (the safety reasons will be discussed later). Thus, a primary-to-secondary power-transformer fault can elevate the charging circuit by the primary potential. If this is coupled with a fault which energizes a battery tray, and grounding is unsatisfactory, the battery tray presents a shock hazard. The serious situation is grounding, because an intact ground system ensures that frame potentials do not exceed reasonably safe levels, irregardless of what other factors contributed to the hazardous condition. Obviously, a paramount hazard always exists when personnel are exposed to live conductors, irrespective of grounding.

From analysis of battery-charger accidents and input from operators, manufacturers, and state and federal regulatory agencies, other problems causing such accidents have included:

1. bad charging-cable insulation;
2. unconnected, exposed charging couplers (plugs) still energized;
3. charging couplers designed to allow cable damage and also having exposed ungrounded metal parts where the cables are attached;
4. charging couplers being damaged frequently or maintained inadequately, thereby causing poor contact;
5. battery surface leakage and internal faults;
6. no overcurrent protection for the a-c power input;
7. faults causing the control circuitry and components to have an elevated potential;
8. connecting a charger to a battery of wrong polarity;
9. repair work performed by unauthorized personnel; and
10. charging station in abnormally wet locations.

Safe Design of Mine Chargers. Considering safe electrical practice, as well as the foregoing, the following are safety features which should be included in mine battery chargers. The proper application of these should substantially reduce the probability of electrocutions and accidents.

1. The charger input cable should contain a monitored ground to ensure that the charger frame remains at ground potential.
2. The charger should be equipped with panel interlocks which de-energize the charger at the outby source when access panels are removed.
3. The charger should have an emergency-off switch located in a conspicuous place on the charger frame. This switch should not be spring-loaded, thus requiring resetting after use.
4. The power transformer should electrically isolate the battery being charged from the power source, with primary and secondary windings being so arranged to eliminate hazardous interwinding faults.
5. A separate grounding conductor and ground-check-monitor circuit should be provided for each battery tray serviced by the charger.
6. The d-c couplers should be of the type which interrupt the ground-check circuit before the charging circuit.
7. The d-c connection between the charger and battery box should consist of a single cable with appropriate grounding and ground-check conductors.
8. The charger should contain battery surface-leakage detection circuitry which prevents a leaky battery from being charged.
9. The power-transformer secondary and all d-c circuits and components should be isolated from the frame ground of the charger.
10. The charger should have a meter or similar device which indicates the state of battery charge.
11. The charger should have overload and short-circuit protection on both the input and output.
12. The charger should contain circuitry which prevents a battery of the wrong voltage from being charged; otherwise, the charging connector shall be keyed or sized such that a battery of fewer number of cells than that for which the charger is designed cannot be connected.

Figure 13.14 is a one-line diagram of a typical solid-state-controlled taper-rate charger. All the desired electrical components specified in the above list are signified by the letters in parentheses. These, as well as other features, will be discussed in the following paragraphs. It will be noted that other practical methods of personnel protection to those given are available in some instances.

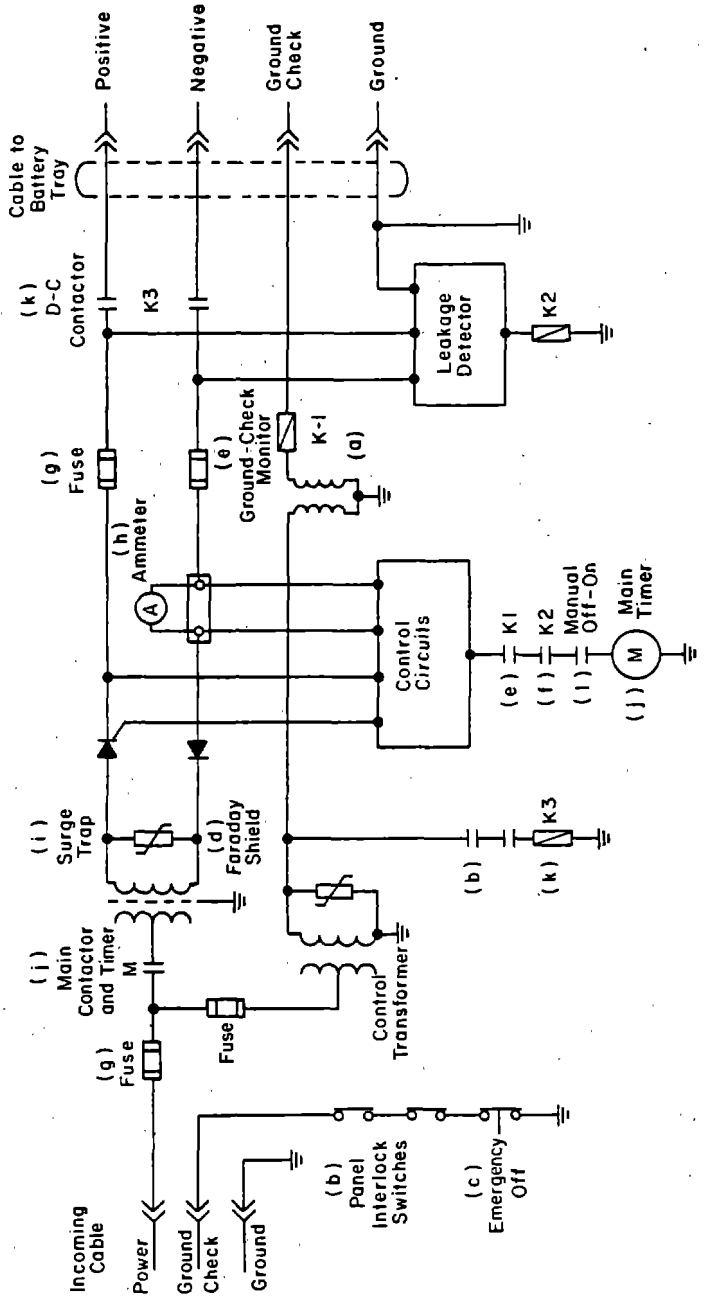

Figure 13.14. One-line Diagram of Desired Charger Features.

System Grounding. Because of the a-c to d-c application, the charger is considered portable electrical equipment, being fed by a resistance-grounded, low- or medium-voltage a-c system. Hence, under federal regulations, a grounding conductor and ground-check monitoring of this grounding conductor are required between the power source (usually a load center) and the charger frame. The portion of the ground-check circuit within the charger is indicated at (a). In series with the ground-check circuit are shown the panel-interlock switches(b) and the emergency-off switch (c). Here, a pilot-type monitor is implied. If the circuit is opened in any manner, the circuit breaker at the source, through which source power is supplied, is tripped. After this, the circuit breaker must be manually reset at the source and cannot be reset until the ground-check circuit is restored.

Electrocutions involving contact with the charger frame have taken place when grounding practices were unsatisfactory and a fault existed between the frame and some charger internal component. One way of preventing this type of hazard would be to completely isolate the enclosure from possible contact with live circuits by using an insulation coating.

There are several shortcomings in protection through insulation coatings of the charger enclosure. Most battery chargers designed for underground use are mounted on skids for practical mobility. In rough mine use, any insulation, especially on the skids, would be quickly worn off. Further, insulation coatings would be difficult to apply everywhere. Devices mounted to the cabinet would have to be coated for 100% protection. Such would create a problem of binding all parts together and bonding components like timers and switches to the exposed panels. Irregardless, any insulating compound deteriorates with time. Thus, any coating might be unpractical and also could result in a false sense of security. Present enclosure grounding standards are a more effective safety approach.

Panel Interlocks. The main reason behind the panel-interlock switch is to prevent unauthorized or even authorized personnel from unknowingly contacting live parts inside the charger. The emergency stop, also termed "emergency off" or "panic button," can provide definite safety advantages. In case of an emergency, it provides a quick power stoppage at the charger. For underground use without the switch, a miner must go back to the load center, which may be as far as 500 feet away. To assist use, the switch has a large red button; pushing the button breaks the outby ground-monitor circuit. The button must be pulled out manually before the outby circuit breaker can be reset. The switch thereby enables a double check on re-energization. This especially helps protect maintenance personnel from having their dangered-off power restored while they are still working.

A justifiable complaint against using panel interlocks is that they must be defeated for maintenance and may be left in that condition, rendering the system dangerous from a false sense of security. However, experience on other mine power equipment that requires panel interlocks has shown that these safety devices rarely remain in a defeated condition. Frankly, any protection system can be knowingly or unknowingly rendered useless, and it is the responsibility of training to make sure this is minimized. Regardless, there are other available ways to discourage unauthorized entry. For example, barriers or partitions can separate energized components within the charger, and special opening tools and attachments can be used on many covers. However, even in these cases, panel interlocks would give an extra safety margin for any panel that is opened or removed for normal adjustments.

Transformer Failures. A Faraday shield is indicated at (d) and prevents primary-to-secondary (interwinding) faults in the power transformer. The shield also has a secondary benefit of isolating any high frequencies on the incoming power from the charger where they could interfere with the control circuitry. Additionally, if the amplitude is high enough, these can destroy solid-state devices. The Faraday shield provides, and likely exceeds, the desired feature of secondary-circuit isolation.

It might be thought that potting transformer windings would also prevent primary-to-secondary faults by providing extra insulation. Yet, layered primary and secondary windings on power transformers are wound in close proximity, and the rather viscous epoxy material likely would not penetrate the core-coil interface sufficiently to cause the desired isolation. Further, some transformer engineers consider such an isolation technique simply impractical on big industrial-type transformers. Thus, the process would not necessarily insure the desired feature and, whenever transformer windings are layered wrapped, the grounded Faraday shield is the only reasonable answer.

In place of the grounded shield, axial displacement of the secondary and primary windings on the transformer core plus separation of primary and secondary circuits is also acceptable. Again, the goal is to accomplish electrical isolation of primary and battery circuits.

Transient-overvoltage conditions on mine power systems by switching or, in some cases, lightning apply large electrical stresses to power-transformer insulation. To protect the transformer, and thereby provide backup for the personnel protection given by the Faraday shield, the transformer insulation should be able to withstand a peak of five times the nominal peak line voltage. Ventilated dry-type transformers designed to IEEE Standard 462-1973 (see reference 38) for low-voltage chargers have a 10-kV BIL, which is well within the transformer transient-protection needs. Accordingly, the voltage ratings of all other charger components are coordinated with the maximum anticipated

overvoltage. The transformer secondary, and thus all circuits connected to it (rectifiers, charge-rate control, and timer circuitry), are further protected from transients by metal-oxide varistors (1).

Outgoing Cables. The cable used to charge the batteries contains grounding and ground-check conductors as well as the two charging power conductors. The battery-tray couplers should have four pins to accomodate the cable. Obviously, the general safety requirements for any coupler should also be adhered to, such as employed on other low-voltage coupler applications. For example, each contact should be able to continuously carry the maximum current in the circuit for which it is designed; all exposed, uninsulated metallic parts should be grounded to the grounding conductor; and the coupler-cable interface should be so designed to prevent cable-insulation damage.

The grounding and ground-check conductors are grounded on separate welded studs inside the battery tray. If only one stud is used and knocked loose, the ground-check circuit could be intact but with the battery tray ungrounded.

A logical safety item is insulated strain relief for all cables supplied with a charger. Unfortunately, one past battery-charger fatality could have been prevented if cable strain-relief had broken charging conductors. To further protect against cable damage, insulated glands should be available for any cable passage through the charger frame. Beyond these, storage on the enclosure outside should be provided for all permanently attached cables. Such would help ease damage resulting from unstored charging cables and couplers that are left on the mine floor.

Outgoing Ground-Check Monitoring. The ground-check circuit is designated by (e) and has the purpose of monitoring the grounding connections to the battery tray. One such circuit is provided for each battery on charge. The monitor shown is a simple current-sensing pilot-type (or loop). If the loop formed by the charger-cable grounding and ground-check conductors, the coupler contacts, and the battery-tray grounding studs is opened, relay K1 will be de-energized, tripping the charging power with contactor K3. A serious problem with ground-check monitoring on battery-charging systems is the abundant possibility of parallel grounding paths. Thus, for this and other reasons, the monitor must be able to meet all the guidelines discussed in Chapter 8.

Surface-Leakage Detection. The charging power is also being tripped if the leakage-detector circuit (f) senses surface-leakage or a ground-fault from the battery to the tray. Following work performed by Virr and Pearson (36) in the United Kingdom, a total battery-leakage resistance threshold of 1000 Ω appears satisfactory. This value should not present nuisance-tripping problems caused by relaying which is too sensitive, but should substantially reduce the gas-ignition and electrical-shock hazards created by such faulting.

Charging-Circuit Isolation. Completely isolating the transformer secondary and d-c charging circuitry from ground is mainly projected at preventing shock hazards caused by charger-battery grounding problems. With either polarity grounded, a low-impedance source of d-c voltage between the frame of the vehicle being charged and the ungrounded battery side is provided. A person touching the vehicle frame and any battery intercell connector could receive a d-c shock of, for instance 80 V. The same would be true for anyone standing on a wet mine floor and touching any ungrounded terminal connected to the charging circuitry. Grounding the positive or negative charger terminal also promotes excessive corrosion of the battery tray.

State-of-Charge Indication. An ammeter (h) is provided so it can be determined, at any given time, what part of the charge cycle the system is operating in. Strictly speaking, this is not a safety feature, but having some idea of the status of the charge cycle is an aid to good operating procedures, which in turn can contribute to safety.

Another desired feature might be a fail-safe means of preventing overcharge. The principal goal here is to protect against excessive battery gassing, and as a first line of defense, almost all manufacturers use timing circuitry to substantially reduce charging current through the last part of the charge cycle. However, there are common occurrences that call for additional protection. For instance, consider that during charging the charge cycle is interrupted, say by a charger-component failure, a power failure, or someone disconnecting the charger from the batteries and then reconnecting them. The bad component could cause the charger to continue the charge at the starting rate for an indefinite period. In the last two cases, the main timing circuitry could reset to zero, and an unknowing individual might manually restart the charger for a full-charge cycle. Considering the real world, a "fail-safe" timer would need to de-energize the charger with any failure mode that could lead to overcharge, many of these are perceivably beyond the control of practical timing circuits. Thus, a more reasonable safety requirement is that the charger-time circuitry operate in a manner to minimize battery overcharge as much as practical.

One means of affording protection against overcharging is to have a redundant timing device that overrides the main timing circuitry to shut the charger down after a set period. The timer (j) in the one-line diagram performs this function. Its d-c motor is tied to the charging power, having an automatic-reset capability. The timer de-energizes the charger after a maximum operational period from its initial setting.

Overcurrent Protection. Fuses (g) in series with each ungrounded incoming and outgoing power conductor provide overload and short-circuit protection. A circuit breaker could also be used for the transformer-primary circuit but is probably not suitable for outgoing-circuit protection. Other relaying can also be included for semiconductor protection and this is discussed in Chapters 11 and 12.

Additional Features. The preceding has covered the minimum number of features that should be included in a mine charger. However, some additional items are also desirable. One of these is a contactor (k) for both the positive and negative outgoing conductors, located near the point where charging power leaves the enclosure. The intent is to remove battery power from any uninsulated component within the enclosure if the charger is opened and the charging cable is still connected. Accordingly, the contactor is tripped anytime the a-c ground-check circuit is broken. Because the contactor load contacts might still be energized upon entry, the device should have a protective cover with a warning notice.

There have been many instances where charging couplers have been removed during the charge cycle, the charger not turned off, and the energized plug left on the mine floor, at times laying in water. The outgoing ground-check circuit will prevent this condition as well as any arcing which might be encountered on plug removal. However, as a back up to power tripping, it would be advantageous to also have the manual on-off device simultaneously reset to off. This could be a simple switch tripped by the d-c ground-check monitor (component "1" in Figure 13.14) or a manual timer that is capable of being automatically reset to zero. Automatic resetting of either device type (for example, when the battery plug and receptacle are re-engaged) is unadvisable, so manual resetting is required. Such necessitates a deliberate act by the user before the charger can be energized, as an automatic restart could pose a hazard to the unwary miner.

Unless prevented, another very serious and quite obvious hazard can occur if an energized charger is connected to a battery of wrong polarity. Therefore, control circuitry must be able to sense the wrong polarity condition and not allow energization of charging power.

In a matter related to couplers, many maintenance personnel have received burns from battery-energized couplers during repair, maintenance, or replacement. It is necessary, therefore, that the battery terminal connections should be constructed so power to the couplers can be removed.

13.8 Summary

This chapter has scanned through the subject of batteries and battery charging in mining. Significant points about the material covered can be summarized as follows.

A good battery-maintenance program is a must for successful battery use. Adequate ventilation of a typical charging station requires little more than common sense. The batteries must be located in the mainstream of air flow during charging, and pro-

visions should be made so 140 cfm is available for each battery on charge. Battery lids should be removed during the charging. Catalyst battery caps should be considered as a viable alternative to ventilation and lid-removal requirements. Safe battery chargers can be made and should be used to provide a larger safety factor in the battery charging and usage process.

The federal requirement to de-energize the mine electrical power system in event of a mine ventilation failure brings about a moot point concerning battery employment not yet mentioned but reserved for here. De-energization should include all non-permissible battery-powered systems at the source. As batteries are independent and cannot sense a mandatory power short-down, a "dead-man" type device may be necessary on battery-powered vehicles, timed to interrupt the battery power, for instance, 20 minutes after the machine is stopped. After which the operator would be required to engage an "interlock" before again using the machine. At least, the device could be interlocked through the battery-tray coupler, de-energizing the receptable contacts when the plug is not present.

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CHAPTER 14

PERMISSIBILITY AND HAZARD REDUCTION

14.1 General

"Hazardous location" can be described as any industrial area in which flammable or explosive gases, vapors, and dust can be encountered. When electrical apparatus is used in hazardous atmospheres, the chance of a gas or dust ignition is ever present. Consequently, in an effort to reduce the hazard, several protection systems have been devised. The basis for these systems relies on three interconnected factors (1).

1. The gas, vapor, or dust (or combination thereof) is available in an ignitable mixture.
2. There is an ignition source.
3. This source contacts the ignitable mixture.

As the probability of ignition cannot be brought to zero, such systems are termed electrical "hazard-reduction" techniques.

Any portion of an underground coal mine and selected parts of surface mines and surface facilities, such as preparation plants, could be involved.

When the principles of hazard reduction have been applied to equipment to render it "safe," two important terms must be connected with this equipment before it is acceptable for use in hazardous locations of United States mines. These are defined in Title 30, Code of Federal Regulations, Part 18 (30 CFR Part 18)(2). The U.S. Department of Labor, Mine Safety and Health Administration, Approval and Certification Center has the responsibility of ascertaining compliance with 30 CFR Part 18 and issuing approvals and certifications. "Approval" means that the manufacturer has been issued by MSHA a formal document which states that a completely assembled electrical machine or accessory has met the applicable requirements of 30 CFR Part 18. Approvals are granted for completely assembled machines or accessories only and not for components, such as motors, controllers, cables, and other individual parts. The term "permissible" is applied to completely assembled electrical machines or accessories for which a formal approval has been issued and that conform in every respect with the approved design. An approval plate indicating this fact must be permanently placed on the equipment.

Even though all areas of underground coal mines could be considered hazardous locations, permissible equipment is normally required only inby the last open crosscut and in return air, and non-permissible electrical equipment can be used in most fresh-air locations. The main worry is the ignition of methane gas, because rock dusting, water sprays, and adherance to federal regulations can render coal

dust harmless. The first line of defense in preventing a methane explosion within the mine is adequate ventilation. In other words, fresh air is forced into the mine and circulated through both active and inactive workings to dilute, render harmless, and carry off any explosive gas. However, even with rigidly maintained adequate ventilation, it is always possible that an accident could disrupt proper air flow or a sudden methane outburst could occur, temporarily creating a dangerous condition. This is most critical inby the last open crosscut, i.e., at the mining face and in return air courses. Thus, ventilation is not sufficient in itself and must be supplemented by hazard-reduction techniques.

This chapter is not intended to specifically discuss the schedule of requirements for approval and permissibility or the theories behind explosions, but rather to cover the hazard-reduction techniques used. The most widely accepted and used of these, the explosion-proof enclosure, will be covered extensively, but other techniques are mentioned.

14.2 Area and Material Classification

Underground coal mines are constrained with the use of permissible equipment in the areas just described. However, hazardous locations in surface mines and surface portions of underground mines are often classified by guidelines based on the National Electrical Code (NEC), Article 500 (3). Coal preparation plants are an outstanding example. As the classification system has wide-spread use and acceptance, and because equipment for use in such locations are designated accordingly, a summary applied to the coal-mining industry is in order. In general, the nature of the hazard and the degree of hazard are the main considerations, and a location is specified by a Class, Group, and Division.

The "Class" designation refers to the generic nature of the hazardous material, and the following are of specific importance (1,3).

1. "Class I" locations contain flammable gases or vapors, which may be sufficiently present in the air to produce an explosive or ignitable mixture.
2. "Class II" locations have combustible dust, which may be at a quantity to cause a hazard.

The "Group" designation is a subclassification, referring to the nature of the hazard. Each group contains a listing of materials that present the same general hazard. The Groups of interest in coal mining could include (1,3):

1. "Group B," atmospheres containing hydrogen or gases or vapors of equivalent hazard such as manufactured gas;

2. "Group D," atmospheres containing gasoline, hexane, naptha, benzine, butane, propane, alcohol, acetone, benzol, lacquer-solvent vapors, or natural gas (methane);
3. "Group F," atmospheres containing carbon black, coal, or coke dust.

When more than one hazard is involved, the classification and group describing the most serious situation usually applies.

The "Division" defines the probability of a hazardous material being present in an ignitable concentration (1,3). "Division 1" locations are those where the hazards exist continuously, intermittently, periodically, or where they may exist during maintenance or equipment failures. "Division 2" locations involve similar hazards but they are presumed to exist only under abnormal conditions. An example would be an area, rendered non-hazardous by forced ventilation, that could become hazardous if the ventilation failed (1). Another Division-2 instance would be where dust layers could accumulate and might interfere with proper and safe heat dissipation from electrical equipment, thereby causing a dust-layer ignition.

Preparation-Plant Applications. There are three conditions which may exist in coal preparation plants that may result in a hazardous-area classification (4,5):

1. levels of coal dust suspended in the plant atmosphere,
2. accumulations of coal dust settled on electrical equipment or other surfaces, and
3. concentrations of readily ignitable gases, as methane, which may be released from the coal.

The extent of the hazard depends on the characteristics of the coal being handled, the preparation-plant design, and the action taken to modify or control the hazardous condition. However, the coal-handling systems within the plant establish the environments which usually create the hazardous conditions.

The unit operations and plant locations that tend to cause hazardous locations from coal dust (Class II) include the following (4,5,6):

1. transfer points in materials-handling systems (i.e., conveyor-to-conveyor, bins-to-feeders, etc.);
2. coal-crushing and rotary-breaking systems (as well as operations that create new particles due to coal friability);
3. coal wetting, sizing, or sorting operations;
4. plant clean-up systems;
5. manual picking tables;
6. thermal dewatering systems.

There are many locations where coal dust may accumulate by settling. Usually associated with the above locations, these include

inside dust covers, covered conveyors, chutes, and so forth, where effective clean-up is difficult. Those operations and locations which can lead to methane accumulations (Class I) are (4,5,6,7):

1. operations causing particle-size reduction;
2. locations having limited ventilation and stored or slow-moving coal, such as storage bins or silos, pressure discharge chutes, and tunnels or chutes leading to these locations.

The National Electrical Code, Article 501, contains the general rules applicable to electrical wiring and equipment in Class-I locations, and Article 502 applies to Class-II locations (3). Electrical equipment used in preparation-plant hazardous locations commonly follow design criteria established by organizations other than MSHA, although MSHA has jurisdiction. The National Electrical Manufacturers Association (NEMA) defines enclosure types (e.g., explosion-proof and dust-ignition-proof), motor classifications, and insulation classifications (8). Underwriters' Laboratories, Incorporated, lists motor and control standards for hazardous locations.

14.3 Hazard-Reduction Principles

14.3-1 General

Hazard reduction is a practice in low probabilities, specifically low incremental probabilities (1). For instance, a safe electrical installation in a hazardous location does not significantly raise the probability of fire or explosion above that which exists without the equipment. There are two general methods of hazard reduction; the ignition is either permitted or prevented. When permitted, the resulting combustion must be so well controlled and contained that it does not cause damage. The most popular system, explosion-proof enclosures, results from this concept. It was stated earlier that for an explosion or fire to occur, a combustible mixture must be present, and a source must be capable of imparting sufficient energy to that mixture to cause ignition. The techniques that prevent ignition remove one of these requirements. Intrinsic-safety and increased-safety methods rely on no energy source. On the other hand, many systems, including purging, potting, and immersion, control the atmosphere around the source to prevent the presence of a combustible mixture.

Whether based on the requirements of 30 CFR Part 18, the guidelines of the NEC, or the standards of Underwriters' Laboratories, Incorporated, the terminology and basic concepts are the same. The following discussion of each method will rely heavily on federal regulations pertaining to coal mining. The next three sections will cover techniques applied to gas-air mixtures. Afterwards, the peculiarities of dust ignitions are presented.

14.3-2 Explosion-Proof Enclosures

The "explosion-proof enclosure" commonly used in U.S. mines is defined as an enclosure that complies with the applicable design requirements in Subpart B of 30 CFR Part 18 and can contain internal explosions of methane-air mixtures without undergoing damage or excessive distortion of its walls or covers and without an ignition of a surrounding methane-air mixture or discharge of flame from inside to outside of the enclosure (2). These enclosures, which may not be vapor tight, are distinguished by heavy-wall cast or welded construction and bolted or threaded close-fitting flanges.

Internationally, the definition remains the same, except the words "discharge of flame" are not present (9). This latter description often refers to "flameproof" enclosures, but the terms "flameproof" and "explosion-proof" commonly have the same connotation. However, flameproof enclosures are not presently allowed in U.S. underground coal mines unless they meet 30 CFR Part 18 (2).

Explosion Transmission. Ignitable gas may enter a properly secured explosion-proof enclosure by several ways (10). Enclosures on machines allowed to stand for several hours in a gas-filled place can become completely filled with that gas from diffusion through openings, even though those openings (as will be seen) are very small. Another process, "breathing," results from the alternate expansion of the enclosure atmosphere during operation and contraction as it cools at rest. Air is forced out during expansion, and the atmosphere outside the enclosure is drawn in when cooling, including any gas present around the machine. In addition, gas may enter the enclosure when covers are removed for inspection or repair.

A methane-air mixture in the proper proportions will explode if an adequate ignition source is present. The approximate explosibility range of methane in air is 5 to 15%, with 9.8% being the critical point for the most violent explosion. Methane and air mixtures above or below this range will burn but will not explode. The lowest auto-ignition temperature (ignition without additional energy) is about 640°C. However, a methane ignition requires that a sufficient gas volume be maintained at or above the auto-ignition temperature for a period of time. In other words, there is a critical ignition energy that must be injected to sustain combustion (1). Empirically, the minimum has been found to be 0.25 mJ for flammable methane-air mixtures (11).

Ignition of the explosive gas by electrical means may take place in several ways. Arcs of sufficient energy are termed "incendive" and can result from normal or abnormal operation of electrical devices. Normal incendive-arcing modes include that occurring during contact closure (or even between fixed electrodes) in a capacitive circuit, opening contacts in inductive circuits, and opening or closing contacts in resistive circuits (1). For the first two, energy stored in the capacitance or inductance is

released to the arc as the contacts close or the contacts interrupt current, respectively (see Chapter 8 on arcing and Chapter 10 on energy storage for details). Examples of abnormal incendive arcing could involve faulted components or, not strictly tied to the enclosure subject, intermachine arcing (as covered in Chapter 15). Another source of ignition is contact with hot surfaces, such as on fine conductors. In terms of gas ignition, this mode depends upon the heating of the surface sufficiently above the auto-ignition temperature (1).

It can be seen from the definition that gas ignitions are allowed in explosion-proof enclosures. The protection concept, however, is the containment of the internal explosion (without damage), with escaping gases not having sufficient energy to propagate the explosion to an explosive mixture surrounding the enclosure (1). Conventionally, these hot gases can escape only through long, narrow "gaps" or "quenching distances." The gas escape is very important; otherwise, pressures capable of rupturing the enclosure might be developed.

Explosion-proof enclosures have been researched since approximately 1906. Even so, little concrete information is available about the mechanisms by which they are effective. Hypotheses have been developed to explain the phenomena: cooling and inhibition (1,12).

Consider Figure 14.1, a cross-sectional sketch of a typical explosion-proof enclosure. An explosive methane-air mixture is inside and outside the chamber. After an explosion is initiated inside the enclosure, a combustion wave propagates towards the enclosure walls, burning the available combustible material. This raises the pressure and temperature inside the chamber, and unburned gas then heated burned gas are forced through the flange gap. The heated-gas jet is first cooled by heat transfer within the flange gap. As it exits the flange, it may be further cooled by adiabatic expansion into the surrounding atmosphere, but combustible gas is entrained (or mixed) in the jet. This additional gas does provide fuel for combustion but also further cools the escaping gases. If all of this cooling does not lower the jet temperature below the gas-ignition temperature, the explosion will propagate to the surrounding atmosphere. Yet, if the jet entrains too much combustible gas in this last phase, the heat supplied by the jet will be less than that lost through cooling, and no ignition of the outside gas will occur.

The action within the flange is believed to go beyond cooling. Combustion of a gas-air mixture does not proceed with a single chemical reaction but rather a chain of reactions. If the "chain carriers," or active molecules from a proceeding step, are inhibited, for instance by contact with the flange wall, then combustion stops. Beyond applying to flame-path areas of explosion-proof enclosures, this theory is also used to explain the protection properties of flame safety lamps.

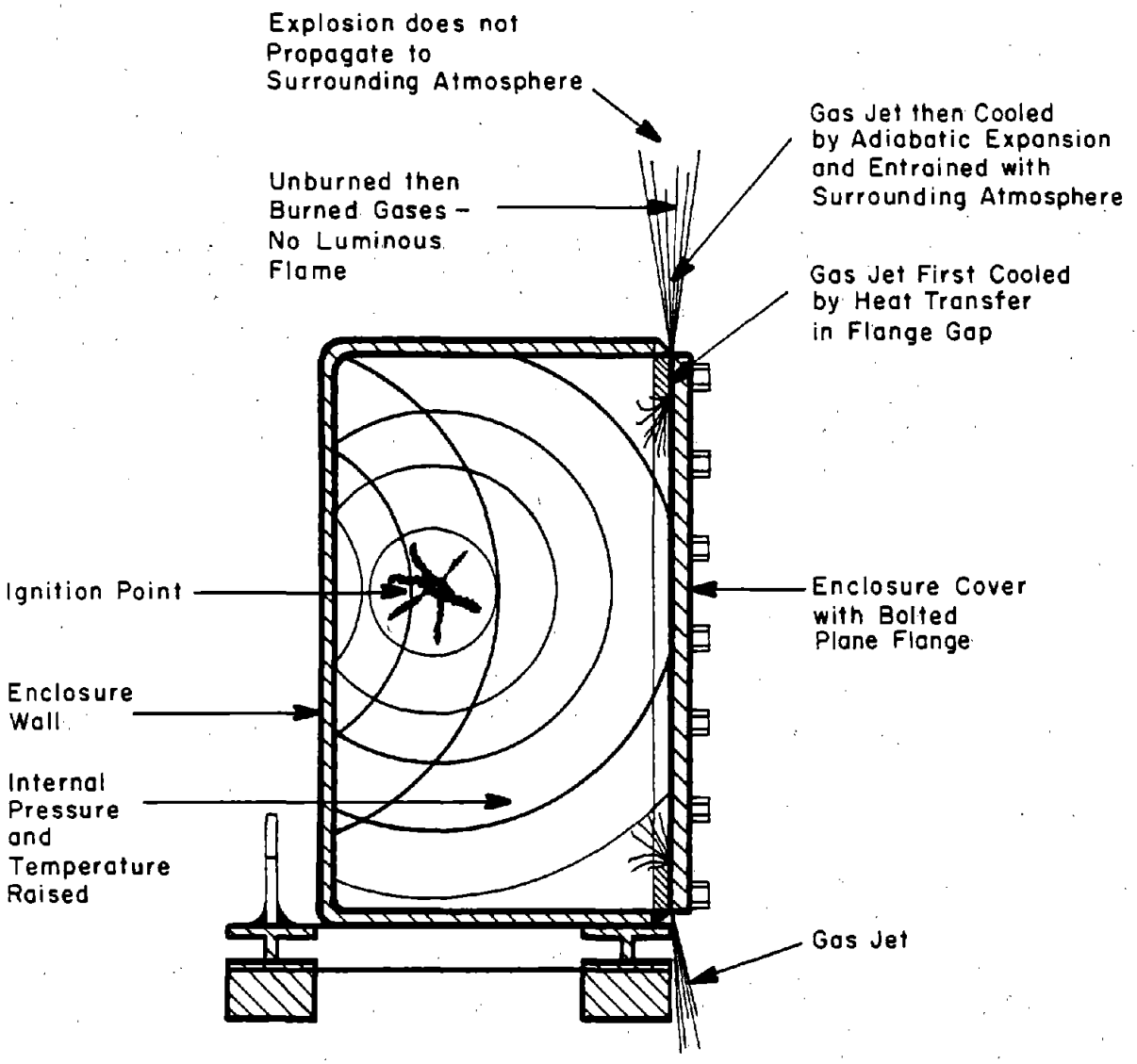

Figure 14.1. A Cross-Sectional Sketch of an Explosion-Proof Enclosure.

A flange has been used to explain the hazard-reduction properties of the explosion-proof enclosure. Other enclosure openings, such as pressure and relief vents, provide the same protection phenomena (13). These will be discussed shortly.

Enclosure Joints. Explosion-proof enclosures must have as few openings as possible to maintain flame paths at a minimum. However, it is essential that limited access be provided for maintenance, such as for inspection and renewal of parts. The joints formed where covers are placed over these openings are either "threaded" or "machine-surface" types. Flanges formed by machining may be flat, cylindrical, or a combination of both. The most common machine-joint types are the "plane-flange" and "step-flange;" uncommon is the "tongue-and-groove." The step-flange joints are often a combination of flat and cylindrical flange surfaces; an example is the joint between end bells and the frame of explosion-proof motors. Typical cross sections of these joints as well as other popular entrances into explosion-proof enclosures are illustrated in Figures 14.2 through 14.5. The maximum and minimum dimensional requirements are given in these figures and in Table 14.1.

For enclosures with volumes greater than 124 $in.^3$, a simple check of plane-flange-joint adequacies is to run a 0.005-in. feeler gauge along the joint; it should not fit between. Step-flange joints can be similarly checked using 0.007-in. gauge (14). (Allowable clearances are 0.004 and 0.006 in., respectively.)

The bolts or other means of fastening or clamping joints should generally be proportional to minimize stripping of threads and to give adequate strength from the stress developed during an internal explosion. Minimum bolt diameters are given in Table 14.1. The maximum spacing for fastenings for joints all in one plane is six inches. The maximum spacing for fastenings for joints, portions of which are in different planes, is based on size and configuration of the enclosure, strength of materials and explosion test results. Holes should not penetrate to the enclosure interior for any reason; otherwise, the omission of a bolt would provide an opening. Through holes must be bottomed or "blind," as shown in Figure 14.6.

The minimum distance from the enclosure interior to the bolt-hole edge is important because it might possibly provide too short a flame-path length. The minimum federal requirements (considering just flange width) are (2):

1. for 1/2-in. joints, distance is 1/8 in. (3.2 mm);
2. for 3/4-in. joints, distance is 3/16 in. (4.8 mm); and
3. for joints 1.0 in. or over, distance is 7/16 in. (11.1 mm).

An example can be seen in Figure 14.3.

To help understand these joint requirements in connection with the explosion-protection properties just discussed, a presentation of past research is in order. Investigations into the external ignition-suppression properties of flange joints have been an active research area for several years, with three countries extensively involved: the United States, the United Kingdom,

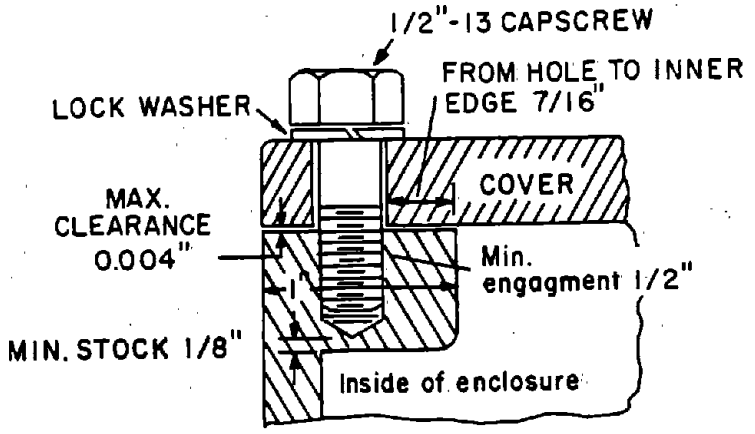

Figure 14.2. Typical Plane-Flange Joint, Enclosure Internal Volume Larger than 124 in^3.

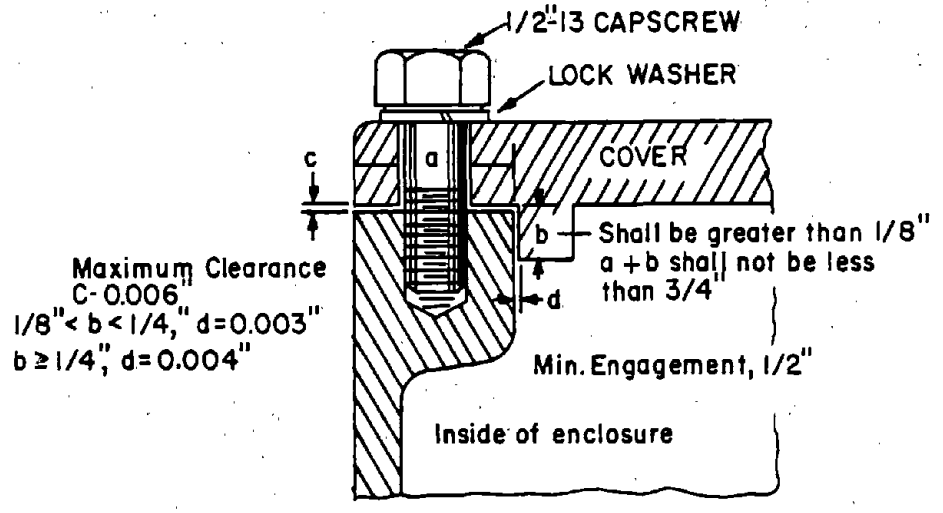

Figure 14.3. Typical Step-Flange Joint, Enclosure Internal Volume Larger than 124 in^3.

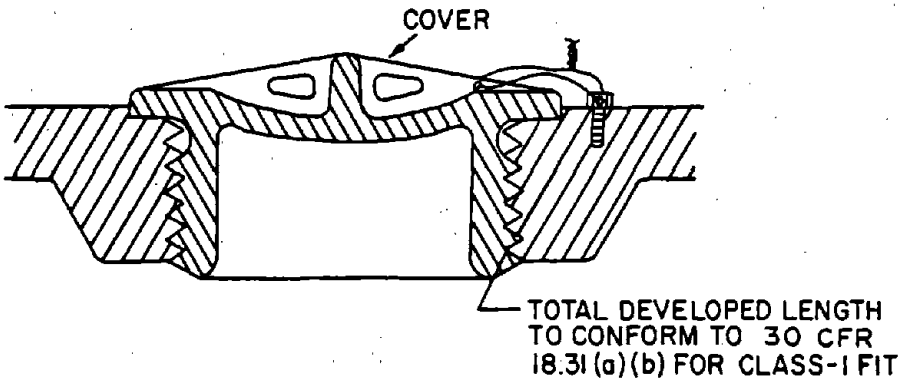

Figure 14.4. Threaded Joint.

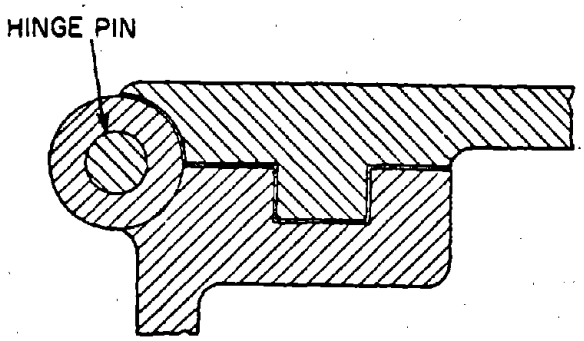

Figure 14.5. A Tongue-and-Groove Joint.

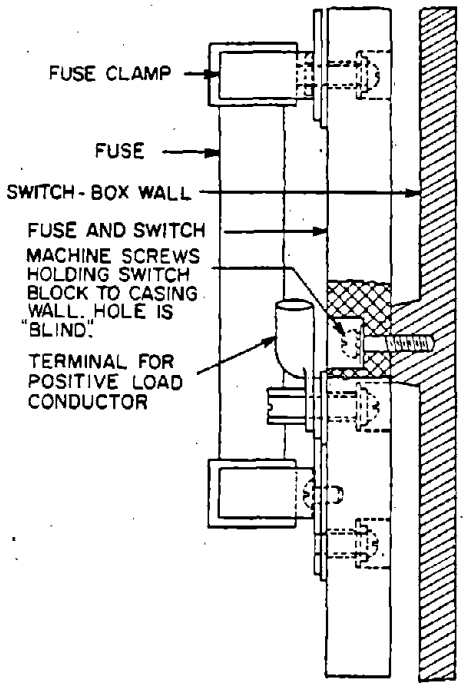

Figure 14.6. A Blind Screw Hole.

Table 14.1. 30 CFR Part 18 Structural-Gap Dimensions.

	EMPTY ENCLOSURE VOLUME, V		
	$V<45in.^3(738cm^3)$	$45in.^3<V<124in.^3$	$V>124in.^3(2032cm^3)$
Flanged joints in one plane:			
Min. width of joint, L:	1/2"(12.7mm)	3/4"(19mm)	1"(25.4mm)
Max. gap: (clearance):	0.002"(0.051)	0.003"(0.076)	0.004"(0.102)
Step-flange joints in two or more planes (cylinders or equiv.):			
Min.width of joint, L:	3/8"(9.53)*	5/8"(15.9)*	3/4"(19)*
Max gap: Plane portion:	0.006"(0.152)	0.006"(0.152)	0.006"(0.152)
Portion perpendicular to plane:	0.008"(0.203)*	0.008"(0.203)*	0.008"(0.203)*
Cylindrical Joints other than Shafts:			
Min. length of flame path, L:	1/2"(12.7)	3/4"(19)	1"(25.4)
Max. radial clearance:	0.0015"(0.038)	0.002"(0.051)	0.003"(0.076)
Shafts with Sleeve Bearings:			
Min. length of flame path, L:	1/2"(12.7)	3/4"(19)	1"(25.4)
Max. radial clearance:	0.003"(0.076)	0.004"(0.102)	0.005"(0.127)
Shafts will ball or roller bearings:			
Min. length of Flame path, L:	1/2"(12.7)	3/4"(19)	1"(25.4)
Max. radial clearance:	0.010"(0.254)	0.0125"(0.546)	0.015"(0.381)
Min. Bolt Diameter	1/4"	1/4"	3/8"

* If perpendicular portion is more than 1/8 in. but less than 1/4 in., Maximum radial clearance shall not exceed 0.006 in. Neither plane nor perpendicular portion shall be less than 1/8 in.

and West Germany. Most work performed has resulted in the same conclusions, but U.S. regulations (2) differ from foreign requirements mainly in philosophy. The general international consensus of opinion is that design standards for explosion-proof enclosures are imperative.

The maximum experimental safe gap (MESG) is often a standard used to determine the explosion-transmission properties of a flame path. MESG is measured by igniting a flammable-gas mixture inside a test system and observing if a surrounding gas mixture outside the enclosure ignites (1). MESG is the largest gap size for a flame-path length that does not permit ignition outside. Relatively speaking, a higher MESG implies a safer situation. A luminous flame can pass through the flange as long as it has insufficient energy to ignite the surrounding atmosphere. The definition given earlier for explosion-proof enclosures used in U.S. mines does not coincide with that for MESG (2). A gap (MESG) that will not allow ignition is 8 to 10 times larger than a gap which quenches the visible flame (1).

The following statements can be made about past research findings (1,15,16). A parenthetical comment is made if these conflict with present federal regulations (2).

1. MESG increases as the enclosure volume decreases because thermal losses predominate in small enclosures. Accordingly, smaller flange widths with the same gap can be allowed for smaller enclosures.
2. It is not likely that the use of gaskets or O-rings to make explosion-proof containers weather-tight has any significant effect on enclosure safety as long as they are restricted from the flange surface.
3. There is no assurance that metallic construction is essential for the flange construction. (Federal regulations generally require metal-to-metal joints except for headlight and meter enclosures.)
4. Surface finish is not considered critical by most authorities. (Federal regulations require that flat surfaces be planed to within one-half the maximum clearance allowed, and finished to not more than 250 μin.)
5. The apparent safe gap between bolted flanges (usual commercial construction) is considerably smaller than would be predicted from immovable flange tests.
6. Evaluating the effectiveness of explosion-proof enclosures or studying flange-gap quenching is still highly empirical.

Certain researchers have dealt with some other specific subjects pertaining to the MESG. Torry (17) established that no affect can be ascertained over the humidity range of zero to 50%, but MESG decreases as humidity increases from 50 to 100%.

Consequently, MESG can be measured confidently when under 50% humidity. By varying the methane-air mixtures inside and outside, in addition to the flange gap, Titman and Torry (18) found the most ignitable outside air mixture was 6.5% methane with a 9.5% internal mixture. James (19) varied the temperature in several plane-flange experiments. Using an 1.0-in. (25.4 mm) joint, he found the gap that would just permit propagation to the outside was 0.045 in. (1.14 mm) at 80°F (25°C) and 0.035 in. (0.89 mm) at 500°F (260°C). He stated that with a safety factor, it is not wise to exceed a gap of 0.020 in. (0.51 mm) for an 1.0-in. flange width. Furthermore, without a consideration of enclosure material strength (for plates, covers, etc.), a value of 0.02 in. cannot be applied to plane flanges, one part of which is a plate which could spring or bend during an internal explosion thus increasing the gap. James also showed that explosion-proof compartment safety was influenced more by slight changes in gaps than by slight changes in the flame path.

With other conditions remaining constant, several researchers have discovered that doubling the flange width increased MESG by about 1.3 (1,15,18). The statement is limited to flange widths 25 mm (1.0 in.) and less, because wider flanges are not common; therefore, very little data are available. As the flange width nears 25 mm, the relative effect of widening decreases.

Phillips (15,16) found quantitatively that the MESG should be smaller if the initial enclosure temperature is raised. Furthermore, turbulence outside the enclosure increases MESG. He empirically substantiated the enclosure-protection theory presented earlier in this section. Most of his work has been further substantiated by other authors' experimental results.

30 CFR Part 18 (2) and Underwriters' Laboratories (1) will not permit passage of flame (their flange-gap and width specifications are almost identical). This consequently means that their allowable gaps can be no less than 8 to 10 times smaller than those just stated. Short (20) says that by using the larger gaps as dictated by MESG, testing authorities can allow for deterioration over a period of years due to corrosion or other adverse elements. However, in talking with various foreign testing authorities, he found that none would accept a product for testing which would be supplied with wide gaps as dictated by the MESG. In practice, other countries want gaps which are very similar to those specified in the United States.

Problems encountered with deterioration, naturally from the mine environment, through neglect, or any other reason, means that the safety factor for a flange must be a significant multiple of the MESG. Thus, U.S. requirements are justified. More will be said about joint deterioration shortly.

Enclosure Mechanical Strength and Internal Pressures. The maximum internal pressure developed during the ignition of an

explosive-air mixture in the enclosure is directly dependent upon the amount of venting through flange gaps and, if available, auxiliary pressure-relief devices. Accordingly, this subject is interconnected with the material just covered, the possible transmission of an explosion to a surrounding atmosphere.

In addition to explosion-proof-enclosure flame tests, explosion-pressure and pressure-rise measurements are normally performed. The former measurement has the main goal of proving that the container will withstand an internal explosion and, combined with another test, that the enclosure's mechanical strength is adequate. Associated is one of the most important reasons for testing, to ensure against flange-gap distortion.

30 CFR Paragraph 18.31 (a)(1) states that cast or welded enclosures shall be designed to withstand an internal pressure of 150 psig (10.6 kg/cm^2) and determines that casting shall be free from blowholes (2). The regulations continue the mechanical-strength subject by specifying that welded joints forming an enclosure shall be continuous gas-tight welds and, further, that all welds shall be in accordance with the American Welding Society standards. In addition, minimum allowed thicknesses for enclosure walls, flanges, and covers are outlined. Again, a comparison of past research will assist in understanding these regulations.

Nagy and others (21) have conducted extensive tests on methane-air and coal-dust explosion pressures in enclosed vessels. Thirty-eight tests were performed on varying enclosure geometries with internal volumes ranging from 0.043 ft^3 (101.5 cm^3) to 905 ft^3 (25.63 m^3) and methane and air mixtures from 6.0 to 14.1%. The test results are summarized by the following.

1. With an ambient internal pressure of about 14.2 psia, the maximum pressure developed for all enclosures was 119.6 psia (8.41 kg/cm^2).
2. When the ambient internal pressure was at 17.6 psia, the maximum was then 143.3 psia (10.07 kg/cm^2).

Both maxima were obtained from examination of a 1.0 ft^3 (2359 cm^3) vessel with 9.4% methane-air mixtures. From 39 experiments, using the same enclosure but a Pittsburgh-seam coal dust, a maximum pressure of 119.3 psia (8.39 kg/cm^2) occurred with a concentration of 0.6 oz/ft^3 (601 g/m^3) in an 0.32 ft^3 (7.55 cm^3) vessel. They concluded from these experiments that:

1. vessel size did not effect the maximum pressure level if heat loss was neglected;
2. the rate of pressure rise decreased as the vessel size increased;
3. the vessel shape did not effect the maximum pressure if heat loss was neglected;
4. a change in initial pressure produces a proportional change in the maximum pressure and the rate of pressure rise;

5. the changes in the initial pressure produced an inverse change in the maximum pressure and rate of pressure rise.

Assuming standard atmospheric pressure, the federal regulations allow 164.7 psia. Noting that the maximum pressure developed in an explosion is a function of venting, the closed-system enclosure could be considered the worst pressure case. The maximum permissible flange gap is rather small and therefore restrictive to venting. Consequently, the federal specification (when compared to Nagy and others' results) does provide some margin of safety.

Magison (1) states that one of the most significant general facts about explosion-proof-container performance is that higher maximum pressures and rates of pressure rise are associated with small flange gaps (for the same flange width with identical explosive gas mixtures). In referring to the work performed by the Safety in Mines Research Establishment (22), he declares that the venting effect of the maximum experimental safe gap in an eight-litre (488 in^3) sphere reduces maximum pressures to a few pounds per square inch (ignition of 9.8% methane-air mixtures). Magison, in disagreement with Nagy and others, indicates that the actual maximum pressure reached in an enclosure will depend on container geometry and size plus the inside equipment arrangement.

Stressing the strength requirement, MSHA pressure tests are two-fold (2). The first primarily determines the explosion-proof characteristics and specifies that an explosive mixture within the enclosure will be ignited electrically and the explosive-pressure developed therefrom recorded. The test is repeated a minimum of 16 times due to the variation of ignition points, atmospheric composition, and operating status of motors. No part of the enclosure shall rupture nor have permanent distortion exceeding 0.04 in. per linear foot. However, when 125 psig is exceeded during any test, the enclosure can be rejected unless it is reconstructed (to reduce the pressure) or can withstand a dynamic pressure twice the highest value recorded in the initial test. The second or "static-pressure" test is only applied when MSHA's Approval and Certification Center determines a visual inspection will not reveal casting or weld defects. The applied pressure is 150 psig or 1.5 times the maximum value recorded during the explosion tests, whichever is greater.

Pressure Vents. Conventional explosion-proof enclosures release internal-explosion pressure through their flange and shaft gaps. At times, "pressure-venting" devices are also added by some manufacturers. The concept is depicted in Figure 14.7, where the vent exhibits a large effective area for gases from an ignition but provides cooling and inhibiting to arrest the flame (13). A cross section of a pressure vent, recently developed under USBM contract, is presented in Figure 14.8. A substantial

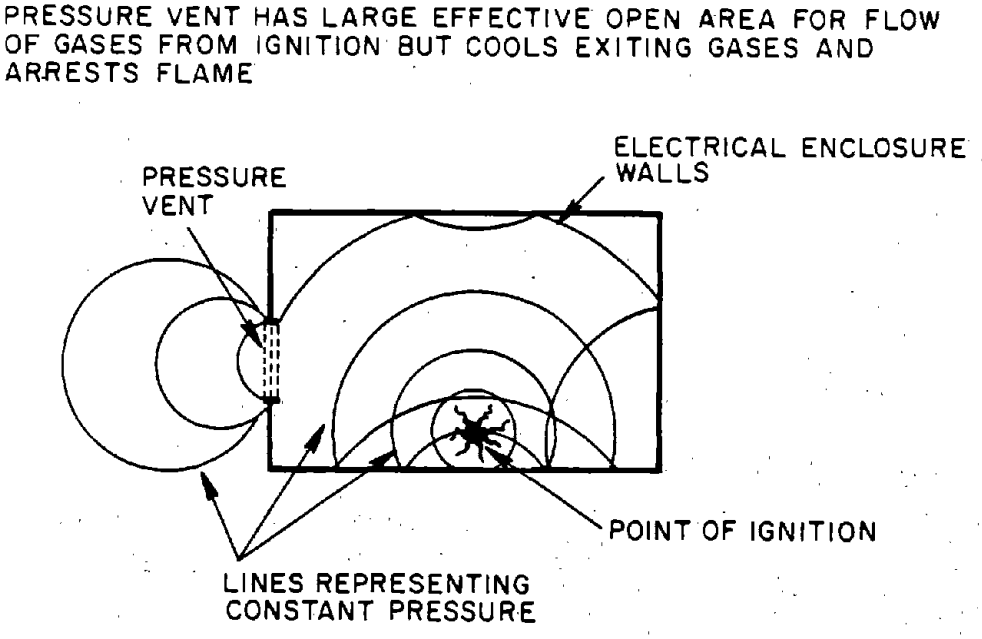

Figure 14.7. A Pressure Vent Limiting Pressure Build-Up During an Internal Explosion.

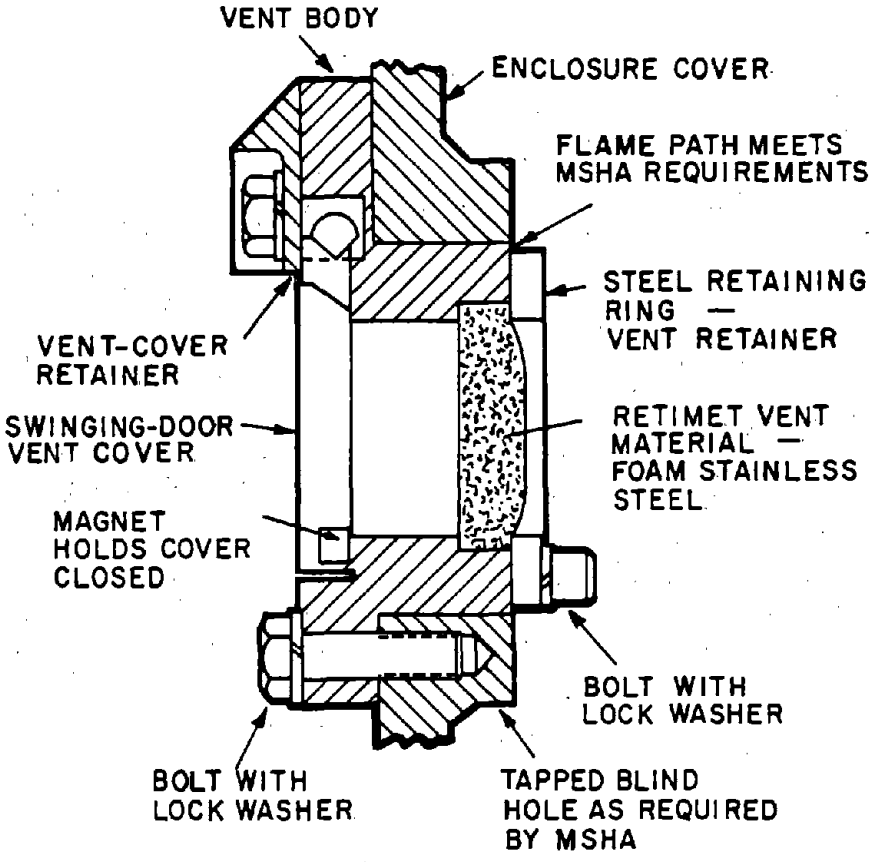

Figure 14.8. A Pressure-Vent Assembly Using a Metal-Foam Material.

improvement is obtained with properly sized vents because maximum pressures during internal explosions are only on the order of 12 to 20 psi (13).

Windows and Lenses. An allied subject but an inherent part of mechanical strength are windows and lenses. Federal regulations declare that MSHA may wave window and lens material testing except for headlight lenses (2). All window and lens material shall be sealed in place or provided with correct flange joints and, furthermore, shall be protected from mechanical damage by structural design, locating, or guarding. If the exposed material area exceeds 8.0 in.^{2} (51.6 cm^2), the window or lens, excluding headlight lens, must be protected with guarding or the equivalent. Both thermal-shock and impact performance tests are outlined in the federal regulations.

Limitations of External Surface Temperature. The external surface temperature of all permissible mechanical or electrical components shall not exceed 150°C under normal operating conditions in U.S. mining applications (2). Underwriters' Laboratories, Inc., has a similar specification but it applies only to dustproof enclosures (23,24).

Considering enclosure surface contact, four hazardous coalmine mixtures may be ignited:

1. a methane-air mixture,
2. a coal-dust-air mixture,
3. a combined methane/coal-dust mixture in air, and
4. collected coal dust on the enclosure surface.

The lowest auto-ignition temperature must be the restraint. Eliminated immediately is the auto-ignition of the most incendive methane-air mixture (9.8%) which is accepted to be approximately 640°C (1).

Nagy and others (25) have performed both coal-dust cloud and layer minimum-ignition-temperature measurements on several U.S. coals. Their dust-cloud experiments of 22 different coals indicated the average minimum ignition temperature was at 617°C. A low ignition value of 440°C occurred for a Colorado high-volatile coal. Layered-dust tests performed on 16 U.S. coal samples showed an average minimum ignition at 222°C, but here the lowest value was 160°C for a high-volatile Illinois coal. Ten of their layer tests resulted in minimum ignition temperatures of 190°C or below.

This last work proves that layered coal dust is the limiting factor for maximum allowable enclosure-surface temperature and shows justification for the 150°C requirements. This is especially important for mining or preparation-plant equipment on which coal dust can easily accumulate.

Cable Entrances. Cable entrances are openings through which electrical connections are safely carried to the interior of

explosion-proof enclosures. They are important components in the construction and maintenance of enclosures, mainly because of the frequent replacement of trailing cables demanded on permissible mobile mining equipment.

The "packing gland" or "stuffing box" is the most popular type of cable entrance. There are two general types: straight-through and angle-entry. Figures 14.9, 14.10, and 14.11 show "slip-fit" stuffing-box types where the box is a separate component, the cylindrical part of which fits into a hole in the enclosure wall (2). Radial clearance between the wall and the box must not exceed 0.003 in. with a flame-path length of 1.0 in. Figure 14.12 illustrates a typical plug for a spare cable-entrance hole (2). Figure 14.13 details a common construction for a packing gland that is an integral part of the enclosure (2).

As shown in Figures 14.9 and 14.13, the conventional construction of a stuffing box is such that the packing-gland nut is threaded into the opening and tightened, forcing the stuffing material against the cable and making a very tight joint. The packing material is almost always untreated asbestos, although elastomeric grommets are allowed (2). When compressed, there must be at least one-half inch of packing along the length of the cable, and the packing-gland-nut clearance from the stuffing box must be no less than 1/8 in. nor more than 1/4 in. (35).

Repacking a stuffing box correctly in the mine can be extremely awkward and time consuming. A recently introduced system, shown in Figure 14.14, greatly simplifies the assembly (13). Although very similar in appearance to the conventional slip-fit packing gland, it uses a tapered polyurethane grommet in place of the asbestos. The grommet has high compressibility so one size might accomodate a range of cable sizes in the future.

The requirements for leads passing between explosion-proof compartments separated by a common wall are not as rigid as where the conductors pass through an exterior wall. One type, the insulated-stud entrance, is shown in Figure 14.15. Here, the conductor does not physically pass through the wall but is connected to a stud, a finished brass casting. The stud is isolated from the enclosure wall by an insulated tube and washers.

Materials Used in Explosion-Proof Enclosures. The basic assumption used to this point in the chapter is that the worst possible case for an explosion-proof-enclosure ignition would be due to a methane-air mixture within the enclosure. The basic definition of an explosion-proof enclosure given earlier contains this assumption. Recently, however, some mining experts have begun to believe that materials used in electrical-equipment construction may lead to hazardous conditions when utilized in an enclosure. The concern is that when an explosion occurs, due to an arc or short circuit within the container, gases may be generated which would defeat the explosion-containment properties.

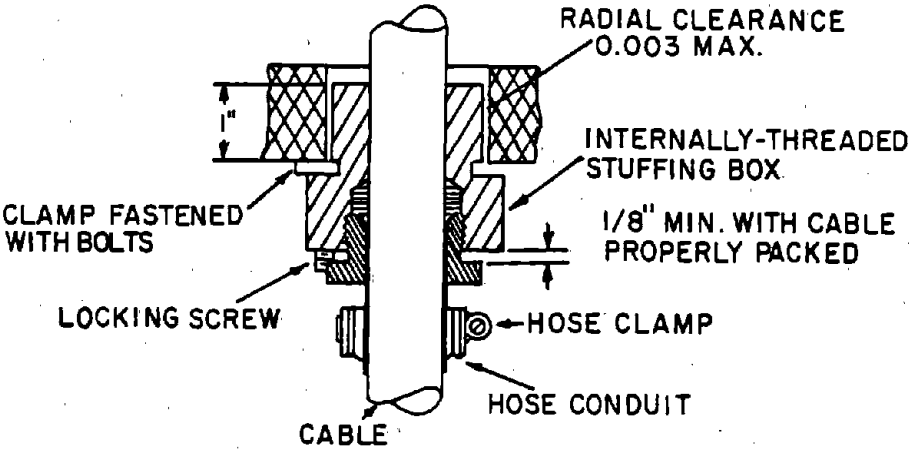

Figure 14.9. Typical Slip-Fit Straight-Type Stuffing-Box and Packing-Gland Lead Entrance.

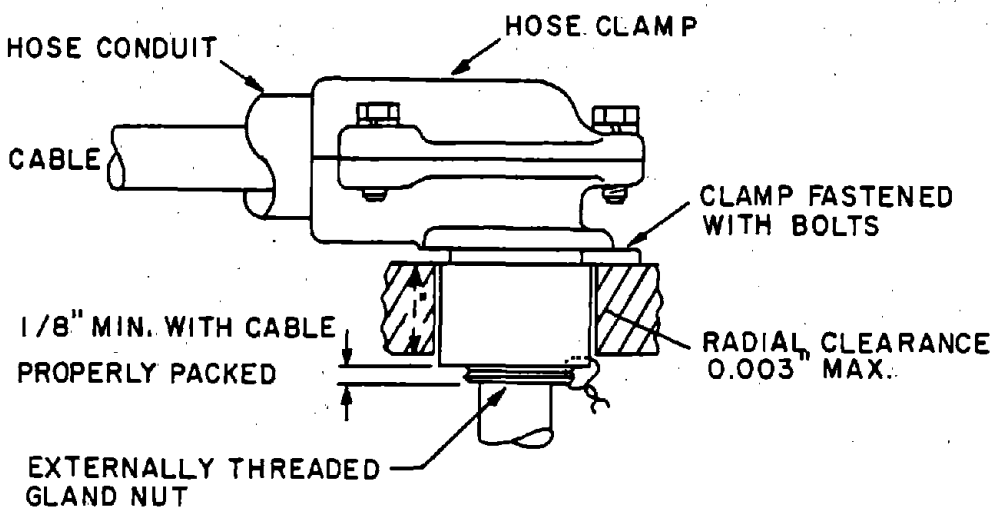

Figure 14.10. Typical Slip-Fit Angle-Type Stuffing-Box and Packing-Gland Lead Entrance with Hose Clamp.

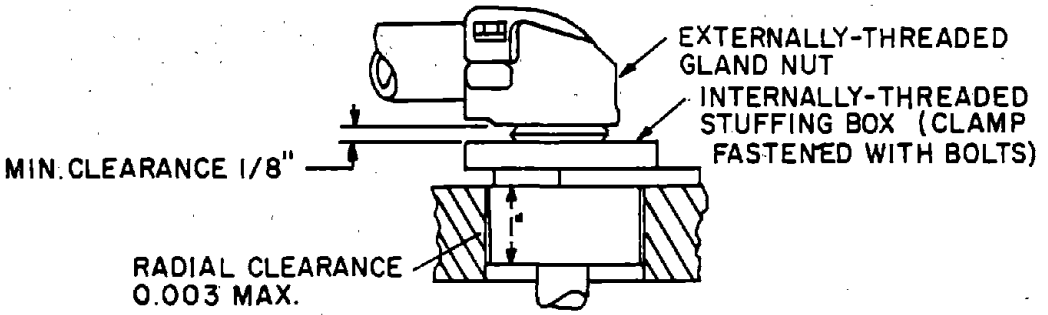

Figure 14.11. Typical Slip-Fit Angle-Type Stuffing-Box and Packing-Gland Lead Entrance.

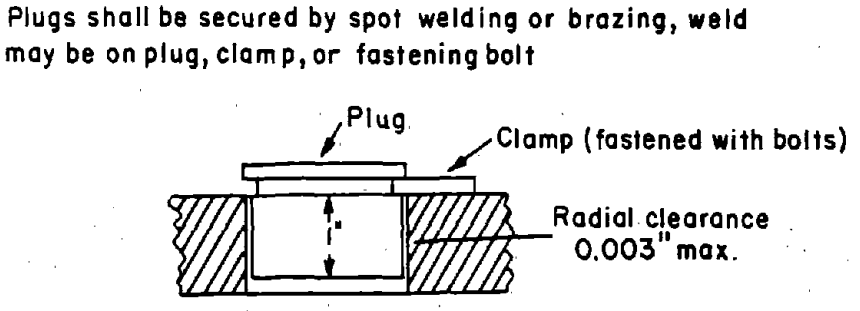

Figure 14.12. Typical Plug for Spare Lead-Entrance Hole.

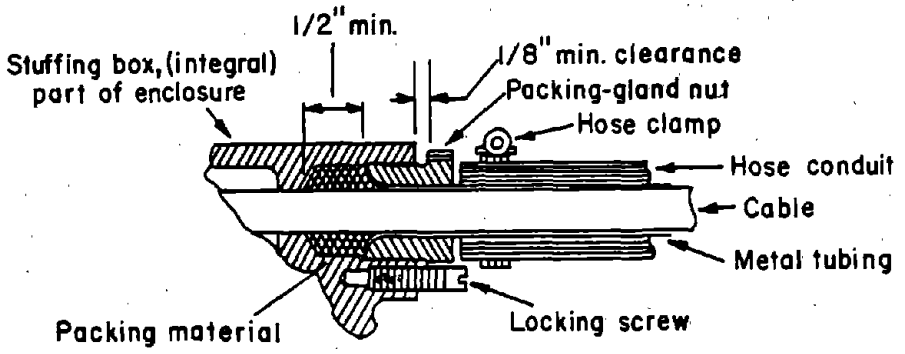

Figure 14.13. Typical Threaded Straight Stuffing-Box and Packing-Gland Lead Entrance with Provision for Hose Conduit.

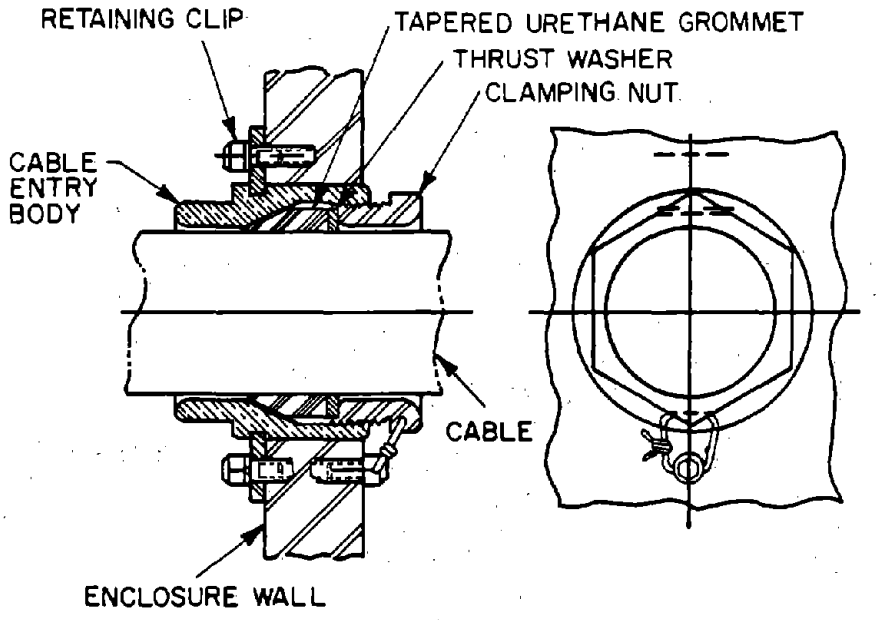

Figure 14.14. Prototype Trailing-Cable Entry with Polyurethane Grommet.

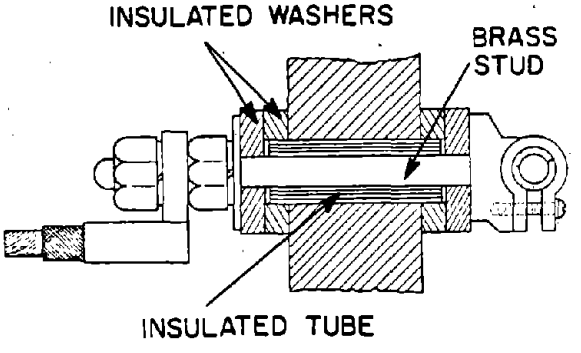

Figure 14.15. Insulated Stud-Lead Entrance.

When a high-voltage short-circuit arc occurs within an explosion-proof enclosure, a number of enclosure-failure modes are known to be possible. Those of most concern may be classified as follows.

Burning Through the Enclosure Wall. The possibility exists that once an arc is established within an enclosure, it may jump across to the enclosure wall. The intense heat and power might then cause the arc to burn through the wall. Killing and Tielke (26) have demonstrated this possibility quite convincingly.

Ignition Transmission by Hot Gases or Flame. To reduce explosion pressures, flange gaps are provided to vent expanding gases. The size of such gaps is critical as they must be large enough to perform the venting function successfully, yet small enough to prevent ignition transmission from inside the enclosure to the surrounding atmosphere. It will be shown later that combustible gases (such as hydrocarbons) may be present under fault conditions if organic insulation is used within the enclosure. This could lead to defeat of an ignition-containment requirement designed only for methane.

Particle-Ignition Transmission. Arc formation between two metal conductors (usually copper) within an explosion-proof enclosure may also cause surrounding-atmosphere ignitions by a particle process. Here, the heat from the arc causes hot-metal particles to be separated from the conductors, and the pressure buildup within the enclosure may cause these particles to be expelled into the surrounding atmosphere through the flange gaps. These hot-conductor particles alone are capable of igniting a surrounding combustible gas-air mixture. Accordingly, the maximum experimental safe gap must be small enough to prevent these particles from reaching the outside. Tests have shown that under certain conditions this MESG may be significantly smaller than that required for flame transmission (27). The small gaps required by U.S. regulations (2) are further substantiated by this concern.

Enclosure Deformation or Bursting. If enclosure flange gaps are made small enough to ensure no ignition propagation by expulsion of hot gases, flame, or hot particles, the possibility then exists for high pressures to build up within the explosion-proof container under fault conditions. In this case, covers may be blown off, and ignition with the surrounding atmosphere may occur.

Davidson and Lord (28) state that half a dozen incidents have been reported in Germany, one in Canada, and two in the United Kingdom, of flameproof enclosures bursting under internal pressure. (The United Kingdom and Canadian instances involved enclosures with gap specifications similar to U.S. regulations.) In a typical instance, a steel cover was thrown several meters after shearing apart fourteen 12.5-mm diameter securing bolts. In all these cases, there has been heavy electrical-fault damage

within the enclosure, including severe charring of organic electrical insulating material. Ciok (29) states that high-voltage short circuits within flame-proof enclosures installed in Polish coal mines have become a matter of concern. In this situation, the subject short circuits have occurred several times, and each time the covers closing the equipment chamber have been blown off.

The cause of such high pressures within enclosures, designed according to present standards, appears partly due to the evolution of gases from organic insulating materials used within the enclosures. Simon (30) describes experiments where organic insulating materials within an enclosure are subjected to heating by an electrical-fault arc. He shows that in such tests, evolved gases are capable of causing pressure build-up leading to enclosure defeat. Upon enclosure bursting, the evolved gases (consisting primarily of H_2, CO, N_2, and CH_4) ignited spontaneously upon contact with the external atmosphere. It is apparent that more gaseous products were produced from the insulating material than could escape through the flange gaps, and the enclosure ruptured after a period of time. If the flange gaps or pressure vents would allow all the volatilization products to escape, no enclosure failure would occur. (However, escaping hot gases must be considered.)

Another factor which might contribute to the worsening of this situation is an effect which has been investigated by Brown and others (31) and Bossert (32). It is known that hydrocarbon-air flames produce free ions which cause an electrical current to flow when the flame front bridges two points of opposite electrical polarity. This current may be enough to form an arc discharge. Therefore, an initial flame within an enclosure (caused by a fault condition) might produce ions that can contribute to additional faults within the enclosure. This may be particularly true if organic insulating materials are present. In such situations, the initial fault may produce hydrocarbon gases through thermal insulation breakdown, and the burning of these gases might induce additional arcing. This possibility should increase as voltage levels are raised. A chain-reaction effect may therefore be possible which could lead to enclosure deformation or bursting.

Apparently, materials that could possibly contribute to overpressures and enclosure failure can be summarized as those that give off gases when they are subjected to heating during an electrical fault. It also appears that materials which evolve combustible gases constitute the greatest hazard. These are primarily insulating materials and accumulated water. The combustion of these gases may cause additional pressure and arcing within the enclosure.

When water is subjected to an electrical current, electrolysis takes place, and hydrogen and oxygen are evolved. This constitutes a very undesirable situation which has been substantiated in

the experiment quoted earlier. Water accumulation within enclosures should be avoided as much as possible. Not only does this have the potential of creating faults but, if a fault does occur, it may contribute significantly to increased enclosure pressure.

When organic insulating materials are subjected to electrical arcing, tracking, or heating, decomposition takes place yielding various gases, both combustible and non-combustible. During the past 30 years, the trend by electrical-equipment manufacturers has been towards the many newly developed organic polymers for insulating purposes and away from the traditional insulants (cellulose, natural fabrics, asbestos, mica, porcelain, glass, etc.). These traditional insulants are still in common use however. Therefore, it is quite possible to find just about any known insulation within an explosion-proof enclosure. Categorizing the many types and variations of insulating and plastic materials that are likely to be found is extremely difficult because of the large number involved. Fortunately, research of the important types has been performed, and a short summary of those that evolve dangerous gaseous products follows (33).

Cross-Linked Synthetic Polymers. This group contains the basic synthetic resins which are commonly utilized in the manufacture of plastic materials. Of these, the phenolic, epoxy, and silicone resins appear to offer the greatest hazard potential due to their high yield of combustible volatile products. The amino (melamine) polyester, polyurethane, and isocyanate resins appear to have a lower yield of combustible volatile products. Materials made with these resins should therefore exhibit a lower (though still quite significant) hazard potential.

Linear Synthetic Polymers and Elastomers. This group contains many of the well-known types of insulators. The worst potential hazards (similar in magnitude to that of the cross-linked group) appear to be associated with polypropylene, polymethylene, polystyrene, polyethylene, neoprene, and polymethylmethacrylate. Other materials such as NBR synthetic rubber, natural rubber, SBR (GR S) synthetic rubber, dacron, teflon, polyvinylchloride, polyurethane, polyvinyl formal, and nylon show less though still very significant hazard potential.

Other Possibly Dangerous Materials. Insulating oils should also be considered a high-hazard material. Even though the gases formed are initially dissolved in the oil, they may eventually (upon saturation) be evolved causing an unsafe situation. A similar statement may be made about oil-impregnated paper. Other materials, such as cellulose and cotton, which do not appear dangerous at first glance, could also contribute to a hazardous condition due to the amounts of water and carbon monoxide evolved.

Safe Materials. Whenever possible, the electrical insulating materials which should be used in explosion-proof enclosures are the electrical porcelains, ceramics, glasses, asbestos, and mica.

These materials are the most resistant to the production of gaseous products when exposed to heating or arcing. These recommendations consider only the contribution of possible evolved gases to increased enclosure pressures. Toxicity is not included.

It does not appear feasible to eliminate all potentially hazardous materials from enclosures. However, the use of any material which will evolve gaseous products under fault conditions should be avoided whenever possible. Of course, it must be realized that if a sustained arc occurs, even the conductors are vaporized, so the above statement is relative. Therefore, the materials to be primarily avoided should be those which are most easily volatilized and particularly those which evolve large amounts of combustible gases.

Permissible Equipment. At the beginning of the chapter, it was stated that the term, "permissible equipment," only applies to a completely assembled electrical machine or accessory which has been granted formal approval as authorized by the Administrator, MSHA. The term, "completely assembled," involves all equipment portions from the protection at the power source, the trailing cable, to all internal and external components of the machine. Furthermore, no machine which has been changed from what was approved may be placed in service until the "field" modification has been reviewed and approved by MSHA. Thus, the subject of explosion-proof enclosures is only one aspect of permissibility, and this chapter's purpose is to cover the unique requirements of hazard-reduction systems. Details on the permissibility requirements for trailing cables and components can be found in Chapter 7; protective devices, Chapters 8 and 9; grounding, Chapter 6; and battery equipment, Chapter 13.

However, to see how all this information is tied together, the next paragraphs briefly present the procedures that MSHA uses to investigate prospective permissible equipment for safety. Afterwards, a discussion is presented about recommended procedures for checking equipment after it has been placed in service. This will summarize basic information on maintaining explosion-proof enclosures and permissible equipment in proper condition.

Permissible-Equipment Schedule.[1] The published regulations for the investigation of mine equipment containing explosion-proof components are contained in 30 CFR Part 18 (2). Other regulations that might be applicable are Parts 19 through 29 for electrical and Parts 30 through 36 for mechanical. Each of these parts is often termed a "schedule." From time to time, they are revised to be in-line with equipment development and to permit as much freedom of design as possible without lowering standards. However, the general nature of the following information likely will not change.

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[1]This information was extracted from a Bureau of Mines publication, Reference 34.

Under the regulations, investigations are made to determine approval (permissibility) of equipment, such as continuous miners, shuttle cars, battery-powered vehicles, pumps, distribution boxes, and so on, and for certification of components, like trailing cables, explosion-proof enclosures, connectors, and battery trays. "Certification" means that the electrical component complies with applicable requirements and is suitable for incorporation in permissible equipment. Investigations for approval are divided into three consecutive major parts: detailed inspection of the equipment offered for approval, tests of the equipment or internal components in explosive gas-air mixtures and/or adequacy tests where desirable, then a final inspection of the tested accessories in the completely assembled unit or machine for which approval is desired. Investigations for certification of components can follow the same process, but often only the first two steps are necessary. Before the investigation can commence, a written application must be made to MSHA, accompanied by a detailed set of applicable drawings, wiring diagrams, specifications, descriptions, and any related material. (Special precaution must be stated if equipment contains intrinsically-safe components; these requirements will be covered later under that section.)

The inspection of the equipment is an important part of the investigation. When approval is being considered, only those components that have a bearing on permissibility are studied. Only one motor, controller, protective device, or any other unit of a given design is required. The work starts with a detailed check of all parts against the drawings to see that both coincide and the minimum requirements have been met. Exact measurements are performed on the dimensions of joints, bearings, pressure vents, and other possible flame-arresting paths in enclosures. The following points are also examined:

1. any unnecessary through holes;
2. adequacy of design and construction of cable and lead entrances;
3. adequacy of electrical insulation and clearances between live parts and between live parts and the enclosure;
4. weaknesses in welds and flaws in castings;
5. distortion of enclosures before tests; and
6. adequacy of fastenings, including size, spacing, security, and possible bottoming.

Quality of material, workmanship, and design is an extremely important aspect of this inspection. Only equipment adhering to the following two statements will pass (2).

1. "Electrically operated equipment intended for use in coal mines shall be rugged in construction and shall be designed to facilitate inspection and maintenance."
2. "Only electrical equipment that is constructed of suitable materials, is of good quality workmanship, based on sound engineering principles, and is safe for its intended use" will be tested by MSHA."

Testing involves two main areas: explosion-proof characteristics and component properties. The general nature of the explosion testing has been covered earlier. No less than 16 internal explosions are made at various ignition points, using a methane-air mixture for all and with bituminous-coal dust added on some. Either the actual internal electrical equipment or dummies of equal dimensions must be in place for a prescribed number of tests. Motor rotors are tested in both stationary and rotating modes. An enclosure can be rejected if there occurs:

1. discharge of flame from any joint or opening,
2. ignition of an explosive mixture surrounding the enclosure,
3. development of afterburning (gas drawn into the enclosure by the vacuum created by the explosion, then ignited by host particles within the enclosure),
4. rupture of any part of the enclosure or any panel or divider within the enclosure, or
5. permanent distortion of the enclosure exceeding 0.04 in. per linear foot.

In addition to the foregoing, certain other tests or examinations are made, some are at the discretion of MSHA investigators, to determine the adequacy of the component for the service intended. These include:

1. to determine mechanically any points that require strengthening, where the durability of such components is in doubt;
2. to check the ventilation, electrical clearances, insulation, drainage, and service suitability for battery boxes;
3. to examine whether switches, circuit breakers, or contactors, intended to function as switches, are capable of interrupting maximum current permitted by the circuit's automatic protection device;
4. to test whether automatic circuit-interrupting devices provide necessary protection without damaging the explosion-proof qualities of their enclosures; and
5. to determine the flame resistance of cables (see Chapter 7), conveyor belting, and hose.

A final inspection of completely assembled new machines or substantially modified (previously approved) designs as a whole are made at the end of the investigation in order to determine whether the assembly has any unsafe features. Specific items cover:

1. compliance with joint, lead entrance, or other pertinent requirements;
2. wiring between components, adequacy of mechanical protection for cables, adequacy of cable clamping, positioning of cables (especially those in proximity of hydraulic components);

3. adequacy of protection against headlight, push-button, or other vulnerable-component damage;
4. settings of overload and short-circuit protection; and
5. suitable means of connecting and protecting the trailing cable.

Finally, a MSHA engineer may check the first of any given design of a machine built for approval, preferably at the factory where it was built.

When approval is granted, MSHA issues a notice of approval. This is sent to the manufacturer, accompanied by a photograph of an "approval-plate" design. Plates reproducing this design and all the information it contains are mounted in a conspicuous place on the machine. It serves to identify the machine or accessory as having met the applicable requirements of 30 CFR Part 18.

Maintenance Requirements. For equipment to retain "permissibility," it must be maintained in the same condition as approved. A definite advantage of knowing the schedule requirements is that essential details may be extracted to establish routine inspection and maintenance procedures in order to comply. Otherwise, safety can be easily compromised.

For instance, the presence of small unnecessary openings in explosion-proof enclosures may constitute an immediate danger. Such openings can result from a lack of understanding or negligence from the mine-maintenance crew; rarely are they caused by a manufacturing error. For instance, one of the most common violations cited by MSHA is "open box - .005," which means that a plane-flange gap has been found to exceed 0.004 in. (14). Other examples of common maintenance problems include (10):

1. undue wear on bearings where shafts enter explosion-proof enclosures,
2. improper assembly of (or loose) cable packing glands,
3. bottomed bolt or screw holes which have been drilled through,
4. drilled through-holes in enclosure walls to attach plates or components, and
5. holes burned through enclosure walls from contact with a current-carrying conductor.

In light of the foregoing statements, the following recommended maintenance precautions and procedures should be heeded when checking for permissibility or when working on explosion-proof equipment (1,10,14,35). For exact wording and in order to ensure precise compliance, reference should be made to federal regulations (2). The first part of this listing specifically concerns explosion-proof enclosures.

1. Before examining any apparatus for permissibility, the power source should be de-energized, locked out, and tagged. Particularly, the explosion-proof enclosure must not be opened until such is performed. (This should be

an obvious practice for any electrical equipment, be it permissible or not.)

2. All joint clearances should be examined with feeler gauges for maximum allowable gaps as given in Table 14.1.
3. The cleanliness of any pressure vent should be verified.
4. Missing bolts, lock washers, or ineffective fastenings of other types must be restored. All screw-type inspection covers must be secured against loosening.
5. All cover flange and thread surfaces must be treated with great respect; they must not be handled roughly. Anything that might possibly scratch or mar a joint or thread surface must not be allowed to come in contact with it, including tools. If a cover thread is damaged, it must be replaced. If any joint is scarred by any means, the equipment must be removed from service.
6. Cleanliness of joint and thread surfaces must be maintained if the enclosure is opened so foreign material cannot enlarge a gap. Before reassembly, all joints and threads should be carefully cleaned and, if necessary, a thin layer of lubricant may be applied. Caution should be taken so a lubricated joint again does not become contaminated. After reassembly all joint clearances should be rechecked.
7. Care should be taken to observe any possible corrosion on flanges, threads, shafts, bearings, and any other flame-arresting path. Corrosion inhibitors and lubricants may be used to retard corrosion. However, if any of these parts becomes corroded, the enclosure should be taken out of service and sent for repair. The corrosion products cannot be removed adequately.
8. Each enclosure should be carefully examined for burned holes.
9. All cable packing glands should be examined for tightness of cable fit. Clearance between the gland nut and housing should be checked for clearance.
10. Headlights should be checked for loose or broken lenses, loose packing glands, missing or broken parts, and improper assembly.
11. Accumulations of loose coal dust or other combustible materials should be removed as much as practical.

The next listing concerns items that are also within the general requirements of permissible equipment, but detailed information is contained in, or related to, other chapters.

12. Portable or mobile equipment must be properly frame grounded or provided with equivalent protection. Grounding and ground-check conductors must be attached to separate studs that are not attached to a removable panel. If a separate grounding conductor is used on d-c machines supplied by trolley power, the return

(usually negative) and grounding conductors must be attached to the rail or grounded conductor with separate clamps. Diode grounding is only acceptable for d-c equipment if the negative conductor at the source is solidly grounded.

13. All electrical components must be solidly attached to the machine frame. Light fixtures must be grounded with a grounding conductor.
14. No splices are allowed in the external wiring of permissible equipment, except for intrinsically safe circuits. Note: Cables in longwall installations are not considered trailing cables.
15. All conduit hose must be flame resistant and MSHA accepted. The condition of mechanical cable protection such as guards, conduit hose, and clamps, should be examined. Conduit hose should not be spliced, but worn or cut conduit hose may be repaired using MSHA approved flame-resistance cable-jacket repair material.
16. The type, size, length, and condition of trailing cables should adhere to federal regulations (see Chapter 7). A temporary splice cannot be made within 25 ft. of the machine, except for reeled applications. Short-circuit protection must be provided for all ungrounded power conductors by either properly adjusted circuit breakers or correctly sized dual-element fuses (see Chapters 8 and 9). Overload protection is recommended.
17. All trailing cables should be provided with effective strain relief at the entrance to the equipment.
18. Machine cable reels and spooling devices must be insulated from the frame with fire-resistant material, except reels insulated with insulating bushings. Rollers, sheaves, and reel flanges should be maintained so as not to damage cables, and reels should maintain a positive tension on the trailing cable during reeling and unreeling. Reel-collector rings should be examined for any deterioration which would cause a high-resistance contact.
19. All circuit breakers and other overload protection on the machine must be maintained in working order. A main circuit breaker, contactor, or disconnect switch must be provided on the machine, capable of de-energizing the entire machine except methane monitors. Headlights and flood lights should have a separate switch or other protection to open circuits in case of lens breakage.

The last portion of the listing addresses specific schedule requirements.

20. All mobile equipment must be provided with brakes, except where the machine design prevents accidental movement when parked.

21. If the machine is capable of traveling faster than 2.5 mph, headlights and red light-reflecting material must be provided on both the front and rear of the vehicle. Such vehicles must have an audible warning device.
22. Guards and "safe-off" devices for push buttons must be maintained in working condition.
23. An approval permissiblity (plate) must be attached to the equipment.

As a final precaution, the equipment should be carefully examined for any unauthorized changes not contained in the approval. Such equipment must be considered nonpermissible.

Explosion-Proof Summary. Explosion-proof enclosure techniques have been utilized in and about U.S. mines for several years, and equipment manufacturers have gained considerable expertise in the design and construction as outlined in the federal regulations. Several problems have been found with the coal-mine use of these enclosures. Specifically, protection properties are based on the proper flange gap, and any corrosion or foreign matter within the gap can reduce its effectiveness. In addition, once enclosures are opened for maintenance, the proper gap is sometimes difficult to reinstate, especially when covers are bent, surfaces marred, and bolts and washers misplaced. Because of "tight-places" hampering human access, checking some gap spacings with a "feeler" gauge is very difficult. Even though these and other problems are encountered, explosion-proof construction is still desirable. If the enclosures are maintained in correct condition, the technique is extremely effective. The heavy-wall construction is strong and robust and well suited to the mining environment. Furthermore, assembly, although not being an easy task, is obtainable by present manufacturing techniques.

14.3-3 Intrinsic Safety

General. "Intrinsically safe" equipment is incapable, under normal or abnormal conditions, of releasing sufficient energy to cause an ignition of the most ignitable methane-air atmosphere (2). Available energy from any component must then be limited to less than about 0.25 mJ (11). The principle applies to complete systems and not to individual components. The advantage is that safety is inherent in the design and is difficult to defeat. Safety cannot be compromised easily by maintenance, as can some other protective measures, such as explosion-proof enclosures.

"Normal conditions" include the effect of extreme power-supply and environmental variations, which are within the equipment specifications, as well as the opening, faulting, or grounding of all conductors leading to the apparatus (1). "Abnormal conditions" involve all failures of internal components and wiring.

Design. The design of intrinsically safe circuits is a subject too vast in scope to cover in this chapter. However, some important considerations.

1. maintenance of suitable spacings between uninsulated conductors (only if firmly tied down);
2. provide additional insulation, barriers, or partitions (isolation by construction);
3. the use of isolated transformer windings (e.g., axial displacement or grounded shields between primary and secondary windings);
4. isolation by potting or encapsulation;
5. limit of circuit capacitance and inductance (thus, the available stored energy);
6. limit of current and voltage; and
7. extensive circuit analysis and fault calculations to ascertain available energy under normal and abnormal conditions.

A prime worry of the last item is that with a failure of a single component, or subsequent failures resulting from that component (still considered a single component failure), the device must remain intrinsically safe (2). The fundamental design concept usually applied is that two unrelated failures, each independently detectable, but occurring simultaneously, cannot compromise safety. Hence, the unsafe might occur with a third failure, and two safeguards always exist between the safe and the unsafe conditions (1).

References 1, 36, and 37 can be consulted if additional information is desired. Furthermore, 30 CFR Part 18 contains extensive requirements and tests for approval of intrinsically safe equipment (2).

14.3-4 Other Hazard-Reduction Systems

Other valid methods of electrical hazard reduction find wide use in other industries and limited use in mining. This section will briefly discuss the concepts behind the more popular techniques. Two systems, lamina and labyrinth, are but variations of common explosion-proof enclosures and, therefore, will not be covered.

Increased Safety. "Increased safety" or "Protection Type 'e'" is an approach in hazard reduction where special design considerations are applied to ensure an extremely low probability of electrical or mechanical breakdown, which could produce a spark or temperature rise (1). Like intrinsic safety, the principal is to remove the ignition source. The technique is widely used in West Germany and is finding very good acceptance for mine lighting fixtures (38). Some of the design approaches include large spacings and creepage distances between live parts, excellence in insulation (in amount and quality), protection against hot spots, large rotor-stator clearances for motors, and special enclosures and fastenings to prevent unauthorized entry (39).

Immersion Techniques. Immersion systems rely on controlled environments to reduce or remove hazardous atmospheres from ignition sources. They can use granular material (e.g., sand),

encapsulation (sealing or potting), liquid (oil), or "inert" gas (purging or pressurized systems) to provide protection (1). The first actually does not isolate the source but quenches any incipient flame; thus, effective contact between the source and the hazardous atmosphere is impossible.

Complexity. The basic problem with most of these other hazard-reduction systems is complexity. The one showing most disfavor for mining applications is the pressurized approach (40). By far the most overriding considerations for electrical hazard reduction are robustness, interchangability, and mobility. As a result, there is no indication that bolted explosion-proof enclosures for coal mining will be replaced by these other systems in the near future.

14.3-5 Coal-Dust Locations

Hazards. The preceding has concerned permissibility and Class-I locations, specifically defined by an explosion methane-air mixture. When coal dust is involved, or Class-II locations, ignitions can occur from two modes.

First, like gases, a coal-dust concentration in air (dust cloud) above the lower explosive limit can be ignited by an arc and can present a severe dust-explosion hazard. However, the cloud is nonhomogeneous and the ignition also depends upon the dust volatile content (chemical composition), moisture content, ash, size, and shape (1). There is almost no explosion hazard when below 8% volatiles, such as in some anthracites and coke, but a fire hazard may exist. Bituminous coals and lignite, 30 to 40% volatiles, present serious dust-explosion hazards. Moisture contents that might prevent ignition range from 15 to 50%. Regardless, Bureau of Mines' research (25) has indicated the following for minus 200-mesh dry (less than 5% moisture) bituminous coal dust:

1. minimum energy, 5 mJ;
2. minimum auto-ignition temperature, 617°C; and
3. lower explosive concentration, 0.05 g/l with the upper limit ranging from 2 to 5 g/l.

It can be seen that the energy needed is many times greater than the minimum for methane-air mixtures. This minimum energy, however, exists at a concentration about 0.2 g/l and above. These variabilities obviously make dust explosions much different than for methane-air mixtures. Concentrations can be easily measured but, as a rule of thumb, the dust cloud is not above the lower explosive concentration if a person can see his outstretched hand in front of his face (25).

The second mode is dust-layer ignitions. Here, the minimum auto-ignition temperature depends mainly on the layer thickness but also on the particle size (41). The worry, then, is what thickness of coal dust is hazardous for a specified electrical-equipment surface temperature? Table 14.2 relates some pertinent

Table 14.2 Minimum Auto-Ignition Temperatures Versus Layer Thickness for Bituminous Coals.

Thickness	Low-Volatile Coal	High-Volatile Coal
5 mm	300°C	240°C
20 mm	250°C	190°C
50 mm	--	175°C
100 mm	--	160°C

values for bituminous coals (25,41). As stated earlier, the minimum surface temperature allowed for permissible equipment, 150°C, was based on this problem. Such apparatus would then be reasonably safe for thicknesses up to 100 mm (about 1/2 in.). However, almost no safety factor would be available if the coal dust were allowed to accumulate to that depth. Referring to Table 14.2, and applying a 1.25 safety factor to a 150°C surface temperature would imply that no more than 20 mm of dust should accumulate, or with a 1.5 factor, 5 mm. West Germany does not require that the maximum surface temperature be 75°C below the auto-ignition temperature for a 5-mm dust layer (38,41).

It could be argued that a particular moisture content might remove the layered-dust hazard. However, it is probable that the moisture would quickly evaporate from a coal dust covering surfaces with temperatures exceeding 100°C.

Area Classification. The decision flow chart of Figure 14.16 has been prepared to assist in the classification of Class-II locations for divisions using the National Electrical Code and the literature (1,3,42). Using the chart, it can be seen that a Division-1 location (see Section 14.2) occurs with:

1. a low-resistivity dust,
2. a high-resistivity dust in a frequent or periodic combustible cloud, or
3. a plant malfunction which may cause both a combustible dust cloud and electrical equipment to spark or overheat.

Division-2 locations are defined when:

1. a layered-dust thickness exceeds the minimum depth to propagate flame, or
2. a high-resistivity dust occurs infrequently in a combustible cloud.

The other Division-2 location should be noted, when the layered dust interferes with safe heat dissipation, but Magison (1) relates that this is implicit with item 1 above for any combustible dust. The cost-dust thicknesses presented earlier agree with his contention.

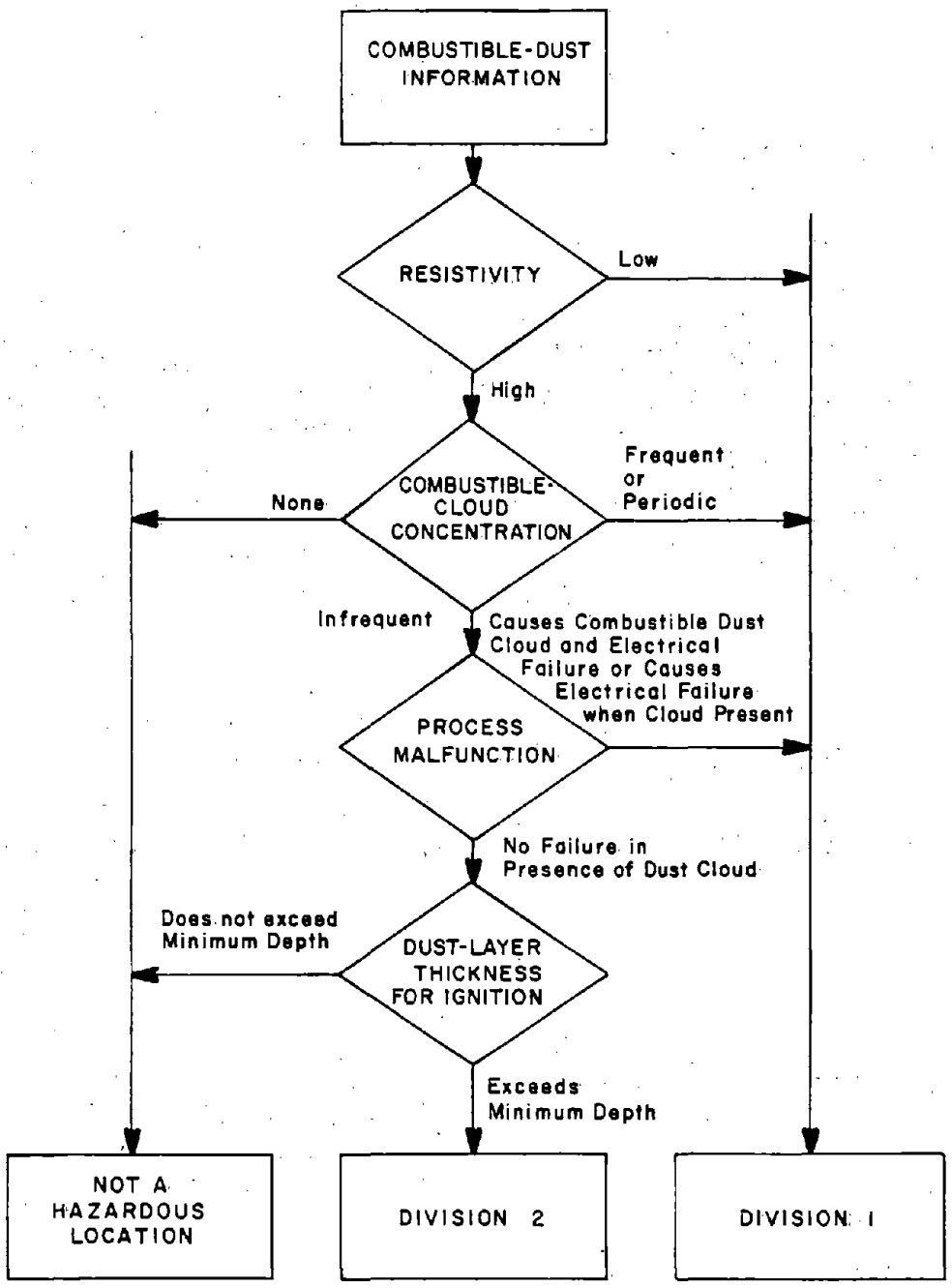

Figure 14.16. Decision Flow Chart of Class II, Division 1 and 2 Locations.

Low resistivity has been defined as values less than 100 Ωcm; a conductive dust is one that breaks down under an electric field of 1000 V/cm or less. A hazard exists directly with such dusts because they can provide conductive paths between live parts and easily enable arc formation (1). However, Moodie (43) has found that coal dust has high resistance and is non-conductive, even when contaminated with mine-drainage water. Hence, hazardous coal-dust locations appear to exist when a cloud concentration (greater than 0.05 g/l) or a layered-dust thickness on electrical equipment (perhaps, greater than 20 mm) is found. (Note: the values given parenthetically should not be construed as fact, but as they have been taken from the literature, they may be used as guides.)

Hazard Reduction. Two common enclosure types are used specifically for Class-II hazardous locations: dust-ignition-proof and dust-tight. Also employed to a lesser extent are pressurized and intrinsically-safe systems (1). The objectives are to keep dust away from sources and to prevent ignition of layered dust.

Dust-ignition-proof motors meeting Underwriters' Laboratories, Inc., requirements cover both objectives (44). The technique is similar but less restrictive than for explosion-proof designs. Joints cannot be less than 3/16-in. wide with maximum gaps of 0.0015 in. With wider joints, maximum clearances are proportionately raised but cannot exceed 0.008 in. As an alternative, gasketing is allowed between mated surfaces, but the surface and gasket width cannot be less than 3/8 in. Such gasketing cannot normally deteriorate with age and cannot be glued on the surface. The goal is to provide an enclosure that prevents entrance of dust and hot particles from escaping (1). Maximum surface temperatures for coal-dust applications are 200°C for equipment that usually will not overload, but 150°C for those that will. Dust-ignition-proof motors are suitable for both Division-1 and Division-2 locations.

Dust-tight enclosures are designed to be of tight construction to prevent dust entrance as well as to contain the ignition source. Intended only for Division-2 locations, their testing by Underwriters' Laboratories, Inc. is less restrictive than that for equipment in Division-1 locations, but the actual tests for dust-tight enclosures are the same as for dust-ignition-proof enclosures (44).

14.4 Summary

The purpose of the chapter has been to introduce hazard-reduction techniques that are used in and about coal mines. Frankly, portions of coal-mine operations can be rendered dangerous without diligent adherence to the procedures and regulations presented in the foregoing paragraphs. Anyone desirous of gaining more knowledge in this subject should seriously read reference 1.

14.5 References

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Chapter 15

MAINTENANCE[1]

15.1 General

An integral part of any power system is the protective circuitry that protects personnel and equipment from system anomalies. As was shown in Chapters 8 through 11, these include overloads, faults, and transient overvoltages, among others. The ultimate goal is to maximize system availability while minimizing personnel hazards. There is no question that devices, such as relays, circuit breakers, and surge arresters, play a necessary part in the overall power-system design and operation. System protection, however, extends beyond protective circuitry. Indeed, more protection can be gained in the application of a good maintenance program than in the mere application of protective circuitry.

Maintenance is a topic of familiarity to most engineers, yet, this familiarity does not usually extend beyond repair or emergency maintenance. Although the concept of preventive maintenance (PM) is as old as industrialization, it is practiced by few in the mining industry. The most recent advances in preventive maintenance are techniques of predictive maintenance. Knowing the principles of each type of maintenance, and when to use them, can save much time and money, while improving overall system safety.

The purpose of this chapter is to explore some of the fundamental concepts of maintenance, to illustrate the techniques of preventive maintenance from the most basic to the computerized systems, and to examine some of the problems in implementing a program. This information, along with suggestions on management and public-relations practices, is integrated into a concept for a feasible preventive-maintenance system. Because of the direct tie to the maintenance subject, a discussion of some major mine-power-system problems is included this chapter.

15.2 Maintenance-Program Justification

Terminology. Before personnel, materials, and money can be released for a maintenance program, the program needs to be justified for each mine or plant. This is an unfortunate reality. Accordingly, it might be helpful to define maintenance terminology, as it provides some insight into the justification process.

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[1] This chapter was originally written for the report by Jeffrey L. Kohler, Instructor of Mining Engineering, The Pennsylvania State University. The author edited and included additional material.

There are three types of maintenance: emergency or repair, preventive, and predictive. "Emergency maintenance" is just what its name indicates. A component, for instance, a motor, operates until it fails. Then, in the heat of a production environment, maintenance crews make the repair as quickly as possible.

"Preventive maintenance" traditionally means performing various tasks on a periodic basis, which extend the life of a component. An example is the periodic lubrication of bearings. However, a more general definition is the process of prolonging the useful life for a component, and then when failure is imminent replacing the component when it causes minimum down-time and personnel hazard. This is the definition which will be used in this chapter.

"Predictive maintenance" is the prediction of component failure by measuring key parameters and observing any changes which occur over a long period of time. The measurement of insulation resistance, which is then recorded and compared to previously observed values, is an example. When the curve approaches a critical value, failure is impending and predictable. Although this technology is commonly practiced in some industries, it is relatively new to mining. The advances in electronic technology have opened the door for more sophisticated prediction techniques, and this will be discussed later. From the foregoing general definition, predictive maintenance can actually be included as a preventive-maintenance type.

A study of existing conditions in numerous mine power systems indicates that a properly designed and maintained power system is characterized by its safe, reliable, and economic operation (1). Similarly, poorly designed or maintained systems tend to be unsafe and experience low availability. These conclusions are not surprising, as power engineers working in surface transmission and distribution have known them for years (2). A significant point, however, is the close relationship between safety and availability.

"Availability" can be defined as the component's mean time of operation or, in more common form, as the ratio of total operating time to total time in which the component could be operated (3). Mathematically, it is a function of reliability and maintainability. It is impossible to define the precise balance of reliability to maintainability, which combined produce a specified availability. However, the two factors can be infinitely varied to produce the desired result.

"Reliability," i.e., the mean time between failures, is primarily affected by the component design (3). It can be lessened, however, by abuse or improper application. A portable cable, for example, which is rated for 8000 V can be used on a 15-kV system, but the life and reliability of the cable will be considerably reduced. Increased component or system complexity tends to degrade reliability, which is rather paradoxical since complexity often results from attempts to improve performance. It should be noted that these statements are in line with the Basic Design Criteria that were specified in Chapter 2.

The U.S. Department of Defense defines "maintainability" as a quality of the combined features and characteristics of equipment design that permits the accomplishment of maintenance by personnel of average skills under natural conditions of operation (3). As the definition implies, this factor is affected by the original design. The skill and integrity of the maintenance personnel are important factors in maintainability of a component or a full system. The ratio of preventive-to-emergency maintenance is another factor often overlooked. For instance, the maintainability of a trailing cable will be poorer if it is repaired only after a failure, as opposed to a repair initiated by "signs of wear" discovered during a preventive-maintenance shift. In such a case, the reliability of the cable is also affected; this statement is substantiated by the fact that splices made on production shifts tend to be less reliable than those made on preventive-maintenance shifts (4).

Unreliable components are normally rare, and the group of engineers who do not understand good design principles is small. If these two concerns are not considered, mine-power-system reliability can be assumed as essentially fixed. Manufacturers could, of course, try to improve the reliability of their individual components, but the effort and additional cost probably would not be commensurate with the results.

Based on these remarks, any significant improvement in the availability of a mine power system will have to come through increased maintainability. The initial responsibility for such an increase would appear to fall to the manufacturer. However, manufacturer changes to improve maintainability do not have the desired effect on total availability in the mine. Consequently, the solution lies in the maintenance effort at the mine where emphasis must be switched from repair and emergency work to preventive maintenance. This, of course, is easier said than done, and experience indicates that PM programs at the mine are generally haphazard and neglected (5).

Economics of Maintenance. The quantification of the costs and benefits of a PM program is always difficult, especially when maintenance and production departments have the notion that they have opposing goals. It is easy for a plant superintendent to visualize the PM-program costs, but it is more difficult to see the long-range savings. Likewise, it is easy for a foreman to compute the lost production costs when a machine is shut down for an hour of PM, but usually difficult for the maintenance people to compute the long-term savings due to the increased machine availability. Unfortunately, managers, from the faceboss to the superintendent, often feel that preventive maintenance is worthless until proven otherwise.

A good economic analysis is more difficult to achieve if there is insufficient historical data on component failure. At best, maintenance records on mining equipment at many operations are incomplete. Consequently, it is necessary to make reasonable assumptions about the effects of a good PM program. Manufacturer data as well as data from related operations (for instance, other mines) will be helpful. In the absence of this information, there are some general guidelines which can be used to present a strong justification for a PM program.

Three ratios are available for a first-order approximation (6):

$$\frac{\text{Cost of Component Relationship}}{\text{Cost of Component PM}} \qquad (15.1)$$

$$\frac{\text{Cost of Downtime}}{\text{Cost of PM}} \qquad (15.2)$$

$$\frac{\text{Safety Hazards}}{\text{Cost of PM}} \qquad (15.3)$$

If the value of any one of these ratios exceeds 1.0, then preventive maintenance can be justified. Although the application of these ratios should be obvious, an example of each will be given.

If a motor bearing fails, there is a good chance that the motor will be damaged and short out. The repair costs then become substantial because the motor has to be pulled and rebuilt. The PM costs in this case would be very small, consisting of monthly vibration measurements on the bearing. Ratio 15.1 is applicable to this case. Depending on the down-time involved, ratio 15.2 could also be used.

The second ratio is more applicable to situations where the failed-component cost is insignificant, but the failure

causes a significant amount of downtime. For instance, if a contactor fails on the starter for a wound-rotor induction motor which is driving the main conveyor belt, the contactor replacement costs will be minor compared to the cost for idling a major portion of the mine.

Ratio 15.3 cannot be evaluated in dollars, at least not in good conscience. Although some industries, most notably the automobile industry, have placed dollar values on human lives, this cannot be condoned. Rather, preventive maintenance must be practiced to the point of removing any reasonable chance of personal injury.

Other techniques, such as investment analysis, can be performed in the absence of extensive historical data. This is probably best approached by considering the investment as labor and overhead, and then conservatively estimating the effects of the PM program on a cost per unit of output. In the mine, the cost could be dollars per raw ton, whereas in a preparation plant it could be dollars per clean ton. When this is done, the PM investment is often found to be not just profit-maintaining, but actually profit-adding.

Since it is not the intent of this chapter to review economic analysis, the reader is referred to the literature. It must be remembered, however, that preventive maintenance follows the law of diminishing returns.

15.3 The Techniques of Preventive Maintenance

The purpose of the following sections is to discuss the more important tests that provide the data necessary for an effective PM program. The tests are divided into two categories: electrical and mechanical. In motors, for example, up to 75% of all electrical failures can be caused by the failure of a non-electrical component. As a result, it is important to recognize the inter-relationships of mechanical and electrical components in the overall system. This will be discussed in more detail after the measurement techniques have been covered.

15.4 Electrical Measurements

Elementary. The principal reason for taking measurements of the mine power system is to discover impending failure. Many problems in and about mines and preparation plants can be detected with a simple voltmeter. Voltages on machines, at transformers, and so forth should be checked periodically to detect excessive voltage drops. Voltage drops of 20 to 30%

under machine rated voltage are too common, and the ramifications of this undervoltage have been stated in Chapter 5. A voltmeter is also a valuable tool for trouble-shooting the solid-state circuits which are becoming more common.

Another worthwhile voltmeter test is to check the voltage difference between phases at a given location. This is particularly applicable at a transformer which supplies power to motors. If the voltage difference between phases is more than a few percent, motor damage can result. In fact, one research group has found that negative-sequence current, caused by a two-percent voltage difference, creates enough heat to cut motor life by 50% (6).

The measurement of current is simple and can be achieved by using a current transformer (for a-c) or a resistance shunt (d-c) with the voltmeter. Current measurements taken periodically on a motor at no-load and full-load can provide valuable information on a motor's health. Although this type of measurement is better suited to stationary motors such as in belt or pump applications, there is no reason why it cannot be used on mobile equipment. A specific application for current measurements is in the periodic checking of dual-motor belt drives. It is normal for the load to be shared unequally (for example, 52% to 48%) by the two motors, but it is not normal for this ratio to change by more than a few percent with time. If such a change occurs, there may be an electrical or mechanical problem. Coupling misalignment would be suspected.

Resistance readings can also be invaluable. Although some can be made with a volt-ohm meter (VOM), others need to be performed with a megohmmeter or bridge meter. For the moment consider some of the things that can be investigated with an inexpensive VOM. These include resistor-bank values, contact resistance, open relay coils, and so on. In some cases, such as contact-resistance measurements, it would be more accurate to use a Kelvin Bridge, however the utility of the VOM should not be overlooked.

Insulation. Insulation is the only material used in electrical components that begins to deteriorate the moment it is manufactured. Strictly speaking, insulation should be called a dielectric, as insulation is simply one application of dielectric material (7). "Dielectric" can be defined as a material which, when placed in an electric field, permits a negligible current flow. As it is the material most likely to fail, periodic measurements to detect incipient

failures are necessary. The model for dielectric, as shown in Figure 15.1, provides a clue as to what parameters might be measured to determine the integrity of the insulation (7). The two obvious ones are resistance and capacitance. Resistance is measured directly and is known as "insulation resistance." (Note: A perfect insulation would have $R_p = \infty$ and $R_s = 0$.) Capacitance, however, is not measured directly. Instead, the phase angle between the voltage and the current is measured, as shown in Figure 15.2. Because of the importance of insulation in the mine power system, a discussion of failure ramifications is in order.

Insulation Failure. There are three primary stresses that can cause dielectric deterioration in the mine power system: electrical, mechanical, and thermal. Electrical stresses result from an overvoltage (that is, a voltage in excess of the dielectrics rated withstand level) and may cause immediate failure or gradual deterioration, depending on the level of the disturbances. Generally, dielectrics do not have significant mechanical strength, so actual or circumferential stress may cause a failure. Similarly, they usually do not have much resistance to fatigue. Thermal stress resulting from an operating temperature in excess of rated, causes a change in the physical properties of the insulator, which usually changes its electrical and mechanical properties. A discussion of insulation failure by overvoltage has already been covered in Chapter 10; thus only thermal and mechanical stresses will be entertained here. Another mechanism that will degrade insulation, partial discharge, will be presented later in the chapter.

The integrity of insulation is eroded as the temperature increases. The decrease in resistance or increase of current flow is due to the combined effects of several mechanisms. The primary cause, however, is the increased carrier mobility at elevated temperatures (7). In addition to changing the electrical properties of the insulator, some insulation types (especially some of the enamels used in motor wire) tend to become brittle. As they expand and contract under the changing temperature conditions, cracking will result. The aftermath will be leakage currents which will be larger than in insulation with a decreased resistance. A third effect of thermal stressing manifests itself in a mechanical stress. This is more likely to occur when two or more different dielectrics are sandwiched together, as in a portable cable. Since each insulation has its particular coefficient of thermal expansion, the expansion for each material will not be the same. This is more critical when an underlying material is being constrained, since mechanical stresses will result. Strain may then occur, resulting in voids or weakened areas. As a result of these degradations, the ultimate failure may appear to be electrical or mechanical in nature.

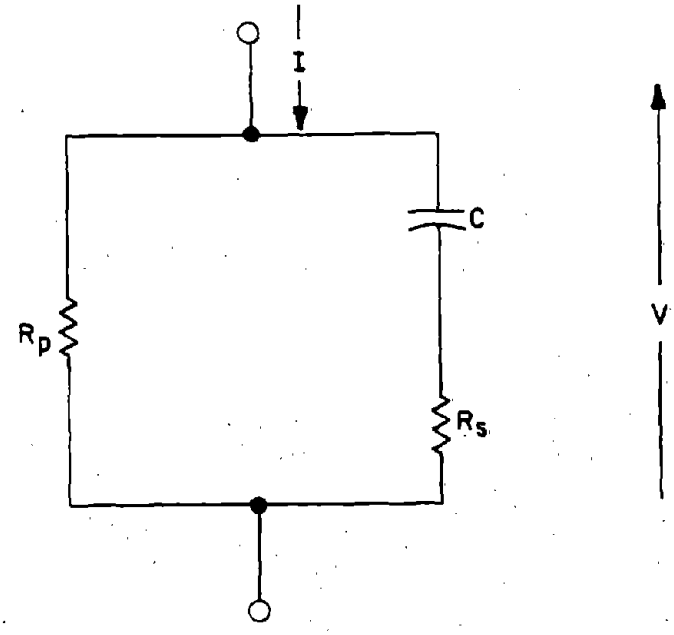


Figure 15.1. A Circuit Modeling a Dielectric.

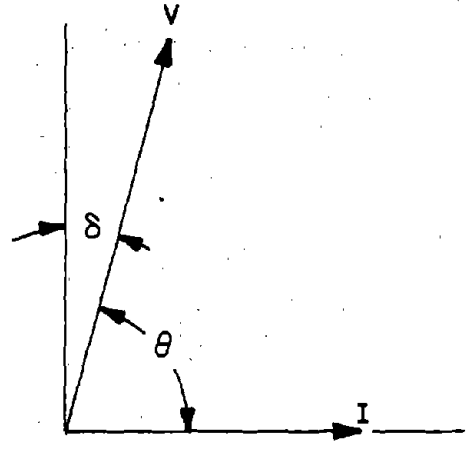


Figure 15.2. Current-Voltage Characteristics in a Dielectric.

Mechanical stress to mine-power-system insulation is perhaps most significant in cables. Instances occur when a cable is dragged (abrasion), reeled (tensile and bending), and run over (compressive). The worst case is probably a shuttle-car cable, where tension may reach a few hundred pounds during spooling. Dragging the cable abrades the insulation, thereby reducing its thickness, hence its effectiveness. The compressive forces exerted on a cable when it is trammed over by a machine are enormous and can result in conductor strands puncturing the dielectric. Failure may be immediate (catastrophic) or gradual (time-dependent). In the latter case, deterioriation may be hastened by electrical or thermal stresses which begin after the mechanical damage.

With this short discussion, the importance of insulation measurements in a maintenance program should be quite obvious. The following paragraphs will discuss a few of the techniques available.

Unloaded Power Factor and Dissipation Factor. Referring to Figure 16.2, the tangent of δ (or the co-tangent of θ) is known as the dissipation factor, and the cosine of θ is called the "unloaded power factor" (7). At power angles near 90 degrees, the two factors are nearly equal. The voltage-current relationships for a sound dielectric will be almost purely capacitive, and the unloaded power factor and the dissipation factor should be very low or very close to zero. As insulation deteriorates, large leakage currents will tend to increase these factors significantly (8). The dissipation factor is used frequently in the technical literature. Whereas, the unloaded power factor is used more frequently by manufacturers when specifying component tolerances (7). Hence, the latter might be of more interest in preventive maintenance than the dissipation factor.

Regardless of the factor selected, readings should be taken at periodic intervals. Records should be kept of each reading so that any trends can be detected. Typically, a manufacturer will specify the maximum acceptable unloaded power factor, usually two percent or less. If this value is exceeded, one of two problems is usually indicated. Either the insulation is severely deteriorated, or it is water soaked. In either case, failure may be imminent although allowing the insulation to dry would correct the latter problem.

A suitable instrument for making these measurements is a capacitance and dissipation-factor bridge. Since the temperature affects the power-factor readings, a correction factor must be applied. These factors are dependent upon the particular dielectric type and should therefore be obtained from the manufacturer. Interestingly, the instrument connections to the

apparatus under test are identical to those of the Megger tests, which are discussed in the next section.

Insulation Resistance. The shunt resistance of the leaky capacitor, R_p shown in the insulation model of Figure 15.1, can be measured and used to predict insulation failure, as well as to observe some measure of the insulation integrity. In practice, this measurement usually is performed with a Megger (see Section 4.9 for an operational description). The current, which flows due to the potential impressed on the dielectric, is composed of two parts: a leakage component across the insulation surface, and a current actually through the insulation. When the detection of deterioration is of interest, the superficial leakage current must be minimal. Otherwise, the insulation-resistance reading will be artifically low. Consequently, it is necessary to examine those factors which will cause incorrect measurements.

It is generally accepted that five factors will affect the reading. They are:

1. surface conditions
   a. abrasion,
   b. foreign material,
   c. moisture;
2. moisture;
3. temperature;
4. method of test;
   a. test-instrument potential,
   b. duration of test;
5. residual charge.

The surface condition of the insulation normally will have the largest effect on the superficial-current component. For instance, an abraded surface will collect air-borne dust. If the dust is from a highly conductive material (such as from carbon brushes), the possibility of establishing a conductive path on the insulation surface is rather high. Even dust with a much lower conductivity (such as coal dust) can allow enough current to flow so a significant error is introduced. A non-abraded surface will have a tendency to collect some dust, but the problem is not as severe.

If the dielectric surface is moist, a conductive path can also be created, and foreign material on the surface will aggravate the problem considerably. The surface-moisture problem can normally be minimized by taking the measurements only when the temperature of the component is above the dew point. In the case of machines, surface moisture is of no significance at the normal operating temperature, but some researchers have expressed concern over the effect of high relative humidity during testing (9). While it is true that

experiments conducted in a controlled environment do reveal a decreased insulation resistance with increased relative humidity, the changes are not troublesome if the data are correctly analyzed. More will be said about this later.

The second factor is moisture, excluding surface moisture. Some insulating materials are hygroscopic; they absorb moisture. The effect is entirely different from surface moisture and presents a more serious problem because it compromises the dielectric integrity. Although a dielectric may exhibit a greater propensity for water as it ages, this characteristic is not a reliable method of determining aging, at least not outside the laboratory.

The hygroscopic moisture content can be reduced by bringing the component to normal operating temperature for a few hours before making any measurements. If a measurement is low and moisture absorption is suspected, caution should be observed when energizing the component to prevent failure. In some cases, such as with large motors, it may be worthwhile to pass a current equal to load current, through the windings at a low voltage. The heating which occurs will "dry out" the windings.

The insulation temperature (factor 3) has a significant effect on the measured resistance. If the insulation temperature is known, a normalized resistance can be calculated:

$$R_c = K_t R_t \tag{15.4}$$

where,

R_c = insulation resistance corrected to 40°C (Ω),
R_t = measured insulation resistance (Ω),
K_t = temperature coefficient.

The temperature-coefficient factor is obtained from a graph such as shown in Figure 15.3, which is valid for rotating machines (10).

The measurement of the insulation temperature is sometimes difficult. Neglecting this factor can be risky, but a suitable compromise can be reached in many cases. For example, taking the measurements consistently before, or after, the component is at operating temperature, may stabilize the readings. The ambient temperature may vary over a small enough range to ignore its effect on the pre-operating temperature of the component. Of course, steps such as these must be evaluated for each situation, and what might work well for a large motor could be meaningless in the case of a circuit breaker.

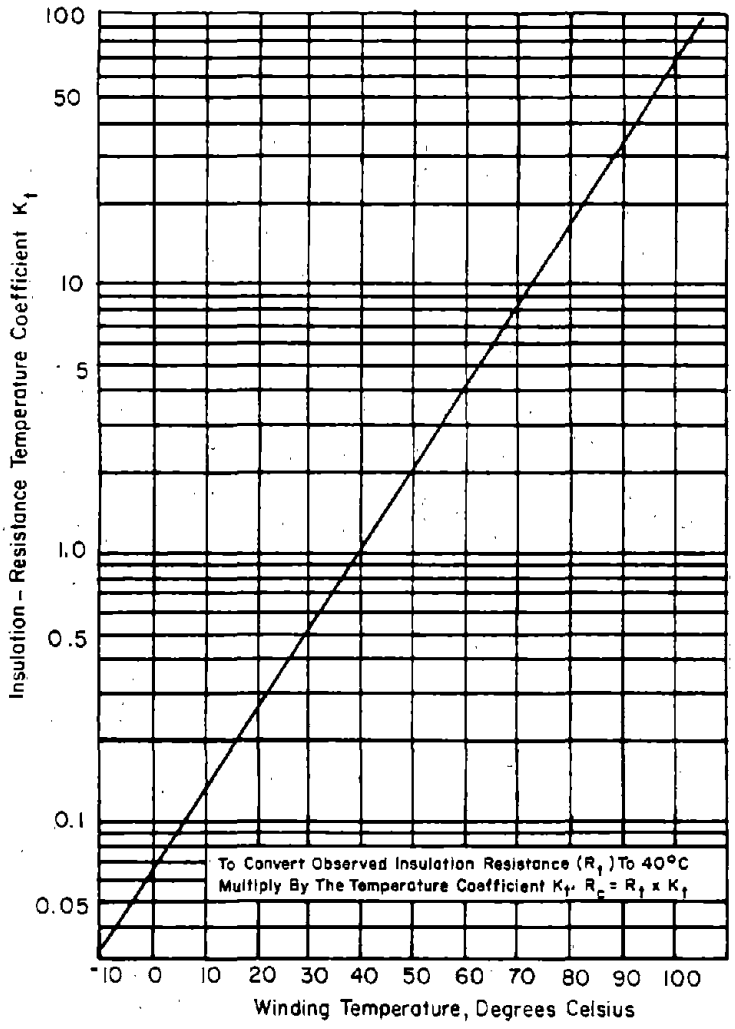


Figure 15.3. Graph Relating the Approximate Insulation Resistance Variation with Temperature for Rotating Machines.

The fourth factor, method of test, is important but presents no real application problems. The test potential of a Megger is usually 500 or 1000 V. Measurements on a given component should always be taken at the same test potential. The basic format of a test for a given component is fixed, and will be suggested shortly. Beyond this, however, the test measures and procedures should always be duplicated precisely. Since the purpose of the test is to analyze the trend over time, small errors introduced by nuances of the test procedure will not pose a problem, as long as the methodology is consistent.

Residual charge is the final factor. The leaky capacitor of the dielectric model must be discharged before a resistance

measurement is taken. This is achieved by shorting the outer skin of the dielectric and the conductor, which the dielectric surrounds, to ground. The short should remain in place for a few minutes. When multireadings are taken on the same insulation system, the dielectric should be shorted for at least three minutes, assuming the standard three-minute test (10). In specialized Megger tests, where parameters such as the time, rate-of-rise of resistance are analyzed, this factor is critical.

Megohmmeter Testing. As was described in Chapter 4, a megohmmeter is a portable instrument consisting basically of an integral voltage source and a meter calibrated in megohms. The voltage source is either a hand-crank generator or a battery pack. The instrument form most suitable for routine insulation-resistance measurements has only two probes, much like that for a voltmeter. The test itself is conducted by placing the probes across the insulation system and measuring the resistance. There are three different tests that can be performed with a megohmmeter: spot reading, time resistance, and multivoltage. These will be discussed in order. Component manufacturers generally provide instructions on megohmmeter testing of their components. For component groups, such as motors, transformers, or cables, there are basic procedures which will be discussed here. The data interpretation will be discussed after all the basic procedures have been introduced.

Spot Testing. Conceptually, the most straight-forward spot test is on cables. The key point to remember is that one phase or power conductor is checked at a time, and all other components in the cable are shorted together and to ground. Figure 15.4 shows the connections for checking the phase-A conductor. After the connections are made, the test voltage is applied for one minute. The resistance at the end of the minute is recorded. It is necessary to read the megohmmeter consistently at 60 s, as the resistance in a good and dry insulation will always increase with time, as shown in Figure 15.5. When the reading is taken at 60 s, the test is known as the "spot reading" test.

By testing periodically and keeping records, any persistent downward trend is indicative of a possible future failure, even if the actual insulation resistance is above minimum safe values (8).

Megohmmeter testing of motors is similar to cables. The test connections are shown in Figure 15.6 for an a-c motor, and Figure 15.7 for a d-c motor. Only the connections for a Phase-A test are shown (a-c motor). It should be mentioned that this test only checks the insulation system to ground and not the turn-to-turn insulation system.

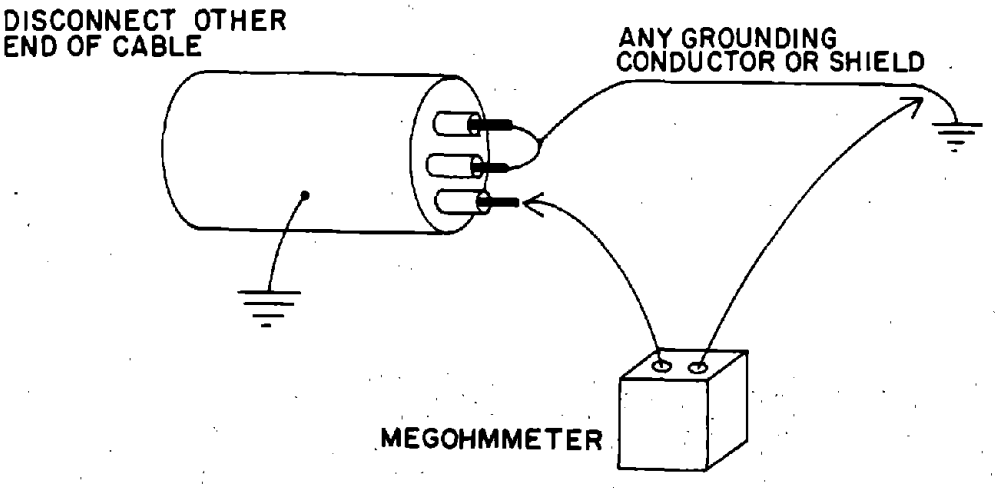


Figure 15.4. Megohmmeter Test Connections for Checking Cable Insulation in Phase A.

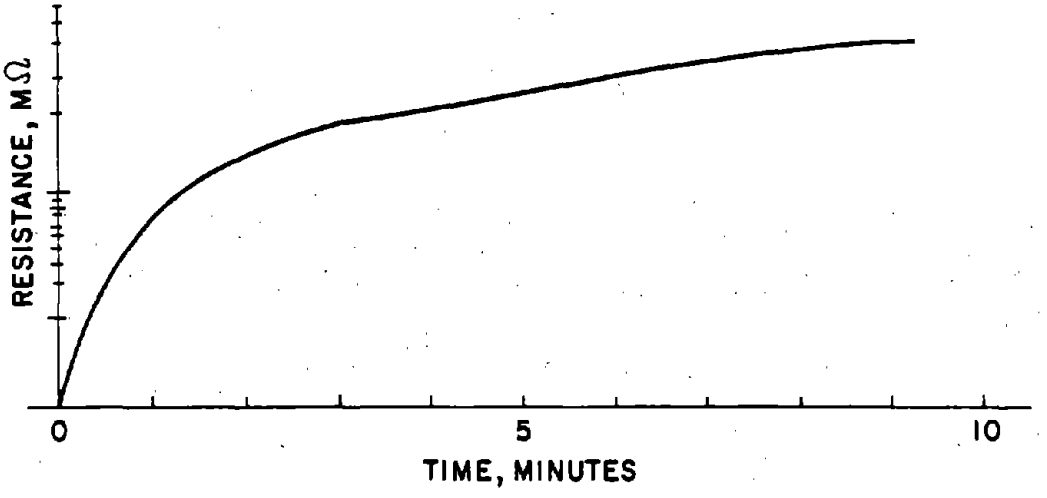


Figure 15.5. Insulation Resistance Versus Application Time of Test Voltage.

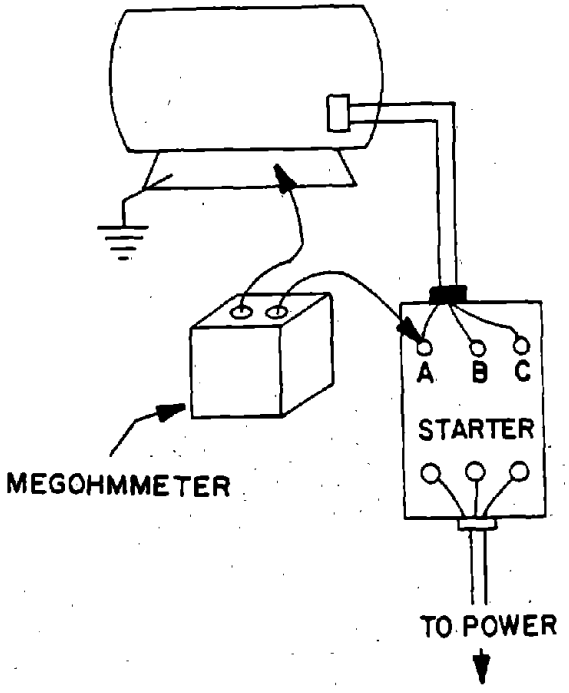


Figure 15.6. Megohmmeter Test Connections for an Alternating-Current Motor.

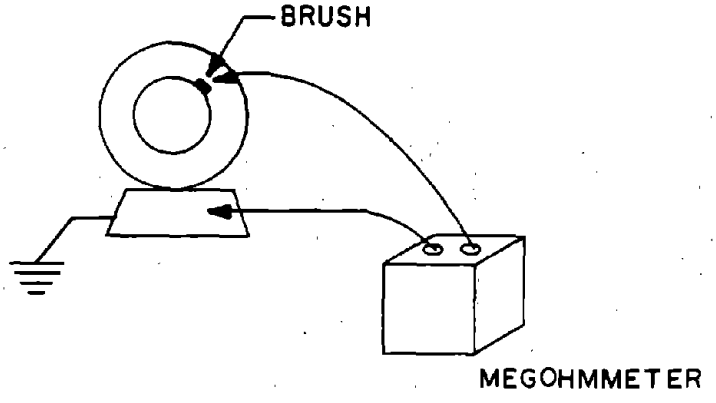


Figure 15.7. Megohmmeter Test Connections for a Direct-Current Motor.

Prior to testing a transformer, the core iron must be grounded and the resistance- or solidly-grounded connections must be removed. Then, all windings, except the one under test, must be shorted together and grounded. The procedure from this point on is the same as for cables. The test connections are shown in Figure 15.8.

These few short paragraphs should have provided an insight into some of the types of megohmmeter testing available for maintenance. Testing procedures also exist for starters, control boxes, relays, and circuit breakers, to name a few. The tests discussed here were defined as "spot testing"; each component was energized by the megohmmeter for 60 s prior to taking the reading. With no change in the connection, two additional tests can be performed.

Time Resistance. The first of these other tests is known as the "time resistance," where successive readings at specific times are taken. The shape of the resulting time-resistance curve, as shown in Figure 15.9, is of interest, particularly the point where the curve begins to level off. The absorption effect of good insulation versus contaminated insulation is the measurement basis, and a good insulation will have a continual increase in resistance with time (8). As with the "spot reading" test, time-resistance tests must be compared to historical data to have any meaning. By observing the resistance value at 10 minutes and at one minute, the polarization factor, P, can be computed:

$$P = \frac{R_{10}}{R_1} . \qquad (15.5)$$

The polarization factor is independent of temperature and equipment size, and this makes its use very convenient in some applications. This factor alone would be valuable for time-resistance test records.

Multivoltage. The final megohmmeter test is the "multivoltage" test, which is simply repeating insulation-resistance measurements at different voltage levels (for instance, 100, 250, 500, and 1000 V). This is particularly valuable on high-voltage components. The megohmmeter used for this test must obviously have more than one voltage output. A large reduction of insulation resistance with measured voltage is indicative of insulation weakness (8).

Interpretation of Megohmmeter Readings. Megohmmeter values are best used when recorded and plotted against time. Then any trends indicating an incipient failure can be detected. This is one instance, for each of the three types of megohmmeter readings, when

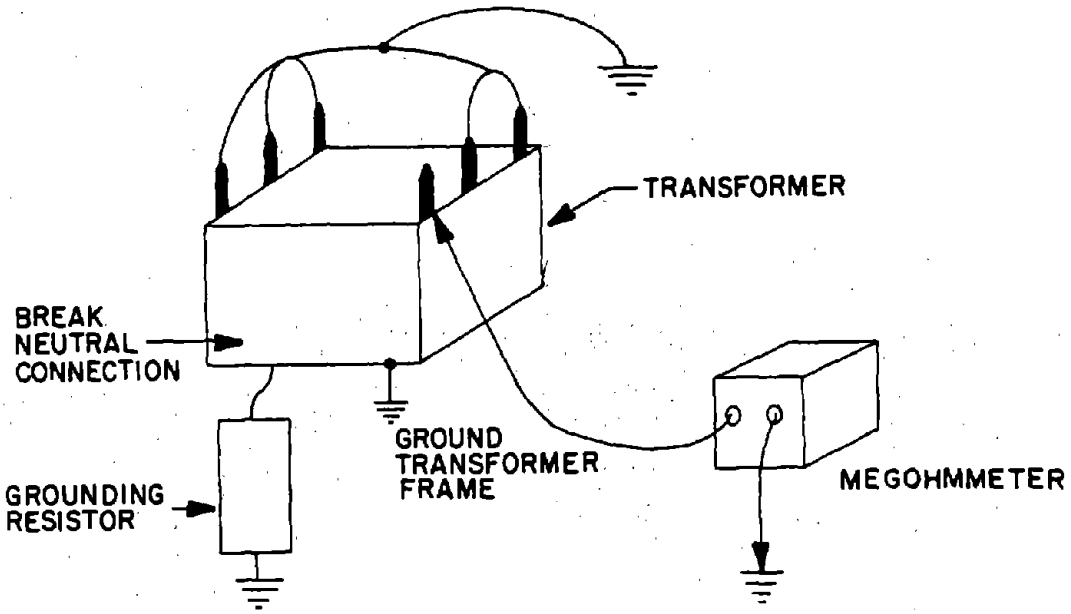


Figure 15.8. Megohmmeter Test Connections for a Transformer.

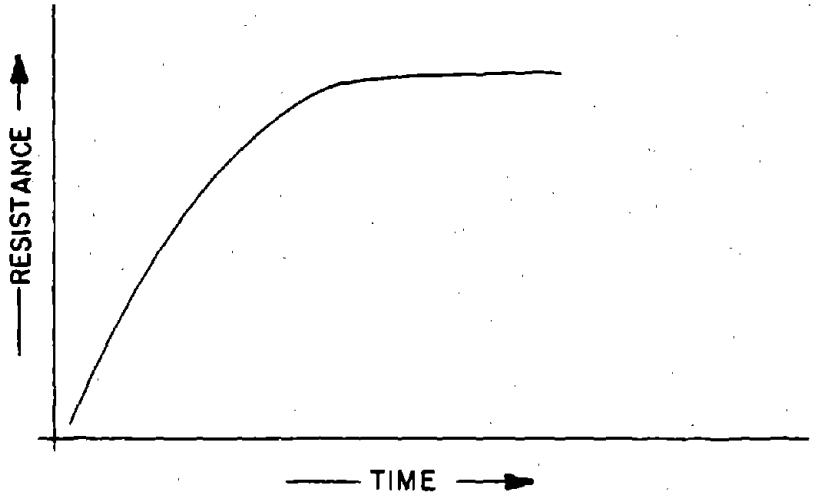


Figure 15.9. A Time-Resistance Curve.

an isolated reading is of significance. For the spot-resistance test, the minimum value should always be 1.0 MΩ plus 1.0 MΩ for each 1.0 kV of nominal voltage rating for the equipment. Therefore, a low- or medium-voltage motor in a mine should have a minimum resistance of 2.0 MΩ. The polarization factor computed from the time-resistance test should have a minimum value of 2.0. In a multivoltage test, the resistance found at the higher voltage should always be equal to or greater than the resistance for the lower voltage. All of these "rules-of-thumb" should only be used in the absence of manufacturer specifications.

Confidence in interpreting megohmmeter readings is only obtained through experience. However, the data shown in Figure 15.10 through 15.16 provides a good overview of what can be expected for some applications. The figures are self-explanatory.

Other Electrical Tests. The foregoing measurements are considered basic to any maintenance program. When warranted, a number of specialized tests also can be performed. These include harmonic analysis, power factor versus voltage, infrared, as well as others. Beyond these, recent research has developed a real-time computer analysis to predict failures.

Harmonic Analysis. From electrical discharge across voids, insulation deterioration can cause a small initial current that is rich in harmonics (8). Partial discharge is the mechanism that probably produces these harmonics, but this will be discussed later under that section. Irregardless, the result is a method of detecting insulation failure.

An instrumentation arrangement to perform harmonic analysis on insulation is given in Figure 15.17. The spectrum analyzer is an electronic instrument that performs a Fourier analysis on a signal and displays the amplitude of each frequency component of that signal. Here it is analyzing the current flowing through the insulation under test from a 60-Hz source. Researchers have shown that in new insulation, the frequency component of a current is primarily that of the source, whereas the current is composed of many frequencies in the old insulation (8). The visual CRT display of the spectrum analyzer quickly indicates insulation of questionable integrity. The method has been demonstrated to be suitable for cables, motors, and transformers insulating oils.

Power Factor Versus Voltage. This test uses the unloaded power factor that was discussed earlier. When this factor is plotted against varying voltage levels for perfect insulators, as shown in Figure 15.18, the curve is a straight line (8). In deteriorating dielectrics, however, the curve rises with increased voltage to form a parabola. The theory for this phenomenon is that voids in the insulation contain entrapped

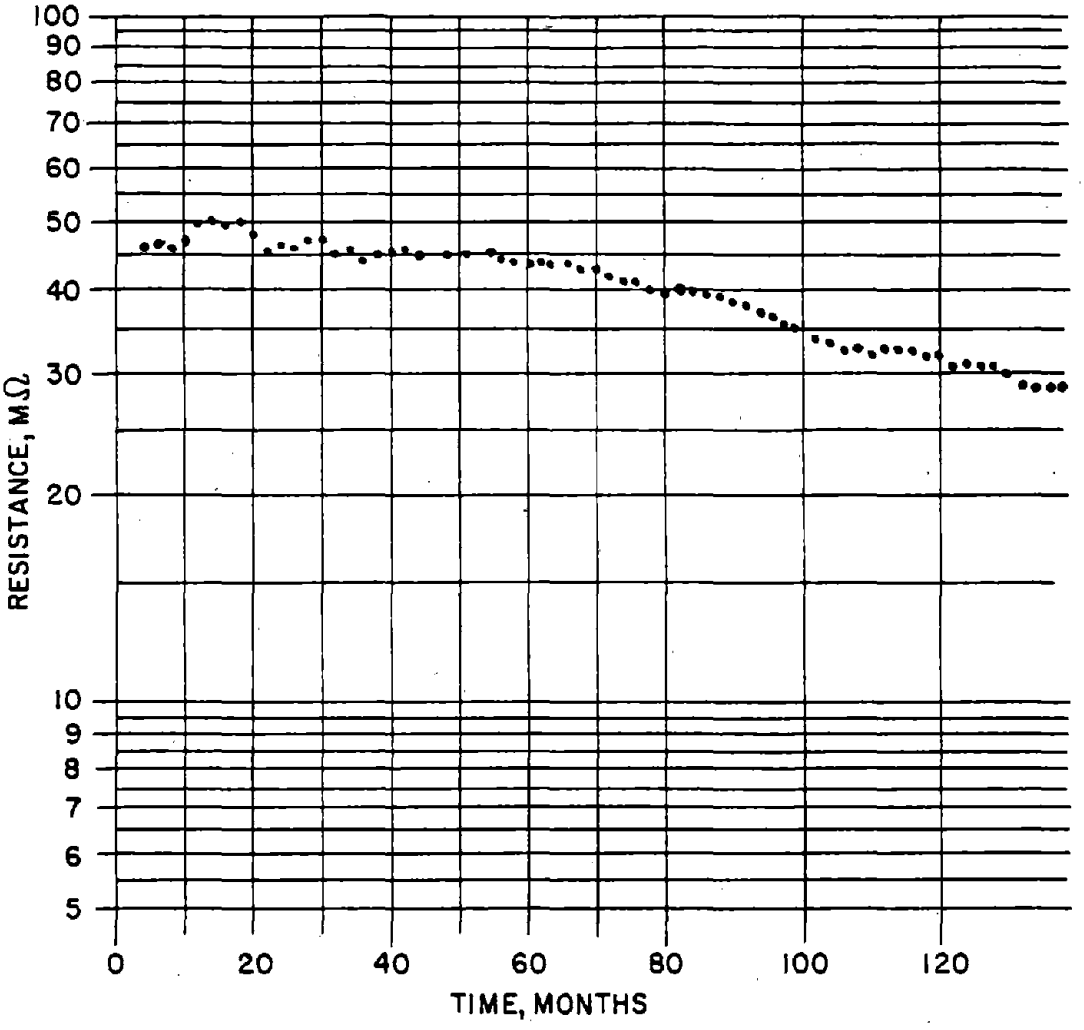


Figure 15.10. A Spot-Resistance Curve for a Normal Motor.

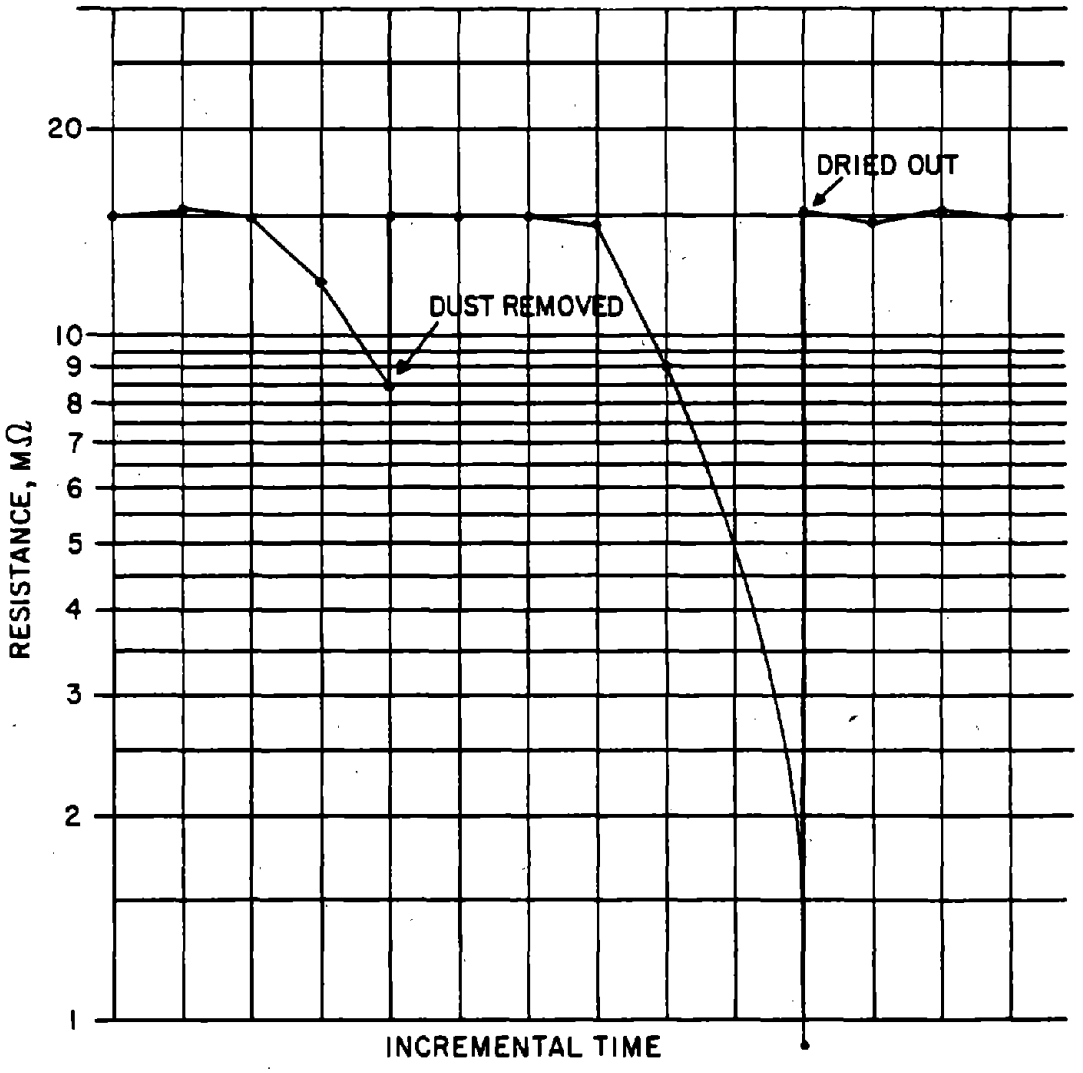


Figure 15.11. A Spot-Resistance Curve Showing the Effect of Dust and Moisture.

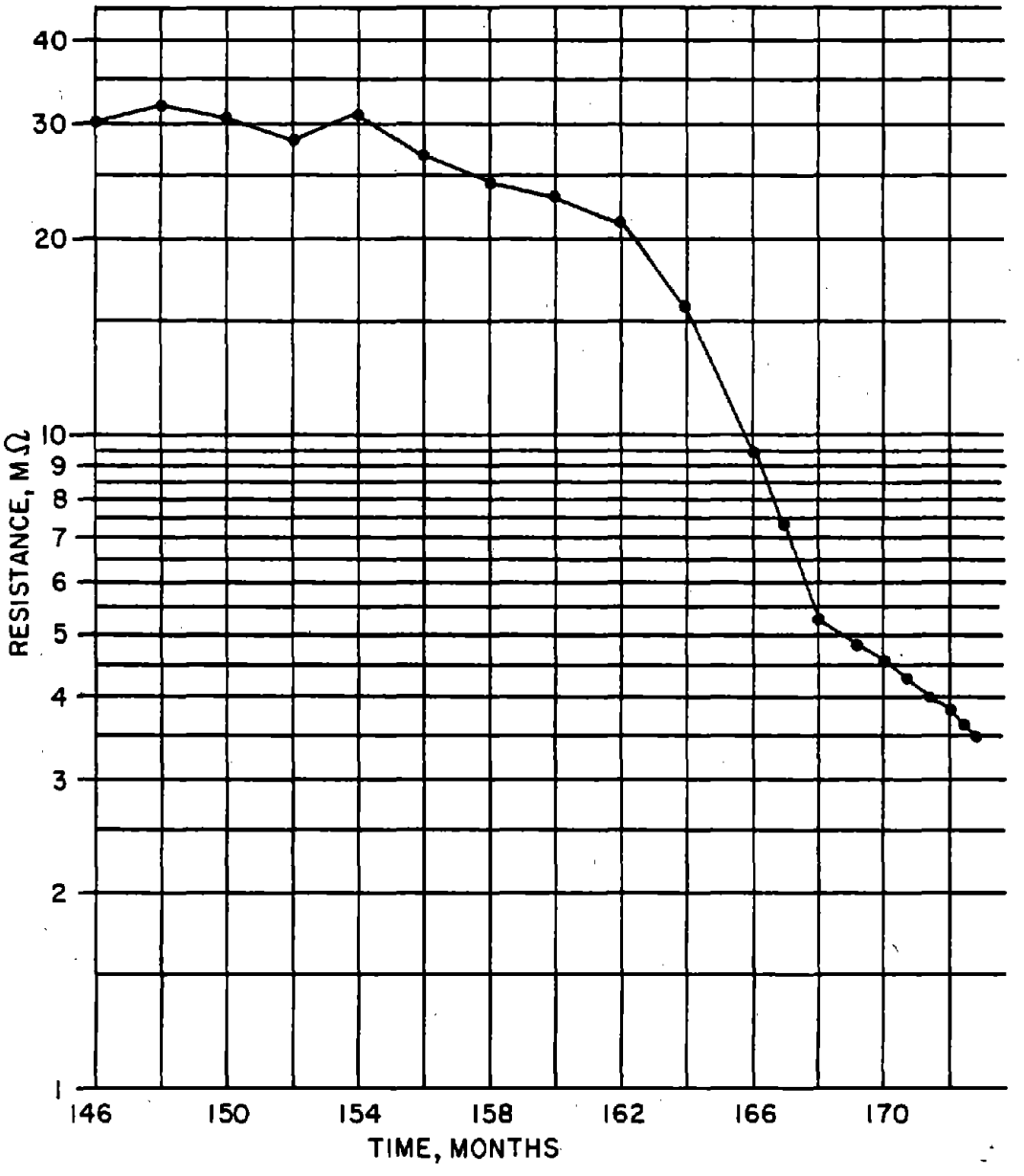


Figure 15.12. A Spot-Resistance Curve for a Defective Motor.

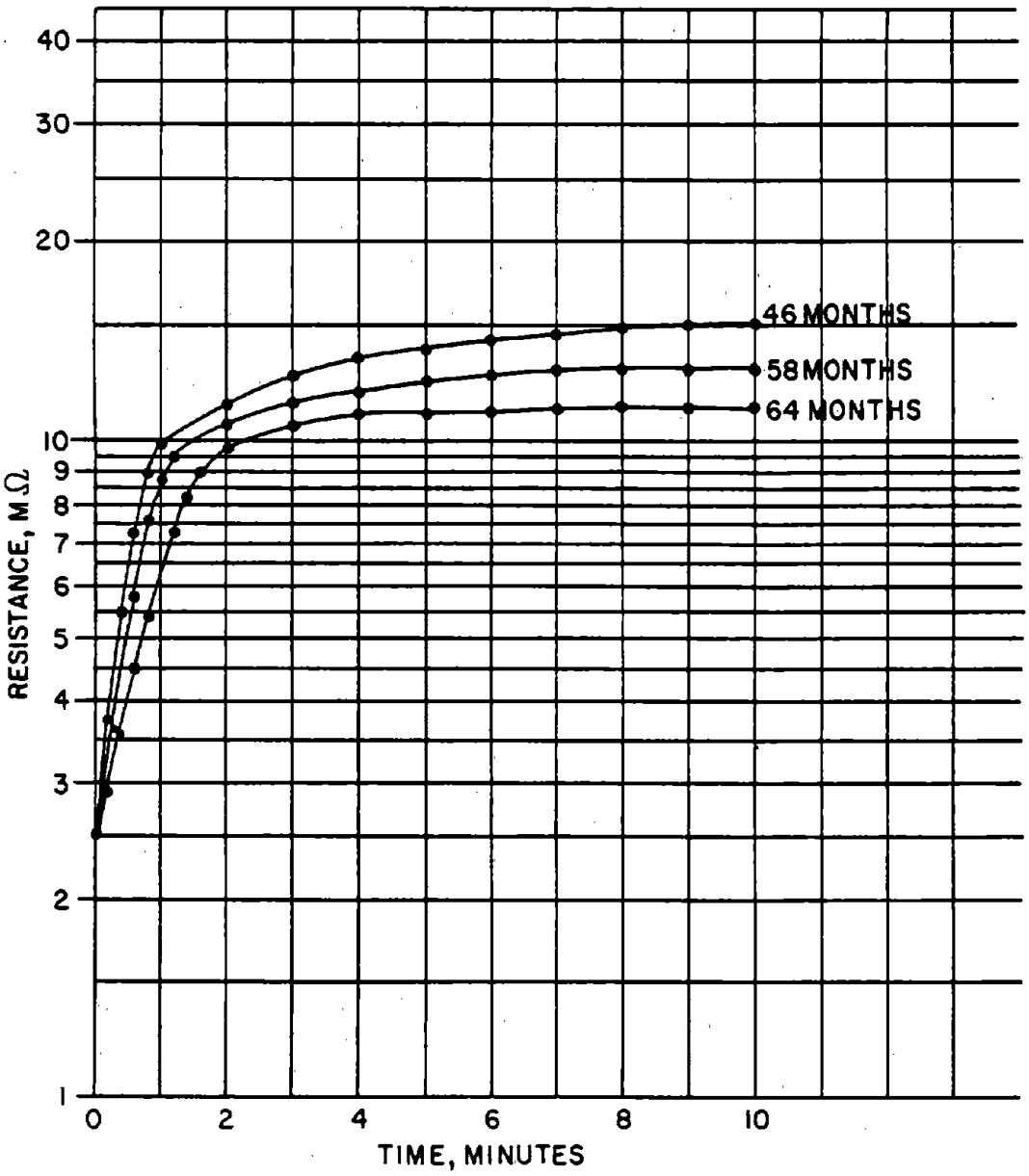


Figure 15.13. Three Time-Resistance Curves for a Deteriorating Motor.

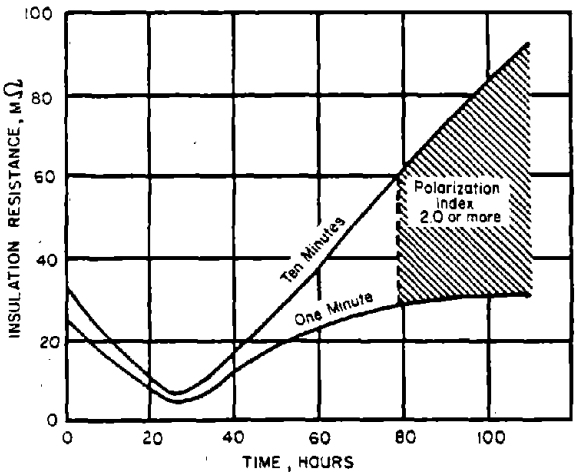


Figure 15.14. Time-Resistance Curves Showing Polarization for a Hypothetical Motor.

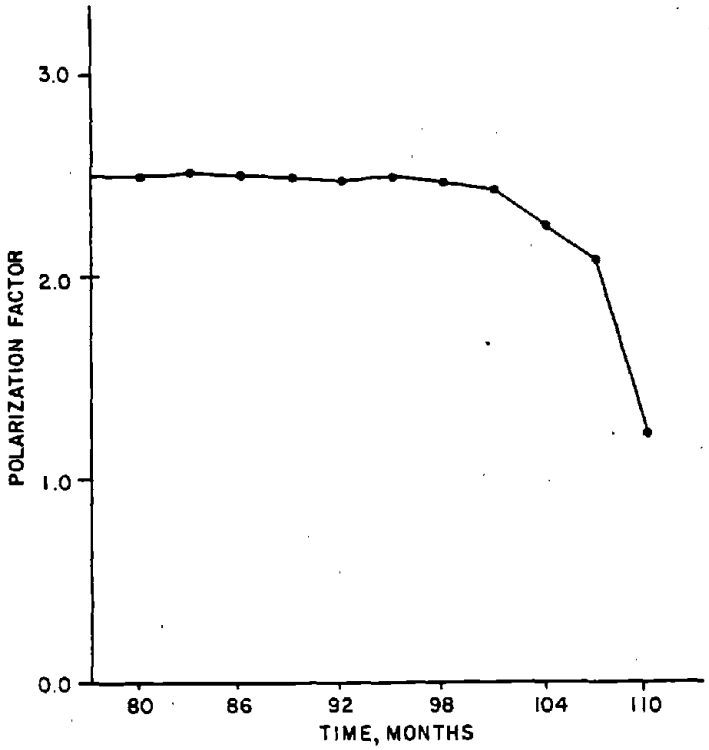


Figure 15.15 A Polarization-Factor Curve for a Deteriorating Motor.

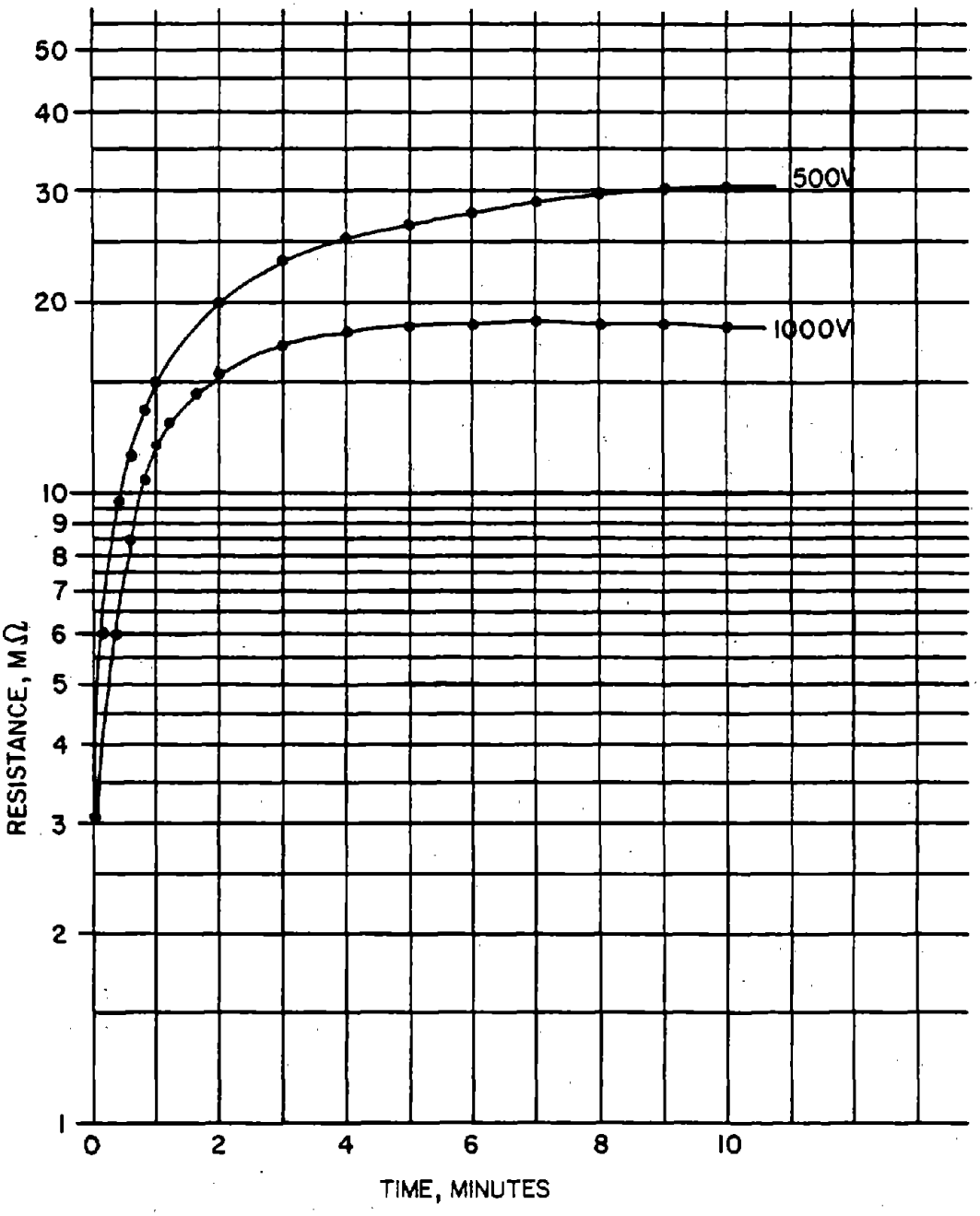


Figure 15.16. Multiple Voltage Curves for a Deteriorating Motor.

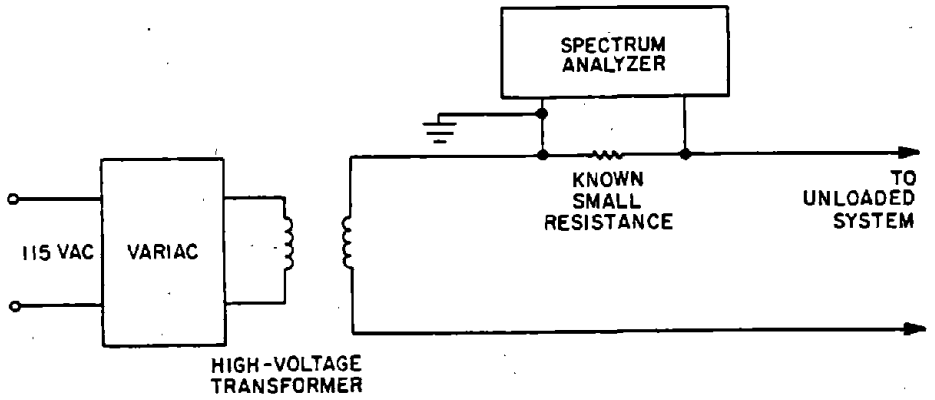


Figure 15.17. A Circuit for Harmonic Tests.

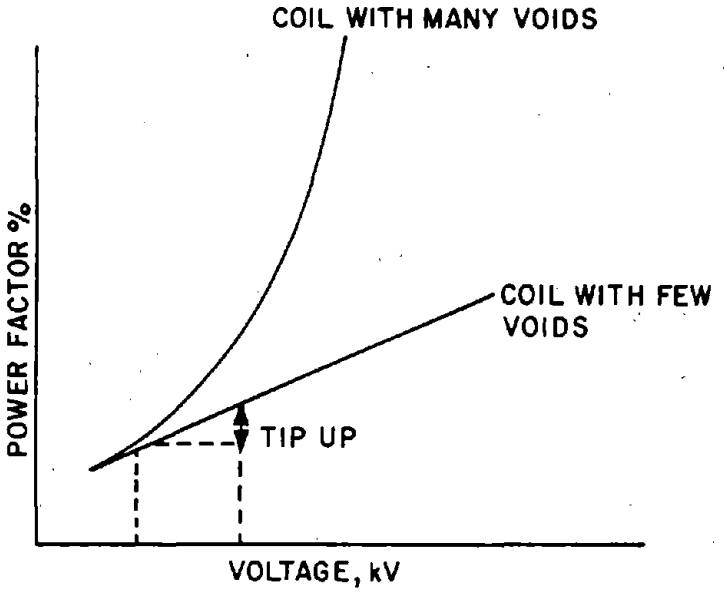


Figure 15.18. Power-Factor Versus Voltage Curves Showing Tip Up.

air which tends to ionize as voltage approaches the breakdown point. Thus the ionization produces an extra loss that causes the divergence of the curve. Reference 8 contains a description of a simple power-factor meter which can be used for in-mine measurements.

Infrared. At any temperature above absolute zero, all bodies radiate energy. The radiation in the infrared region is closely in proportion to the body temperature. Although not directly an electrical test, the observation of infrared emissions with a portable instrument can detect abnormal hot spots in operating electrical equipment. Some excessive-temperature causes include (8):

1. broken conductor strands or excessive insulation leakage in cables,
2. defective coils in motors, and
3. excessive leakage flux in transformers.

By using routine infrared observations as part of the maintenance plan, any sudden temperature increase can indicate trouble.

Real-Time Computer Analysis. Probably the two greatest problems concerning preventive maintenance in the mining industry are depending on personnel to make necessary measurements (this is a management problem just as much as it is one of labor) and the inadequacies of existing techniques for predicting many of the failures which do occur. Research, as described in references 11 and 12, has been an on-going process to alleviate these two problems. The technique is based upon the classification of a deterioration matrix which is composed of electrical features, such as power-frequency harmonics and symmetrical components, which are continuously collected in a real-time environment. This eliminates the human link in the data collection and analysis process, and the system is sensitive to deterioration processes which cannot be detected by more conventional tests. Economic analyses indicate that the cost of the system could be amortized within two years. Practical implementation, however, is probably a decade away. In the meantime, much can be gained by using the conventional tests just described.

15.5 Mechanical Measurements

Mechanical-testing is most applicable to rotating machines. Consequently this section will focus on them. The failure of simple mechanical devices on a machine, such as a bearing, can lead to a catastrophic electrical failure. Even worse, excessive vibration on a machine can cause electrical deterioration. For example, commutator damage, insulation cracking, and squirrel-cage-rotor failures can result.

Electrical problems can cause excessive vibration; one case is open end rings on rotor-bar circuits. In fact, a variety of electrical problems can mimic mechanical deterioration and the only way to pin-point these things is to include mechanical measurements in the maintenance program.

Vibration. Machine vibration is a symptom of a mechanical or electrical problem. Electrically, some of the turns of one phase of the motor may be shorted, or a subharmonic voltage component (15, 30 or 45 Hz) may be present. However, vibration is typically the result of one of three potential problems.

The first problem is unbalance in the motor shaft or coupling. This unbalance may have been caused by improper installation, application damage such as a bent shaft, or it may even have been a manufacturing defect. Some devices, such as fans, require balancing before use and then at periodic intervals thereafter. The unbalance can be of two types: either static (the unbalance is in a single plane) or dynamic (the unbalance is in more than one plane). Whatever the cause, the vibration should be eliminated to reduce the chance of motor damage (for instance, winding-lead fatigue, insulation cracking, commutator damage, and so on). The second source of vibration is due to coupler misalignment. For example, when a motor is coupled to a pump or an air compressor, the coupler must be perfectly aligned or excessive vibration will result. Faulty parts are the third source of vibration, and these are of most interest here. When a bearing begins to fail, its vibration level will increase. By recording vibration levels, say every 60 days, any sharp increase can be detected, allowing an accurate prediction of incipient bearing failure.

The measurement of vibration is not too difficult. The transducer used is typically a linear accelerometer, which for convenience is often attached to a magnet or probe as shown in Figure 15.19. The output signal is connected to an instrument which will give a readout of acceleration, velocity (by integrating the acceleration signal), and displacement (the second integral of the acceleration signal). These instruments are also available with an oscilloscope display for examination of these quantities (acceleration, velocity, and displacement) in real-time and in time or frequency domains.

Analysis of these vibration data is beyond the scope of this chapter. Notwithstanding, there are a few comments which are in order. First, taking the readings involves engineering judgment. In the rather simple case of the motor and pump, the readings would be taken at points A through D, as shown in Figure 15.20. At each point, readings should be taken along each axis as shown in the figure. Careful analysis is required

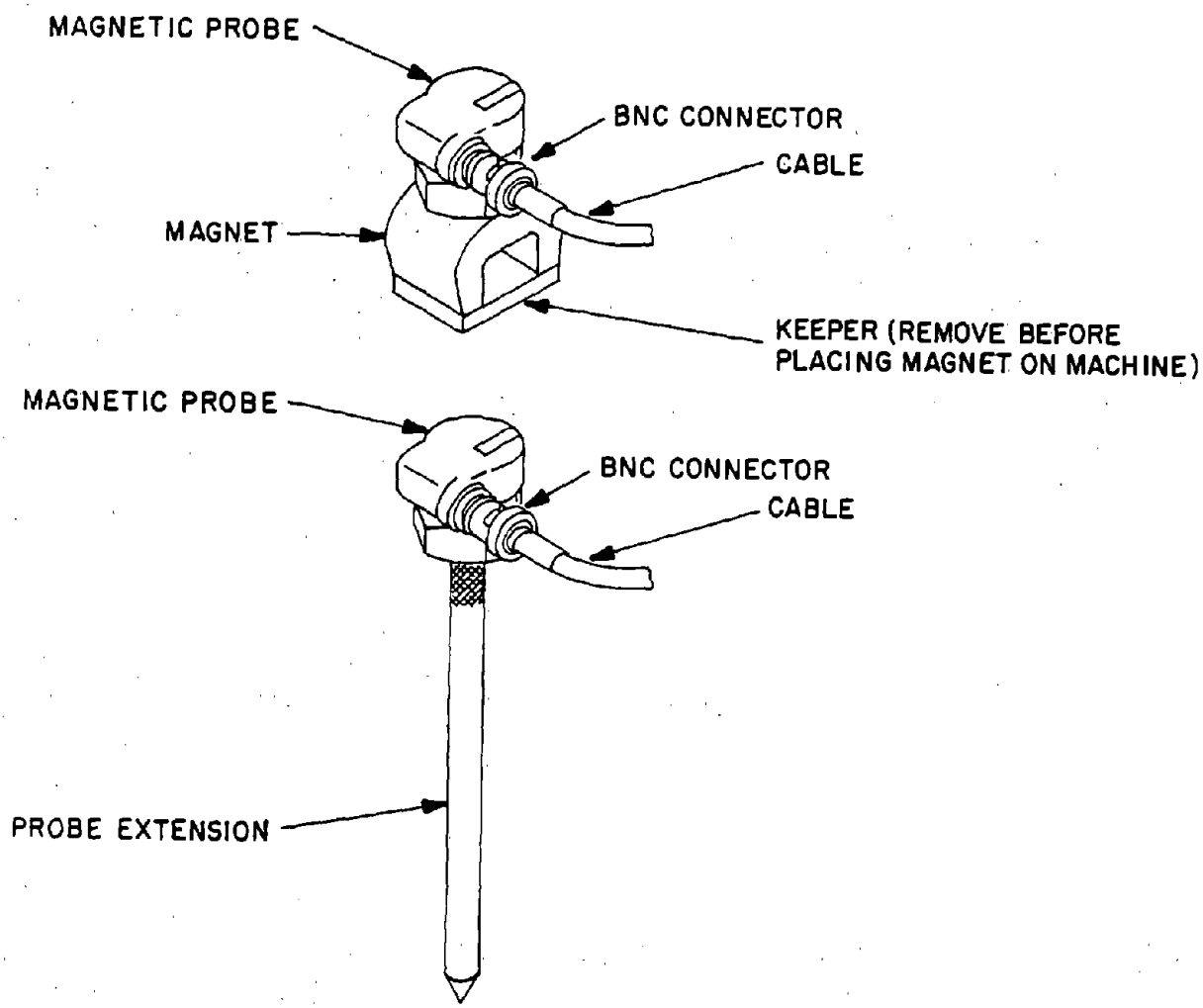


Figure 15.19. Mounting Techniques for Two Vibration Transducers.

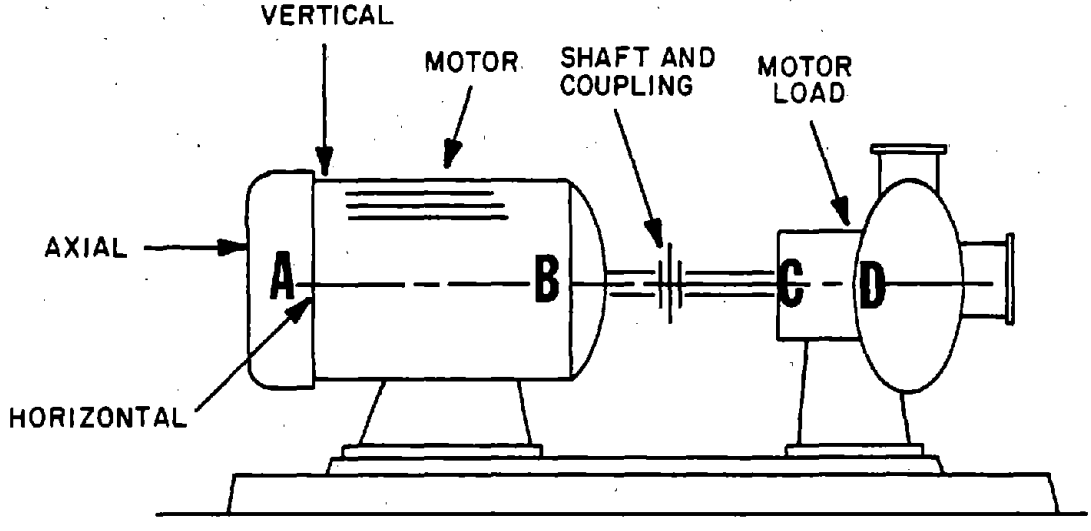


Figure 15.20. Four Typical Vibration Measurement Points.

to avoid various pitfalls. In this simple example, an unknowing person might confuse cavitation with vibration. Figure 15.21 is included to provide some insight into the severity of different levels of vibration. Table 15.1 is a brief summary of some of the more common causes of vibration (13).

Acoustic Emission. All rotating machines produced wide-band acoustic emissions. Knowledge of the frequency distribution, along with the amplitude distribution, can provide insight into incipient failure. Although many failures can be detected with only the frequency distribution, others require the amplitude distribution to supplement the analysis. For instance, crack propagation in a bearing generates a narrow acoustic-emission pulse with a flat frequency distribution, which is almost identical to friction noise in the bearing assembly. After being alerted to the potential failure, an analysis of the amplitude distribution will clearly separate the crack propagation from the friction noise.

Acoustic emissions fall conveniently into two areas: low and high frequency. Low-frequency emissions range from approximately five to 1000 Hz, whereas the high-frequency emissions start around 65 kHz and go up into the megahertz range. Although 1000 kHz is a practical cutoff point, many instruments are designed for low-frequency emissions, and much can be accomplished in this range. Recent advances in this area, however, have uncovered two compelling reasons for confining all work to the high-frequency range (14). First, machine-generated emissions in the high-frequency range are more defect oriented. Low-frequency signals contain many frequencies (harmonics of the 1st critical) caused by normal phenomena. These tend to cloud the picture which results in increased air. High-frequency signals are rapidly attenuated. This is the second advantage because it is easier to locate the source of the acoustic signal. Background-noise problems are also eliminated.

A brief discussion of the failures which can be classified by acoustic-emission techniques are far too numerous to be mentioned here. Let it suffice to say that most incipient mechanical failures, ranging from shaft effects to bearing problems to bad welds, can be predicted many days in advance of the failure. Figure 15.22 is an example of the technique. Portable instruments are available to measure and display acoustic-emissions signals. Either contact or non-contact probes may be used, depending on the application. On bearings, for example, a contact probe is placed on the grease fitting.

Table 15.1. Common Causes of Vibration.

CAUSE	AMPLITUDE	FREQUENCY	PHASE	REMARKS
Unbalance	Proportional to unbalance. Largest in radial direction.	1 x RPM	Single reference mark	Most common cause of vibration.
Misalignment couplings or bearings and bant shaft	Large in axial direction 50% or more of radial vibration	1 x RPM usual 2 & 3 x RPM sometimes	Single, double or triple	Best found by appearance of large axial vibration Use dial indicators or other method for positive diagnosis. If sleeve bearing machine and no coupling alignment balance the rotor.
Bad bearings anti-friction type	Unsteady - use velocity measurement if possible	Very high several times RPM	Erratic	Bearing responsible most likely the one nearest point of largest high-frequency vibration.
Eccentric journals	Usually not large	1 x RPM	Single mark	If on gears largest vibration in line with gear centers. If on motor or generator vibration disappears when power is turned off. If on pump or blower attempt to balance.
Bad gears or gear noise	Low-use velocity measure if possible	Very high gear teeth times RPM	Erratic	
Mechanical looseness		2 x RPM	Two reference marks. Slightly erratic.	Usually accompanied by unbalance and/or misalignment.
Bad drive belts	Erratic or pulsing	1, 2, 3, & 4 x RPM of belts	One or two depending on frequency. Usually unsteady.	Strob light best tool to freeze faulty belt.
Electrical	Disappears when power is turned off	1 x RPM or 1 or 2 x synchronous frequency	Single or rotating double mark.	If vibration amplitude drops off instantly when power is turned off cause is electrical.
Aerodynamic hydraulic forces		1 x RPM or number of blades on fan or impeller x RPM		Rare as a cause of trouble except in cases of resonance.
Reciprocating forces		1, 2 & higher orders x RPM		Inherent in reciprocating machines can only be reduced by design changes or isolation.

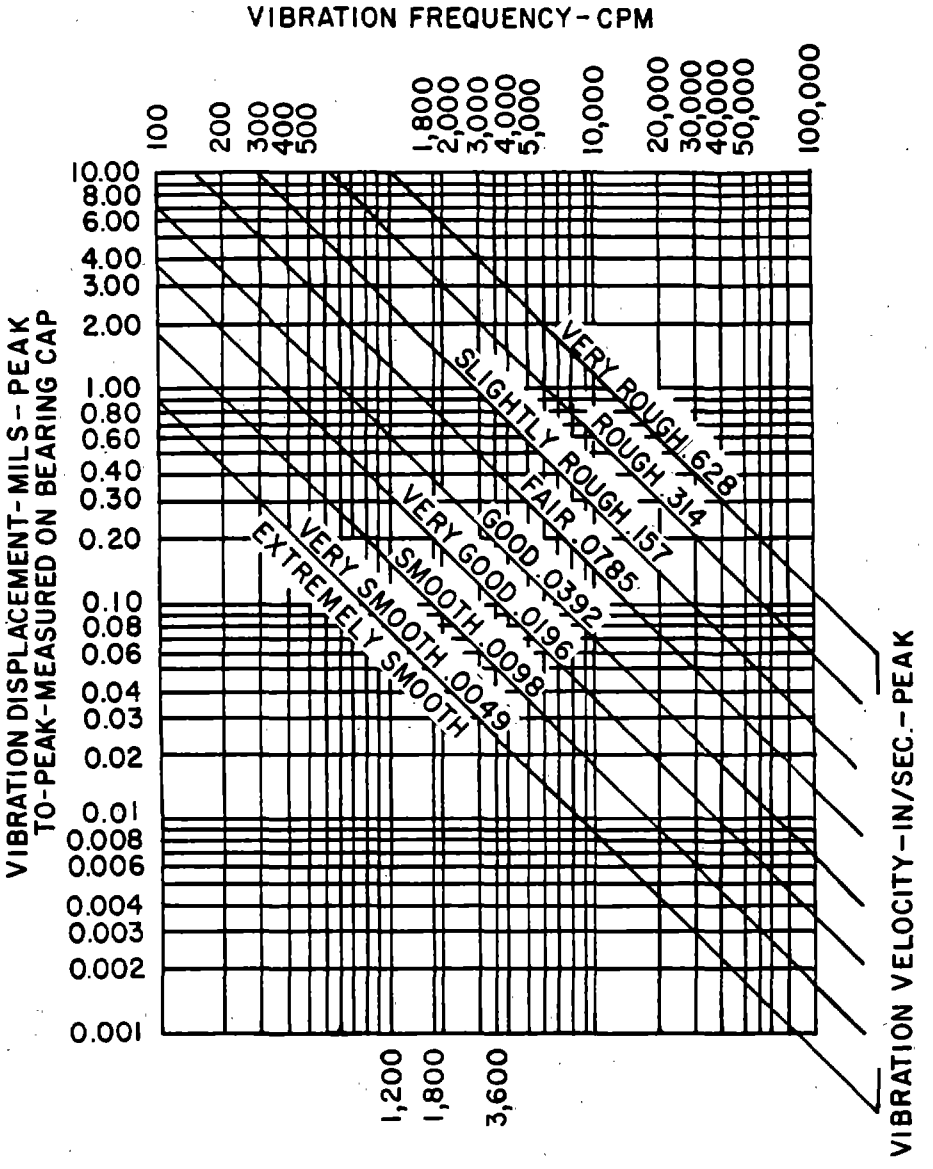


Figure 15.21. A Typical Vibration Severity Chart.

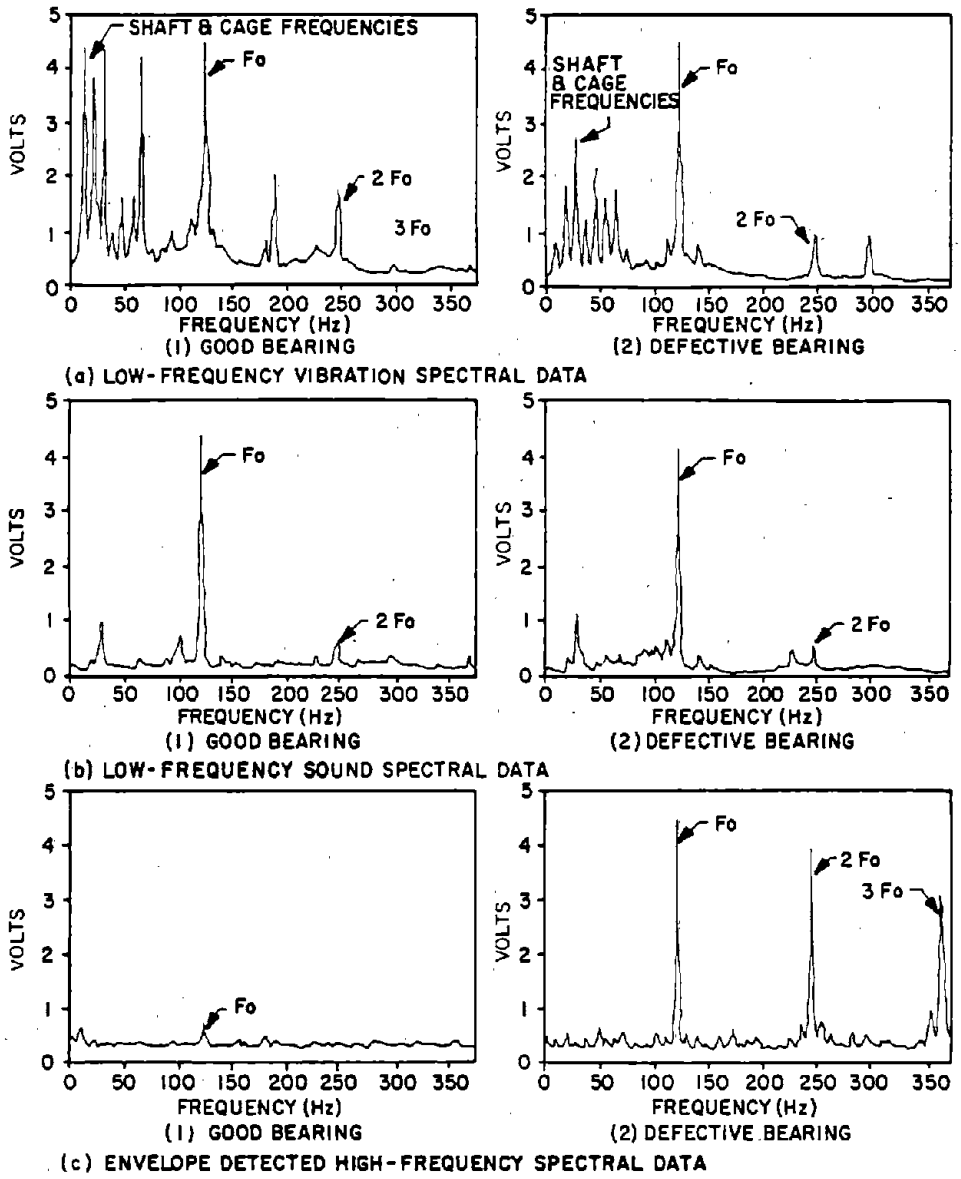


Figure 15.22. A Comparison of Acoustic-Emission Techniques for Detecting a Failing Roller Bearing.

15.6 Other Parameters

In addition to the electrical and mechanical tests already discussed, there are many more that can be applied to maintenance. Simple things such as temperature measurements can provide information. Measuring clearances or runout could alert maintenance personnel to incipient failure requiring appropriate action.

Spectroscopic analysis of the oil in large transformers provides sufficient data to detect many potential problems. Analysis of lubricating oils and greases can also be performed with the same results. The presence of a few parts per million of a metal can indicate excessive wear or other problems. In oil-filled distribution transformers, for example, partial discharge on the windings is indicated by the presence of few parts per million of copper (15).

There are many other techniques that could be mentioned, but the objective of this chapter is to provide an overview of the measurements which are available to form the backbone of a PM program. It should be noted that the mentioned techniques have been shown to work in other industries. Armed with all this technical knowledge, the next logical question is how are the records kept and the program managed over the next several years? This is the topic of the next section.

15.7 Program Implementation

As soon as the need for preventive maintenance is established, the top level of company management must become involved in the decision to implement a program. Since the returns from PM will initially lag behind its cost, management support is crucial. Whenever profits take a turn for the worse and operating budgets must be slashed, PM programs are usually the first to go. However, this is the time when the loss of their services can least be afforded. The backing of management can alleviate this industry-wide problem.

The selection of personnel to staff the PM crew should be well planned. Experience by industries other than mining indicates that at least 50% of the work crew should be composed of seasoned mechanics. These individuals must have a working knowledge of all the electromechanical systems which they will encounter. Special circumstances may warrant specialized individuals. For example, as solid-state equipment becomes more prevalent in and about the mine, an electronics technician would be beneficial. To offset any seniority bidding procedures, it might be best to have all PM personnel as salaried and non-union. Regardless of the crew makeup, one thing must be understood from the beginning at the mine. The PM crew should not be available for normal repair maintenance.

The maintenance superintendent typically assumes responsibility for the PM crew. However, such might not be appropriate in the mining industry. Rather, the job should be filled by someone very knowledgable with electrical or mechanical engineering (preferably both), who has had a few years of industry experience. The individual should report directly to the plant or mine superintendent.

With personnel questions answered, the next decision is what equipment should be covered under the PM program and which items should receive priority.

First priority should be given to new or expanding facilities. Maintainable equipment and installations do not just happen. From the planning stages through equipment purchasing to installation, a maintenance specialist should be involved in all the decisions. In fact, a recent study found that the time required for a new preparation plant to reach capacity operation can be reduced from an average of three to less than 1.5 years with the inclusion of a maintenance specialist in the planning team (16).

In selecting existing equipment for PM coverage, start with the components whose failure would have the greatest impact on production or safety. For an underground coal mine, these items might be surface substations, ventilation fans, and belt-driven motors. After these, rail-haulage motors and rectifiers, face machinery, and dewatering-pump motors might be added. The components to be covered, and the level of coverage for each component, can be determined by the economic factors presented earlier.

The next decision, and the one with the greatest impact on the success or failure of the PM program, is the organization of the data. The question here is should an index-card file or a computer system be used? Computers are very popular and have spawned a lot of computerized preventive maintenance. Commonly, someone in the company decides that a computerized PM system will cure all of the company's ills. Then a consulting firm is commissioned to develop a turn-key system. Usually this system is with the finest hardware available and has good software for solving PM-type problems. In all, the final system would make any operation-researcher proud. Unfortunately, the consulting firm does not collect and analyze the data. This has been the pitfall of almost every computerized-maintenance system tried in the mineral industries. In general, it has not been recognized that the weak link is in collecting the data and getting it to the computer. Computerized systems do have merit, but only when proper thought has been given to all phases of the PM program. The following paragraphs lay out an approach to this problem.

A group of components should be selected for the first stage of the PM program. Tests, which reflect the capabilities of the crew, should be defined. At this time there is no need to incorporate all of the most sophisticated techniques, which would also require a proportionately larger capital investment. A form should then be designed for each component. This form should include only the minimum amount of data required to perform a proper analysis. The layout should be such that the mechanic is led through the required test steps. Preferably, the data should also be transferred to a master form that contains space to record all test data for a one-year period. Forms should be filed according to the date of the next test and cross-filed by component type.

This system should be instituted for a minimum of one year, during which procedural changes can be made, forms modified, and options formed. Following this experience, the time is right to go to a computerized system.

The computer-system specification should involve the preventive-maintenance crew. Their ability to use and understand the computer will return many savings in reduced data-collection errors. They may also have valuable suggestions for improving the system. For instance, in a recent system synthesis, some members of an industrial PM crew expressed a need for a historical-data summary for the component being tested so additional tests could be performed when warranted (17). This suggestion was accommodated by printing-out small graphs of any test parameters which were indicating incipient failure. This sheet was attached to the computer-generated form used in collecting the data. The two sheets for each component were printed out on the day before the component was due for inspection.

15.8 Maintenance Summary

Problems and concerns in implementing the preventive-maintenance program could be discussed at great length. This chapter portion has hardly scratched the surface, yet it has pointed out some of the pitfalls. The references given should be helpful in this area.

Preventive or predictive maintenance is the key to improved productivity and safety in the mines. While it is true that the mining system poses unique problems, these perplexities are no more severe than those of other industries. Technology exists for predicting numerous electro-mechanical failures days or even weeks or months in advance, thereby allowing correction

during scheduled downtime rather than creating costly production delays. Additional savings are often realized by preventing a more serious failure due to the breakdown of a minor part of a component. Protection of the power system goes beyond the circuitry required to provide protection during faulting. Proper protection requires a preventive-maintenance program so efficient that the protective circuitry is only called upon for catastrophic failures.

The preceding has been concerned with preventive-maintenance and measurements that might be applied as part of that program. There are specialized subjects that have created maintenance problems for the industry in recent years. Because of significance, some of these have already been presented as report chapters, for instance, Chapter 6 on grounding or Chapter 10 on transients. The balance of this chapter will be devoted to a few other problems: corona, intermachine arcing, and d-c offset.

15.9 Corona and Partial Discharge

The recent implementation of 12.47-kV distribution systems in some underground coal mines has not resulted in the increased system integrity that was anticipated. There have been anomalous failures in couplers, cables, and stress cones. Corona has been the suspected cause. However, according to classical corona concepts, this would not be expected. In this section, the nature of corona, and its effects on dielectric material, will be reviewed. Afterwards, applications to mine power systems are considered.

15.9.1 Fundamentals of Electrical Discharges and Gases

Conduction in a Gas. Figure 15.24 is a general graph of conduction effects in a gas, for instance, air. It can be explained in terms of the ionic theory of conduction (18,19). Up to point A, Ohm's law is valid; shortly thereafter saturation occurs, due to the space-charge density. After increasing the potential to point B, the gas begins to ionize. The field has changed from a subdischarge field to an ionizing field. A small increase in potential will cause complete breakdown; in other words, a discharge field has been attained.

The proportionality between current and voltage up to point A occurs because the electric field is so weak that it ionizes very few gas molecules. Hence, the number of ions and free electrons is very small compared to the number of gas molecules. Multiplication effects are minimal so, in general, the current depends only on the mean speed of the ions and their relative numbers. Saturation, between

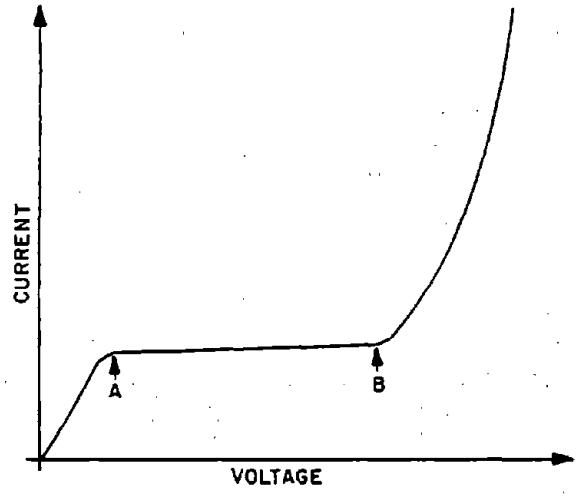


Figure 15.23. Conduction in a Gas.

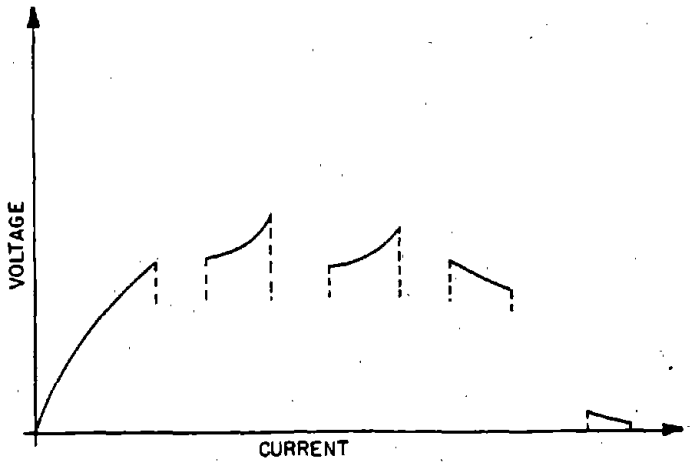


Figure 15.24. Gas-Discharge Sequence.

points A and B, occurs when the electron density reaches such a level as to decrease the field intensity. The flux of ions and electrons, thus current, remains constant. The formation of ions and free electrons is approximately equal to the number of recombinations. The current will depend on the rate of this process. A further increase in potential causes the ions and free electrons to acquire sufficient velocity that on colliding with neutral molecules, enough energy is imparted to split the molecule into ions and free electrons. This process increases exponentially and, therefore, the current increases exponentially. This "ionization by collision," is the most important mechanism of conductivity in gases. Secondary mechanisms include ionization by absorption of radiation, an important factor in arcing and thermal ionization. (Note: These statements are in agreement and complimentary to those made in Chapter 8 on Arcing Phenomena.)

Types of Discharge. Figure 15.24 is a plot of the ionizing field which occurs for gases. It portrays the different types of discharges which happen. In a given situation, any particular discharge may occur first, but any sequence of discharges will always progress in the order in which they are shown (18).

1. Partial Discharge - The discharge cannot be detected visually, but chemical changes in the gas occur.
2. Corona Discharge - Some form of glow signals the onset of corona. This type probably got its name from the halo or crown (corona) which appears during the process.
3. Brush Discharge - This discharge consists of a small number of sparks terminating in the air. Brush discharges are an instability of corona and often are considered an anomaly of corona.
4. Spark Discharge - The most complete breakdown occurs as a spark. It is very unstable since the passage of current lowers the voltage. Essentially, a spark consists of a quanta of electrical energy traveling through the gas with the associated current limited only by the source.
5. Arc - The arc is not a result of ionization by collision, and hence it is mentioned here only for completeness. Arcing will occur when the electrodes are hot enough to supply electrons for the current and to vaporize the anode and create positive particles which will heat the electrode by impact. This is a very unstable unprocess, dependent on many factors (see Chapter 8).

Terminology. Although the term "corona discharge" refers to a specific gaseous discharge, the term "corona" has come to be a generic name of partial corona and brush discharges. The term, "partial discharge," is often used interchangeably with corona, but the latter should be reserved for visual phenomenon. Regardless, the term corona will be used for all phenomena in the following discussion.

15.9-2 Characteristics of Corona

Occurrence and Maintenance of Corona. Mathematically, the conditions for the occurrence and maintenance of the discharge are given by Townsend's Continuity Theorem (18).

$$\int_0^{\ell} \left(\alpha e^{\int_0^x (\beta-\alpha)\, dx}\, dx\right) = 1 \qquad (15.6)$$

where,

α = ionizing coefficient of positive ions,

β = ionizing coefficient of negative ions,

ℓ = path of ionization (e.g., wire).

A very important part of Townsend's theory shows that corona can only occur in non-uniform electric fields, which are also the points of greatest electric-stress concentration. Common geometric configurations conducive to high stresses are shown in Figure 15.25.

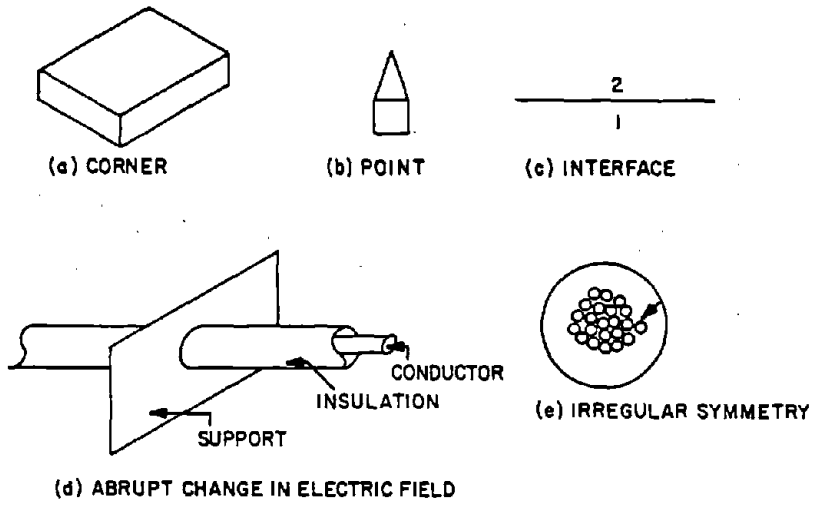


Figure 15.25. High-Stress Geometrics.

Appearance of Corona. The literature is saturated with two terms: "threshold corona level" and "visual corona level." Experimental results are given using either level, and different researchers conducting the same experiment will invariably state their results using a different level. This, of course, was probably due to a misunderstanding of gaseous discharges. Until recently, the visual level was determined by the human eye. Now sophisticated instrumentation is used to detect and quantify the visual level. Since this method includes the ultraviolet light which is often imperceptible to the eye, great care must be exercised when comparing data given in the literature. Corona inception and extinction levels are also used. Usually they refer to the level at which a corona dependent parameter, such as apparent charge, appears or disappears, respectively. Furthermore, the appearance of visual corona depends on the polarity of the conductor.

The inception and behavior of corona from an a-c potential is easily illustrated by considering a single bare conductor in air that is parallel to a ground plane. The dielectric or insulator, for this case, is air. A high-voltage test set is connected to the conductor. As the voltage of the conductor is increased, the gradient between the conductor and the ground plane increases. When the gradient reaches a critical value, the air molecules at the conductor interface are ionized. The voltage at this point is referred to as the "corona-inception level."

The ionization rate is a function of the air temperature, pressure, and the potential gradient. Larger gradients result in higher ion and electron velocities, hence greater energies. When these particles strike other molecules, the energy transfer is sufficient to cause ionization, so there is an exponential increase in ionized gas. The ionization process will continue outward until the ionized particles do not have sufficient energy to split another molecule. During this stage, the conductor will have the characteristic violet halo or crown, extending out two or three times the conductor diameter.

Closer examination of the conductor reveals a group of bright beads evenly spaced and superimposed on the uniform halo. The beads (negative corona) occur on the negative half of the sign wave, and the uniform glow (positive corona) occurs on the positive half. It is also thought that negative corona is more destructive (20). Sensitive detection equipment has been used to determine the macroscopic ionization frequency, which varies from 1 to 10,000 Hz (21).

If the line voltage is now reduced to the corona-inception level, the corona will not disappear although it will be

significantly reduced. The "corona-extinction level" will be a few percent less for a surface discharge, as is illustrated here, to 15 to 20% lower for a discharge in a void (22).

Corona in or on three-phase cable behaves essentially the same as the bare conductor (actually the use of partial discharge is perhaps more correct here). Calculation of the corona-inception level is more involved since the potential gradient is a function of both the conductor geometry and construction, plus the cable geometry and construction. Additionally, the maximum potential may occur between phases, rather than one phase and ground.

The characteristics of d-c corona are basically the same as those of a-c corona, for their respective polarities. However, d-c corona usually occurs at a slightly higher potential and intermittently. Since the d-c conductor will not change polarity, as in an a-c conductor, a surface charge will be deposited by the initial discharge. This must leak away before another discharge occurs, which decreases the frequency of discharges. Alternating-current corona is often considered to be the mean of positive d-c and negative d-c corona (23).

Harmonics. Harmonics due to corona can range into several thousand. The third harmonic, however, is the chief development (24). An investigation into corona and harmonics reveals two distinct roles played by the harmonics. First, there are the harmonics which result from corona; then there are corona losses associated with the presence of harmonics. The latter is more important in transmission systems.

Corona occurs during part of each half cycle in 60-Hz systems. Under this condition, the corona discharge is pulsated at twice the line frequency. This causes a cyclic change in line admittance which results in a modified or distorted waveform (7). The sinusoid has considerable harmonic content, particularly the third harmonic. The fifth, seventh, and ninth harmonics are often present.

A Fourier analysis of the symmetrical components for the current shows that the third harmonic must be composed only of zero-sequence current or voltage. Therefore, if the lines are connected in a grounded-wye configuration, the triple-frequency (third harmonic) currents caused by corona will flow through the lines and into the ground loop. In delta-connected systems, zero-sequence currents do not flow, instead a triple-frequency voltage pulsates between lines. The appearance of other harmonics as currents or voltages is easily determined by knowing the sequence of the harmonic in question (11).

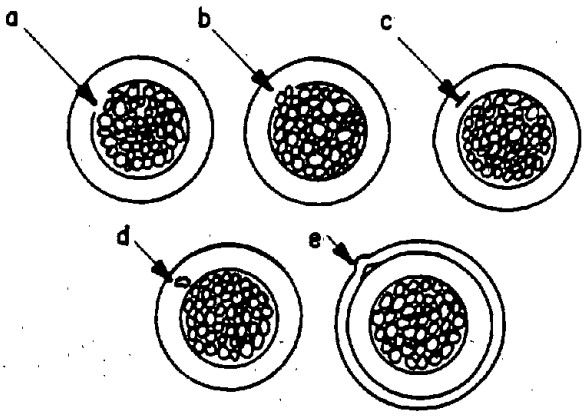
Radio-Interference Voltage. Ionization during corona causes radiation of radio-frequency noise. Below the visual corona level, radio-frequency noise is negligible, on the order of 10 μV. Corresponding almost exactly to the appearance of visual corona, the radio-interference voltage increases rapidly up to 100 or 200 μV (25).

15.9-3. Corona and Dielectrics

Corona in Dielectric Voids. Commercially-available insulated conductors contain air in the insulation or, stated more precisely, dielectric voids. Usually these occur as small bubbles within the insulation (approximately 0.1 mm to 0.01 mm in diameter on average). However, an air film between the conductor-semiconductor interface or between layers of insulation may occur, and occluded gases in the interstices of the dielectric have also been observed (22). Despite excellent quality control, present technology and economics prohibit the manufacture of insulated conductors (e.g., cables or couplers) which do not contain dielectric voids, as shown in Figure 15.26. The voids can also result from careless handling in the mine.

The boundary between the dielectric void and the insulation can be represented by two materials having dielectric constance, ε_1 and ε_2, with a potential across them (see Figure 15.25c). This series combination of the two materials results in an effective dielectric constant ε_k, which is less than both ε_1 and ε_2. From electromagnetic theory, it is known that this effect is due to the increased electric-filled intensity at the interface caused by the discrete change of the dielectric property (26). This results in a breakdown potential of the contained air which is less than the breakdown potential of air. Thus, corona can occur in a void at a voltage that is below the rated corona-extinction level. Normally, little is known about the air spaces within a given insulation. The size, location, distribution, pressure, and gas content of air spaces are unknown, thereby making corona evaluations difficult.

Degradation of insulation by corona can be explained by two separate mechanisms, which result in chemical decomposition of the dielectric. The first, believed to be the primary mechanism, is electron bombardment. As explained earlier, ionization by collision depends upon the continuance of the energy transferral during collision. Then depending on the potential gradient, the ionization extends outward at some finite distance. However, in a dielectric void, the contained gas will be ionized, and then the ions and free electrons strike the molecular structure of the dielectric. The energy transfer is usually sufficient to break the weak bonds, resulting in lower molecular weight volatile products (27). As the void begins to deteriorate, the electrical stresses increase, resulting in a "snowball effect" until the surface of the insulation is pierced.



(a) MISSING SEMICONDUCTOR TAPE
(b) VOID CREATED BY CONDUCTOR DAMAGE
(c) METAL PARTICLE WITH ASSOCIATED AIR POCKET
(d) BUBBLE
(e) BLISTER IN SPLICE JACKET

Figure 15.26. Typical Dielectric Voids in Cables.

Depending on the location of the punch-through and the cable application, a line-to-line or a line-to-ground fault may occur. The corona site may not result in an immediate failure, but remain active, thus deteriorating other dielectric material.

Chemical degradation by the volatile products, which include some very caustic acids, enhance the deterioration process during ion bombardment but can be considered a secondary mechanism. The chemical products which occur during surface ionization, however, are solely responsible for the dielectric degradation.

Corona on Dielectric Surfaces. When air is ionized, as during a surface discharge, ozone and nitrogen oxides are the principle products. If moisture is present, the nitrogen oxides combine with the water to form nitric acid. The nitric acid attacks the insulation, deteriorating it step by step. Ozone is very unstable and quickly goes to harmless diatomic oxygen. However, a thin layer of ozone persists in the vicinity of the insulation, where it can cause extensive damage. This damage can be simply described as a hardening process making the insulation brittle so, if the insulation is under flexure stress, it will develop large cracks.

15.9-4 Corona Detection

Numerous tests have been devised to determine the presence of corona. These tests have been primarily designed for checking corona levels in commercially-produced cables, and hence are of limited use in the mine. Perhaps the principles underlying these detectors could be applied with slight modification to this application. For details on these methods and commercial experience in their use, references 28 through 33 can be consulted.

The most widely-used method for detecting corona and making measurements reveals the presence of corona by displaying electrical signals that have been modified by the presence of corona. Any system where corona may be initiated is known as a "corona source," and the specific area of discharge is the "corona site." A corona site will be the source of corona pulses, which are very small transient currents.

These individual corona pulses normally last only a few nanoseconds and may occur at regular intervals. If these pulses occur at regular intervals for several minutes then it is called "continuous corona." Corona pulses, which recur for periods up to a few seconds but whose periods succeed each other at longer time intervals, are known as "intermittent corona." The recurrence frequency may vary from one pulse per minute for d-c to 100,000 pulses per second for 60-Hz a-c (21).

The shape of the corona pulse varies widely. It is primarily affected by the path taken by the corona current in the corona region. Hence, the "typical corona pulse" shown by some investigators is of very limited application.

The current of the corona pulse is too small to be measured. Instead, its effect on a traveling wave is monitored. This change in the traveling wave can be related to the apparent charge of the corona pulse. The apparent charge is proportional to the damage caused by the corona. An apparent charge greater than 4 pC is usually considered helpful.

The basic corona-discharge-detection system, as shown in Figure 15.27, consists of a detector, power-separation filter, power supply, and a calibration-signal coupler. The calibration coupler is used only for determining the sensitivity of the detector. It is disconnected during the actual test. The power supply is used to deliver a high voltage which is great enough to initiate corona. The 60-Hz signal and its harmonics are filtered out, leaving only the high frequency due to corona discharge, by using the power-separation filter. The detector contains the electronics necessary to integrate the pulses and determine the peak-pulse values. Various circuits are in present use to perform these operations.

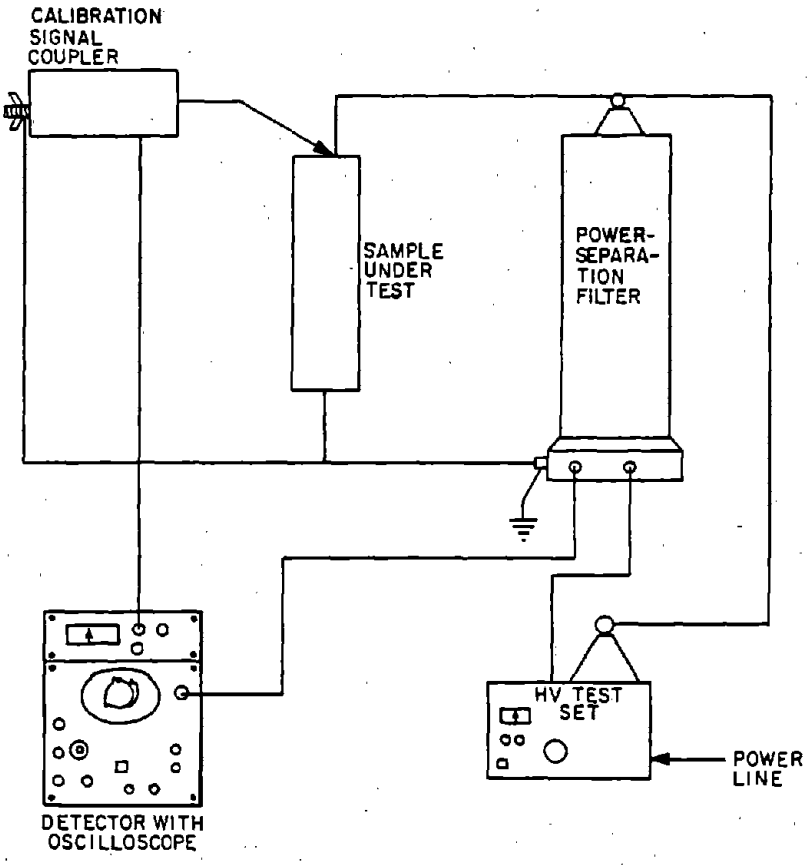


Figure 15.27. Block Diagram for a Corona-Detection System.

Practically all detectors work on the principle just described. Variations are sometimes incorporated to obtain results under special or adverse conditions. The technology is changing rapidly, and new techniques to overcome old shortcomings are imminent.

There is another fundamentally different technique with possible application to mine power systems, ultrasonics. Corona breakdowns cause both audible and ultrasonic pressure waves at the corona source. If the medium containing the corona source is in free-moving air, the pressure waves can be detected by an ultrasonic transducer. Successful tests have been reported using this technique, in which a barium-titanate transducer was used (30). There are advantages in using this method over previously described techniques. These are primarily the portability of the equipment and the relative simplicity with which it determines the presence of discharges. The disadvantages include difficulty in obtaining the quantitative data without the addition of complex equipment. When traveling through a solid, the pressure wave will follow a path of least resistance, thereby increasing the time of travel and making it difficult to obtain the location of the corona site. Furthermore, noise in transformer cores, known as magneto-striction noise, renders the detector useless around transformers.

15.9-5 Partial-Discharge Problems in Mining

The preceding paragraphs contained information that was general in nature, thus all discussion of discharges was incorporated under the generic term "corona." When discussing applications of corona theory to mine power systems, it is better to use the term for the actual time-dependent mechanism that causes failures, partial discharge. Most destruction that goes undetected and results from discharge can be linked to this first discharge level.

Partial-discharge-related failures fall into two groups. The first group consists of those failures where analyses have revealed that partial discharge is the source. Examples include occurrences in couplers, stress cones, cables and cable splices. The second group is composed of those failures that are suspected to result from partial discharge but cannot be directly correlated to it due to a lack of data. The source of failures in this group is more elusive and has been attributed to anything from "bad cable" to "transients," which may not be entirely accurate.

The next few paragraphs will cover some problems where partial-discharge is suspected. The presentation is pointed at high-voltage-system components and is most applicable to distribution requiring a 15-kV insulation class.

Cables. High-voltage transients may cause failure in a good distribution feeder cable but, as shown in Chapter 10, most transients do not contain enough energy to do this. However, a cable that has been weakened by partial-discharge degradation, may be susceptible to these lower energy transients. When a transient occurs, the weakened dielectric may fail or may deteriorate at a higher rate from the increased stress. Failure of the dielectric can result from a large energy transient or from a number of smaller transients over a given period of time. For this reason, among others, it is important to minimize transients in the mine power system.

Partial-discharge initiation can be caused by improper cable applications. Just two direct problems are sharply bending cables and passing cables directly over metal parts or through insulation. An abrupt change in the electric field along the cable length creates enough stress to initiate partial discharge, then the associated chemical deterioration can begin. In time, this can reach the conductor surface with a fault terminating the process. It is necessary to investigate intended cable applications before installing them in power centers, distribution transformers, or other units. A specific installation may be partial-discharge resistant in one case but partial-discharge susceptible in another.

Couplers. When a high-voltage cable is terminated, a serious discontinuity in the electric field can occur, creating substantial stress than can initiate partial discharge. As was mentioned in Chapter 7, high-voltage couplers and other terminations contain stress-relief systems to grade the stress over a sufficient distance. At the end of the system, the electrical stress must be less than the partial-discharge inception level.

High-voltage mine couplers are of special interest because their confined space creates stress-relief problems. Here, the cable insulation shield is replaced by gradually increasing insulation, and two conventional means are used: filler moldings and electrical-stress-control tape (34). Filler moldings are preformed stress cones, which are slipped onto each power conductor and conductor insulation of the cable, and the stress-relief properties are enhanced by tightly-stretched semi-con tape. With stress-control tape, the relief system is hand-built with wrapped tapes. In both cases, air-void elimination is extremely important; otherwise, partial-discharge sites can be created by any manufacturing or mounting defect.

Beyond stress-relief problems, couplers can be subjected to other partial-discharge by-product damage. One instance is a coupler with a folded insulator tube, causing a restricted area with lower surface resistivity at the fold (34). Whatever the

cause, ozone and nitric acid can be formed, creating a rapid deterioration of insulation within the coupler housing. The end result can be a catastrophic failure.

The partial-discharge extinction level is not only important to couplers but to all portions of the mine power system as well. The critical value for initiating or extinguishing partial discharge is the potential to the ground plane. As the neutral in high-voltage mine distribution systems establishes the ground plane, the worry is line-to-neutral voltage. Obviously, the extinction level must be safely above the nominal line-to-neutral system voltage. Otherwise, partial-discharge, for instance from inception created by a transient overvoltage, would continue. A safety factor of 25% above the maximum line-to-neutral voltage appears to be realistic (34). This relates to an 11-kV extinction level for the 15-kV couplers used on mine distribution systems.

Recent research by Bise (34) verified the main failure mechanism for high-voltage mine couplers as partial discharge. Carefully assembled random samples from several coupler manufacturers were used and subjected to an extensive battery of tests. Generally, every coupler failed to satisfy the 11-kV extinction test but passed all other examinations. In order to see what was required to improve performance, a coupler pair was carefully prepared for testing. Hand-taped stress cones were used. In addition to following the manufacturer's procedures, two notable modifications were made.

1. The stress-relief systems were carefully checked to eliminate any frayed edges.
2. A flame-retardant epoxy was poured between the contact and the insulating-tubes back end to fill any gaps, as well as to provide a seal against the potting compound.

The completed coupler set met or exceeded the 11-kV extinction level. As a result, Bise concluded that voids or partial-discharge sites were responsible for the poor readings.

15.9-6 Corona Summary

Partial discharges reduce the mine-power-system integrity by deteriorating insulation. This deterioration, either by ion bombardment or chemical decomposition, may be reduced or eliminated by following the suggestions presented.

1. Minimize high-voltage transients.
2. When installing cables inside power centers, belt transformers, and so on, do not bend or stretch them, unless they have been designed for that purpose.
3. Pay special attention in high-voltage systems to eliminate insulation voids and possible partial-discharge sites.

15.10 Intermachine Arcing

Wolf and others (35) have adequately described the sources and corrections for a-c intermachine arcing on mobile face equipment. Instead of duplicating their efforts, this section will briefly summarize it. Intermachine arcing resulting from d-c sources is covered in the succeeding section.

15.10-1 The Problem

When the 1969 Coal Mine Health and Safety Act specified that all low- and medium-voltage trailing cables for a-c mobile equipment must contain an insulated conductor for the ground-monitoring circuit, mine operators could not comply because available cables did not meet the specified requirements. This demand prompted conversion from three-conductor Type G round and flat cables to a newly-developed Type G-GC. In this cable one of the grounding conductors is insulated and the cross-sectional area of the remaining grounding conductors is increased. In 1971, mining companies began replacing their mining-equipment trailing cables with this new type. Soon after, sparks were observed between equipment frames. Following exhaustive tests by MESA (now MSHA), it was concluded that this sparking was caused by an induced voltage in the grounding conductors of continuous-miner trailing cables because of cable asymmetry. Subsequent investigations confirmed that the energy released by the arc was incendive.

A review of the conditions associated with this phenomenon indicates that the problem increases with the trailing-cable length, the power demand of the machine, and the cable-conductor asymmetrical geometry. Because of the physical asymmetry, the presence of the ground-check conductor in the cable aggravates the problem. Such is true whether the cable is shielded or non-shielded.

15.10-2 Arc-Suppression Devices or Methods

There are four basic methods for solving the induced-voltage problem and the subsequent arcs:

1. transposition of the phase conductors,
2. use of symmetrical-cable types,
3. use of diodes to suppress arc currents, and
4. use of saturable reactors to suppress arc currents.

Cable Transposition. This term means to change the phase-conductor position with respect to the individual neutral conductors at various positions along the cable length. Induced voltages in the grounding conductors are cancelled by dividing the cable precisely into thirds, cutting the cable twice, and splicing it as shown in Figure 15.28. If a grounding conductor is located at equal distances from the three-phase conductors,

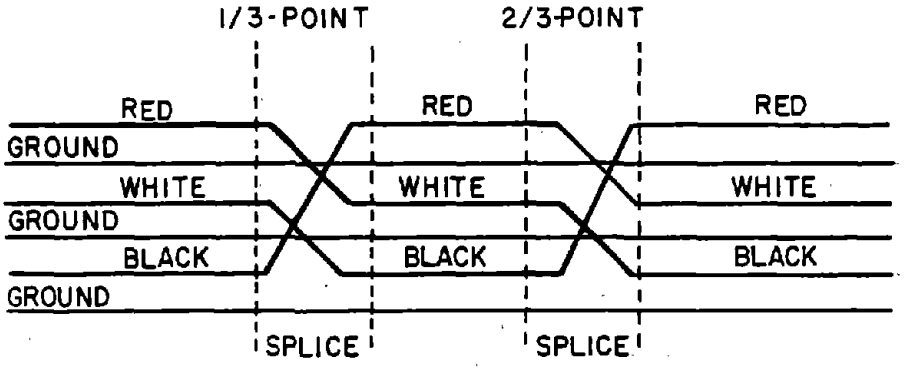


Figure 15.28. Power-Conductor Transposition in a Three-Conductor Type G Cable.

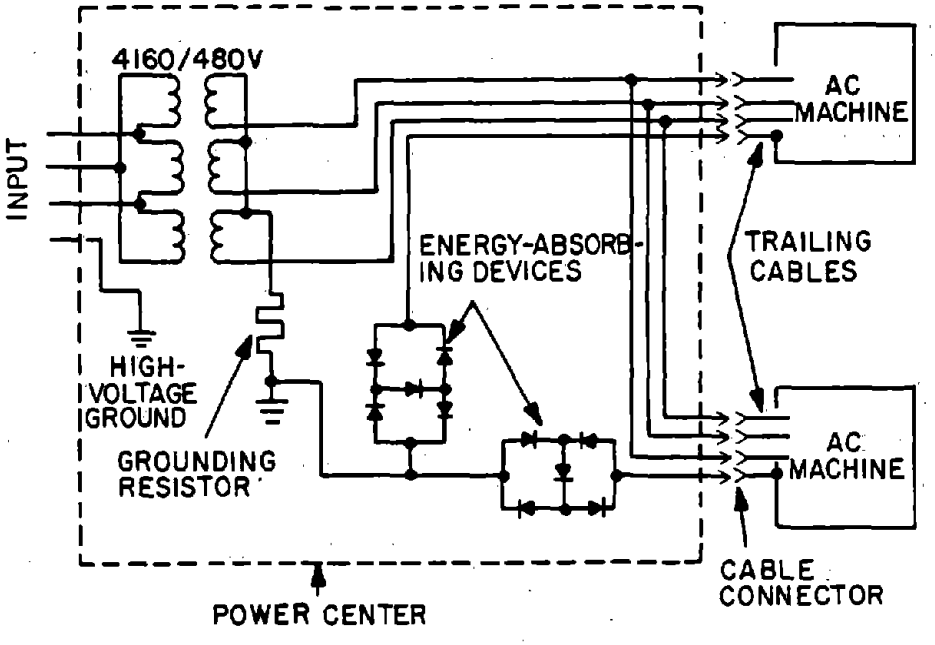


Figure 15.29. Application of Diode-Suppression Bridges in a Power Center.

the voltages induced by the phase currents sum vectorially to zero. Equal transposition of the phase conductors along the cable length results in the same effect.

Although a simple and effective method, the disadvantages of cable transposition negate its use in mining. It shortens cable life and physical strength, and in actual practice equal transposition lengths are difficult to maintain. Correct transposition may be easily upset during subsequent splicing.

Symmetrical-Cable Types. Symmetrical cables theoretically exhibit no induced-voltage or arcing-current phenomenon. The common symmetrical cables are Type G round and Type G+GC round (see Chapter 7). However, a symmetrical cable that has been spooled has considerable distortion and is not truly symmetrical. Actually, the same is true for any cable that is run over or similarly physically abused. Further, any unbalanced power-conductor load or conductor defect will alter the cable symmetry, and the resultant induced voltage will be impressed on the machine frame. Regardless, the use of symmetrical cables appears to be the best long-term solution. It should be noted that induced grounding-conductor voltages can only be negated if the continuity of each individual neutral conductor is assured through monitoring. This is obviously impossible with SH-D cable types.

Diode Suppression. Another approach to problem solution is to insert a non-linear impedance in the grounding circuit. The device must have a high effective impedance at low induced voltages, but a low effective impedance to the higher voltages and currents that are available during a ground fault. Any such device must have a continuous-current rating of at least 25 A and have a short-circuit capability equivalent to the cable grounding conductors.

Diodes connected in a bridge arrangement, as shown in Figure 15.29, apply this concept. The center diodes conduct at all times, and the outer diodes conduct every alternate half-cycle. The devices normally used will conduct about 1.0 A with a voltage drop of 0.6 V. As an incendive arc occurs with about 1.0 A, the danger of explosion can be eliminated with a sufficient number of diodes. For instance, with an induced voltage of 6.0 V, 10 diodes in series are needed. This means a total of 12 diodes are required in the bridge arrangement. Because simultaneous line-to-neutral faults on different phases at different system points are possible, it is necessary that if the diodes fail, they fail short as opposed to open.

Saturable Reactors. A non-linear element, which can also limit arcing current without affecting fault current, is a saturable reactor. The saturable reactor has several advantages

over diodes. Mainly, there is no junction of semi-conducting material that is subject to damage. The device is simply an iron-core inductor that has a high impedance to the point where the core is saturated. The inductance of the reactor is much less after saturation than before. This means that the device will limit induced voltages and arcing currents to a safe value, operating as a linear device. For fault currents and voltages, the saturable reactor operates in both the linear and non-linear regions. In other words, the currents are not sinusoidal, but the effective impedance will be low because the majority of operation is in the non-linear region. Thus, the grounding-system is still effective.

The selection of a suitable saturable-reactor characteristic is somewhat similar to that of diodes. The main input is the amount of induced voltage present and, once known, a reactor can be chosen to operate in a linear region for the induced voltage, limiting arc current to 1.0 A or less. The reactor should saturate for a slightly higher voltage, thus be effective to limit machine-frame potentials during faults. An acceptable saturable-reactor characteristic is shown in Figure 15.30.

Saturable reactors can be damaged by high separate-phase simultaneous-fault currents, and the winding conductor can be fused by the large current if it is not large enough. In such cases, just as for diodes, the device must fail short. Another problem is that saturable reactors can store energy, which can lower the actual incendive current. However, energy storage can be restricted by selecting a low quality factor (X/R ratio).

Saturable reactors and diodes are equally effective if installed between the machine frame and the grounding conductor or in the power center between the grounding conductor and frame ground. However, when applied in power centers, the grounding pin in metal-enclosed cable couplers must be isolated from ground. Otherwise, the device will be shorted out. (Note: This is the same precaution that was made in Chapter 8 for wireless ground-check monitors.)

15.10-3 Intermachine-Arcing Summary

Alternating-current induced voltages and intermachine arcing can be controlled by any one of the four methods described. Two of these involve the elimination of the source; where the other two involve the insertion of a non-linear impedance.

15.11 Ground Direct-Current Offsets

15.11-1 General

Direct-current offsets in grounding can be a serious problem whenever mixed a-c/d-c systems are involved. Intermachine arcing

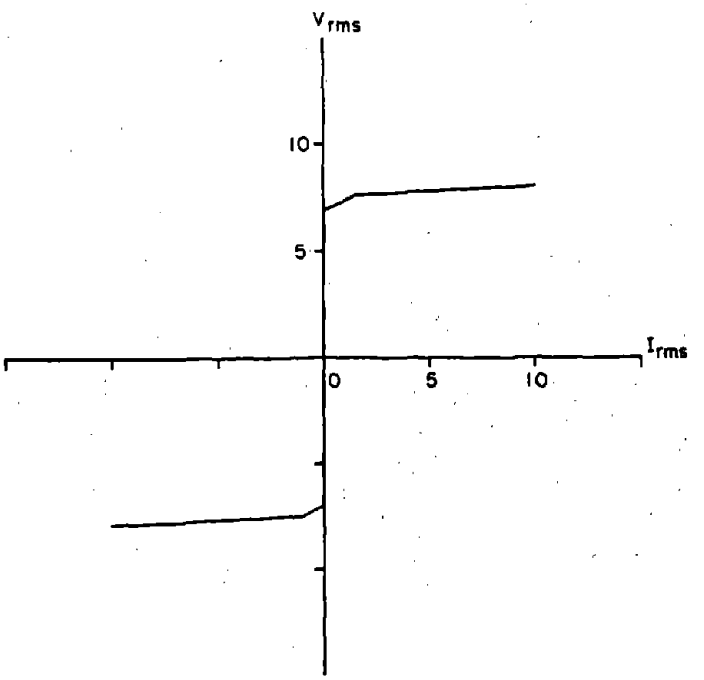


Figure 15.30. A Typical Saturable-Reactor Characteristic.

can result not only from a-c induced voltage on grounding conductors, but also from stray d-c. Yet, the presence of d-c ground currents on the a-c grounding system can also cause protective-relaying malfunctions, specifically ground-fault relays and ground-check monitors. This section will discuss these offset currents and competent methods to eliminate them. Background and sources of such currents have been covered in Section 6.4-2.

A corrective-method discussion cannot be constrained to d-c offset currents alone since they are only one anomaly in a bi-power (a-c and d-c) system where d-c is superimposed on the a-c ground. All major problems, including ground-bed deterioration by electrolysis, must be considered. However, analysis of these can be conveniently broken into three parts:

1. feasible power-system modifications,
2. grounding-system construction, and
3. water-distribution systems.

The following paragraphs will discuss each of these.

15.11-2 Feasible Power-System Modifications

Direct current finds its way onto the a-c ground by several means:

1. mine-floor/machine-frame contact, such as continuous miners or other a-c powered face equipment, pumps, power centers, distribution boxes, belt drives, and so forth;
2. two-wire d-c shuttle-car supplies, where the negative lead is tied directly to the frame of the shuttle car and rectifier.

In the first case, stray current from the mine's trolley system, flowing in the mine floor (or in the roof or ribs), gets onto an a-c equipment frame and thence onto the a-c safety-ground circuit. Much of the stray current flows in the mine floor because it finds a lower-resistance path (back to the rectifier) in the floor than it does in the track. There are several reasons for this. It is often quite difficult to bond track systems satisfactorily underground. Some bonding procedures are hard to follow and lead to improper bonds. Other methods are easier to use, but the result is a bond which is physically unsound and easily damaged. If a good bond is achieved, heavy rail usage or even abuse (such as moving continuous miners into the section over the tracks) can often destroy them. A parallel feeder, bonded at each rectifier and also bonded to the track at 100-ft intervals, should greatly attenuate the amplitude of stray direct currents flowing in the mine floor. When this arrangement is used in conjunction with careful a-c equipment and rectifier placement (e.g., a minimum of 25 ft from the track or, at worst, placing close a-c equipment on insulating mats), stray d-c from trolley sources should present little problem.

The use of isolated or floating d-c feed for shuttle cars would help to alleviate the second case. A two-wire negative-ground system is cheaper than a three-wire arrangement, but represents a serious electrical compromise, as does the concept of diode grounding. A two-conductor Type G shuttle-car trailing cable should always be advocated. Although often not found in practice, ground-check monitoring of the d-c cables is advisable.

15.11-3 Grounding-System Construction

Construction of a ground mat or grid is governed by three considerations: achieving a low value of earth resistance, controlling potential gradients, and preventing corrosion. The low earth resistance is achieved by placing a sufficient length or surface area of metal in intimate contact with the soil. If

the soil has a high conductivity, less metal will be required than would be the case if the soil resistivity were high. For safe grounding, a very low resistance is required between the soil and the buried metallic grid. Potential gradients are controlled by the placement of the grounding conductors in relation to one another and to the depth of burial beneath the surface. The manner in which a grounding grid responds to the flow of current through it, depends on the magnitude and duration of the loading. Generally, all metal structures should be tied together to eliminate potential-gradient hazards. However, corrosion protection necessitates the isolation of underground metallic structures from the soil effects. Detailed information on these subjects in relation to direct current is available in Sections 6.2-2, 6.2-3, and 6.2-6.

15.11-4 Water-Distribution Systems

There is no doubt that underground water-pipe systems presently serve as excellent sinks for any stray currents which may find themselves in the mine floor. If certain system precautions are made, as will be suggested shortly, then the magnitude of these stray currents should greatly diminish. When present, however, it is likely that nothing can be done to prevent their flow in the water-pipe system. Non-conductive pipe sections could be inserted in the line at intervals, which would serve to limit the amount of current carried by the pipe. Yet, the problem which remains is that due to the water inside the pipe. Distilled water is an insulator, but the presence of dissolved ions renders it conductive, and most mine water is rich in impurities.

15.11-5 Offset Summary

When the material just presented is combined with that in Chapter 6, the following list of expanded methods for reducing the effects of ground d-c offset currents can be assembled.

1. Employ good rail bonds and cross bonds, verified through preventive maintenance.
2. Use parallel feeders on (at least) intermediate and main line haulage for both positive and negative, bonded to the rail at least every 100 ft and at each rectifier.
3. Maintain isolation of a-c equipment frames (especially rectifiers) in proximity to trolley system by placing them at least 25 ft from the track or, in worst cases, placing equipment on insulating mats with maximum isolation from the mine floor.
4. For d-c face equipment, utilize Type G trailing cables.
5. Pay careful attention to the establishment of ground beds and the effects d-c can have on them (such as using cathodic protection and superficial anodes).

6. Maintain isolation (as much as practical) of the water distribution system from possible a-c or d-c stray ground-current sources.

These suggestions must be general in nature because no two mine systems have identical problems. Hence guidelines are more effective than specific rulings in this instance.

15.12 Summary

The foregoing sections have covered many aspects of maintenance, including justification, measurements, and planning, as well as some specific problems related to the subject. Many other areas fall under this general title and its supervision in the mining industry. Frankly, these aspects are major portions of Chapters 5 through 14 of this report, where they are presented in detail. Using this knowledge as background, the main objective of Chapter 15 has been to integrate additional information into a concept for a feasible preventive-maintenance program.

The importance of adequate preventive maintenance cannot be overemphasized. Through its employment, equipment availability can be maximized while personnel hazards are minimized. On the other hand, poorly done preventive maintenance is worse than worthless, and managers who have experienced this are very opposed to any approach to preventive maintenance in their mines.

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