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16. Abstract (Limit: 200 words)

This seven-chapter document is the first 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. After a short introductory chapter, chapter 2 discusses the history of electrical use in mining and introduces typical mine power system arrangements. Chapters 3-5 supply basic information on electrical theory, circuit analysis, and motors. Chapters 6-7 detail unique aspects of mine power systems. Elements of surface and underground use are included in all chapters. An index concludes volume I 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.

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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 1

INTRODUCTION

1.1 Importance

To paraphrase a common cliché, a mining operation is only as good as its electrical power system. The reason is simple: the use of electricity to produce a mine's commodity can be extremely extensive. For example, practically every vehicle in underground coal mining runs on some form of electricity, be it from batteries or a direct tie to the mine distribution system. Underground metal and non-metal mines can approach this dependency; included are trona, potash, salt, and copper. In addition to ventilation, deep mines are often hampered by severe water-pumping requirements which can only be effectively handled by electric motors. In surface mining, all moderate to large draglines and stripping shovels, all large production shovels, and numerous auxilary equipment are electrically driven. In other words, production, maintenance, and many functions of a mining operation are intimately tied to the subject of mine power systems. Such enormous use must obviously affect mine safety. These bonds will remain for the foreseeable future as no other energy source can be as efficiently and simply converted to perform mechanical work.

For these reasons alone, careful attention to the mine-power-system arrangement, from planning through installation to maintenance, is extremely important. Such efforts, however, often are not easy. Present-day power systems can be extremely large and complex and, as no two mines have identical requirements, a standard electrical system is not always adaptable. Additionally, plans can change from day to day to keep pace with production. As a result, qualitative and quantitative methods are necessary to design and maintain a power system so it matches the particular mine's requirements.

Probably no other mining area has grown as rapidly but been so little understood by the average person as electrical power systems. Traditionally, the field has interested mining engineers very little and, therefore, they have tended to avoid it. Unfortunately, several electrical engineers have also been equally disinterested. Since these systems are now complicated and, further, tied to numerous legal constraints, it is no longer possible to treat them with the same indifference as in the past.

Responsibility for the decisions leading to a mine-electrical system design is normally divided among the operator, governmental regulatory agencies, and manufacturers furnishing the equipment plus sometimes supplying the detailed engineering. However, because of industry indifference, what usually happens is not a power study, designing the system needs, but a decision

to use what was employed in the last mine. Many times such thinking works, but sometimes new concepts would have worked at a lower cost, higher efficiency, and improved safety.

Accordingly, the mine operator who plans to run a mine electrically, or anyone responsible for the efficiency or safety of such an operation, must be familiar with mine electrical systems. They should know the advantages and disadvantages of one system over another, both from personnel protection and production standpoints. If the power system is poorly designed, not only can safety be compromised (apparent by the loss of human life), but a mine operator will pay for the resulting conditions with high power bills, high-cost maintenance, and loss of production.

Obviously, this subject is extremely important and has a vast impact on the mining industry, and it is unfortunate that mine power systems have received the past neglect. Most often, the situation has been tied to ignorance. Therefore, this report is projected at removing the knowledge problem by presenting a comprehensive outline of mine electrical power systems from theory to practice. If the information contained within this document is utilized by the industry, the ultimate objective of the work will be achieved: improving electrical safety in the nation's coal mines.

By investigating the most complex system, any arrangement should be understood. In mining, the most intricate are generally those in underground coal. Therefore, several report segments will center around these systems, but surface-coal-mining designs are covered in detail. Although projected at coal mining, the report can be employed by the metal and non-metal industry for the same stated objectives.

1.2 Complexity

Today's underground coal-mine electrical system can be compared to a mechanic running a drill and a light at the end of a 1000-ft extension cord while, at the same time, being required to maintain and monitor a competent ground system with substantial protection devices for safety. Voltage at the equipment must be held reasonably constant, and variations are detrimental in various ways (1). For instance, below-normal voltage reduces light output from incandescent lamps; above-normal voltage increases the light output but reduces the life of the lamp. Motors (in this case, the mechanic's drill), operated at below-normal voltage, can draw abnormally high currents and may overheat, even when carrying no more than the rated horsepower load. Overvoltage on a motor may cause excessive heat loss in the motor's iron, wasting energy and perhaps damaging the machine. A further complication to the situation is that any of the required safety devices can easily shut down the work for various reasons.

If this one instance is expanded by 75 for face equipment then doubled for auxiliary equipment, the result is a conservative estimate of the power system problems for a present underground coal mine of just moderate size. However, the example excludes past and current neglect, traditionally poor maintenance, plus a power system that is employed like no other.

In diagram, the mine power system appears similar to any modern power installation for an industrial plant; however, there are differences that create unique problems beyond those just mentioned. It might be obvious from the foregoing comparison that the main dissimilarity is the nature and location of the load (2). Mining equipment is mobile and self-propelled, and the majority is powered electrically through portable cables. These machines and most power equipment (which distributes the power to the machinery) are seldom stationary: for safety, the power system must carry a ground from the equipment frames back to the source and earth. Among the most compact, rugged work machines ever designed are used in underground coal, and individual units can have up to 1000 total horsepower. Surface mining involves the largest earth-moving equipment built; one piece can have 12,000 or more connected horsepower (the largest today is 30,000 hp). The electrical loads created by this machinery are cyclic and extremely dynamic. For example, large surface excavator loads can vary from 200% motoring to 100% generating every 50 to 60 s (2). Furthermore, the mine (both underground and surface) affords an extremely harsh environment on its own, not to mention the sometimes destructive qualities of the workers.

These are only a few examples of the perplexities synonymous with mine power systems, yet the presentation has been mainly projected at production. However, the primary goal of any electrical-system design is to insure personnel safety but, through the growth of mining, providing this mandatory need has created a prime problem area. Therefore, another objective of the report is to delineate what constitutes a safe, efficient, thus productive mine power system. An extremely important concept, lost in some mining operations, is that good safety is an inherent part of good production.

1.3 Basic Design Considerations

Any power system must meet a minimum number of basic criteria for its design. Although projected at industrial plants, the IEEE "Red Book" (3) lists the necessary considerations:

1. safety to personnel and property,
2. reliability of operation,
3. simplicity,
4. maintenance,

5. adequate interrupting capacity,
6. current-limiting capability,
7. selective system operation,
8. voltage regulation,
9. mine expansion, and
10. first cost.

When applied to mine electrical systems, these provide impetus for many subjects which should be contained in the report. (The author intends to clarify the meaning of the above terms in upcoming sections.)

In general, the first seven items are projected at safety. As mentioned, safety to personnel is the ultimate concept of any electrical system, and it has no compromise. The only exception of safety to property is where such protection jeopardizes personnel safety.

Reliability, the continuity of service required, is often the first consideration towards safety. Reliability is commonly best achieved through simplicity and is dependent on preventive maintenance. As most maintenance in the mine is performed by the miners, planned maintenance should be minimized, with the understanding that most work, if needed, could be done by unskilled personnel.

Adequate interrupting capacity, current-limiting capability, and selective-system operation are projected at safety through reliability. The first two areas insure protection during a disturbance. Current limiting, when applied to grounding, is perhaps the most significant personnel safety feature of mine electrical systems. Selective-system operation is a design concept that minimizes the effect of system disturbances.

Voltage regulation is a limiting design consideration in mining, especially underground. It is often the main constraint on system expansion. Accordingly, increasing the mine's size might involve augmenting the power-system supply through adding additional power sources.

First cost is important but should never be a determining factor. High-cost equipment, projected at maximizing safety and reliability, can easily offset an increased first cost with reduced operational costs. At times, this fact appears to elude some company purchasing departments.

Usually in designing a mine electrical system, the engineer has available to him the following information:

1. size of the mine (number of sections, stripping units, production shovels, etc.),
2. equipment types,
3. haulage methods,
4. possible future expansion,
5. availability of power from the utility, and

6. available capital for the electrial system.

Using this data and the basic design considerations, the designer must then:

1. select one combination of power equipment over another;
2. provide power (or circuit) diagrams;
3. estimate equipment, maintenance, and operating costs;
4. set specifications; and
5. receive proposals.

The goal is to provide that safe, efficient electrical system at maximum safety for the lowest possible cost.

An important avenue to effectively obtain the objective is a firm knowledge of mine power systems, but such knowledge cannot rely on a "standard mine electrical system" because (again) no two mines are exactly alike. The individual must resort to the fundamental concepts, an awareness of what has worked in the past, and an understanding of the legal constraints. By using these, the goal should be attained. Sometimes, the final design decisions will involve making an economic analysis (one of the reasons for referring to costs), but this is beyond the scope of the report. However, as has been stated, providing the necessary knowledge is the main purpose of this document.

1.4 Report Format

The report is divided into two volumes, which together, contain the vital aspects that go into planning and designing a mine electrical system. The presentation is structured so an individual unfamiliar with electrical engineering can first develop the necessary fundamentals before embarking into mine electrical design. A basic physics and calculus knowledge is necessary to completely understand the total report content.

The documents are not intended to replace other electrical or mining engineering texts. Yet, to provide all mining industry segments with a guide to safe mine-electrical-system theory, design, and installation, many engineering concepts are covered but only in the detail necessary to provide a stand-alone report. For further information on individual subjects, the reader can refer to the extensive reference lists that are available at the end of each chapter.

Accordingly, the next four chapters contain information considered elementary and, indeed, many sections of Chapters 3 through 10 are fundamental to power engineers. The content, however, is projected at mine power, and a person with electrical familiarity can employ the material as a review.

The goal of Chapter 2 is to introduce "typical" mine-electrical-system arrangements. The content is rather descriptive, providing an overview of mining systems, power equipment,

and distribution. The purpose is to lay the foundation for the balance of the report.

Chapters 3, 4, and 5 are the most fundamental chapters and supply the reader with basic information form electrical theory through circuit analysis to the mine's most important loads, motors. Grounding and distribution chapters come next and detail significant aspects of mine power systems which set them aside from other industrial applications. Elements of surface and underground use are included.

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. System protection is continued in the next report segment, Transient and Over-voltages, and concludes the elementary presentation.

Chapter 11 describes the design of major power equipment for mining, generally considered to include substations, switchhouses, and power centers. The very active portion of mine electrical technology, solid-state control, is presented in Chapter 12, then the critical safety area of batteries and battery chargers is covered in Chapter 13. Although some material is elementary, this chapter also includes a discussion of battery-charger construction. Permissibility and hazard-reduction techniques are next, and information is given concerning necessary protection in other mining areas beyond underground coal. Significant aspects of maintenance and mine electrical problems are contained in Chapter 15. The problems related include, for example, d-c offsets, intermachine arcing, and corona, special situations that have plagued the mining industry in recent years.

Throughout the report, the author projects the necessary combinations of power equipment and components that should be contained in a mine electrical system.

The assembly of this material has been an overwhelming undertaking. Although the result is comprehensive, it is quite possible that some subjects are missing. Frankly, to include all aspects of mine electrical systems in two documents approaches an impossibility. The attempt, therefore, has been to assemble the most significant information, thereby providing the reader with all the tools needed to continue a knowledgeable involvement in mine electricity.

1.5 References

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3. IEEE, "Recommended Practice for Electrical Power Distribution for Industrial Plants," Std. 141-1976, IEEE, New York, 1976.

Chapter 2

MINE ELECTRICAL SYSTEM ARRANGEMENTS

2.1 General

Several design requirements of a mine electrical system were set forth in the preceding chapter. Also, a terse comparison with common electrical use was made to provide an initial impression of system complexity. This chapter will expand upon these thoughts by examining representative electrical arrangements for the more popular mining activities. The presentation, after covering some important introductory material, will look at major power equipment and basic circuit structures then, by employing these, assemble each power system. These arrangements, as will be seen, are closely related to the mining method (or technique). That is, system organization for a strip mine may be applicable for open-pit mining but is often not directly adaptable to underground work. Yet, with all systems, the basic design considerations and circuit structures still apply.

It is realized that some readers may be unaccustomed to working with electrical diagrams. Because illustrative material is imperative, most drawings in the chapter will therefore use a block-diagram format. These alone are extremely useful tools. They allow an individual to examine the overall system organization without having the investigation hampered or confused by specific electrical complexities within that system. An uniform set of symbols will be utilized for all power-system equipment. For instance, nearly all mine power systems employ three conductors to transmit power between equipment, and one or more additional conductors are used to connect (or ground) the metallic frames of each part or machine together. The diagram, instead of using four or more lines, will represent all these connections with a single line. In Chapter 4, specific symbols will be assigned to each component type (beyond the single line) when the subject of one-line diagrams is introduced.

The goal of this chapter is to place mine power systems in a perspective where the reader can understand why specific subjects need further elaboration (for example, circuit analysis, grounding, system protection, and so on). The report will also contain several terms common to mining, and some knowledge of mining techniques and equipment is assumed in later chapters. Accordingly, the next section will quickly scan the more popular coal-mining techniques. The reason is that (as already implied) the constraints of the mining system usually transfer requirements to the power system.

2.2 Coal-Mining Techniques

The process of opening the mine can be divided into three

major parts: exploration, development, and production (1). "Exploration" is the first step in mining although it can continue during the development and production stages. The objective of exploration is to define the physical properties of the seam and surrounding strata. The resulting data is used for an initial profitability analysis, and if it is decided that the seam can be mined profitably, for mine design. The exploration program usually includes drilling holes from the surface into the coal seam and retrieving core samples of the coal and surrounding rocks. In this way, physical properties, such as thickness, slope, depth, strength, sulfur content, BTU content, and so on, are determined.

The development stage consists of gaining access to the coal seam. "Mine types" are characterized by how the access is accomplished. Shaft, slope, drift (including punch) and surface are considered basic types, and the first three are underground mines. "Surface" simply means above ground so, in this context, there exists surface parts of underground mines. Vertical cross sections of representative mine types are provided in Figure 2.1.

Perhaps the earliest mine type is the "drift." The drift mine is developed directly from a surface outcrop (where the seam appears on the surface) by driving entries into the coal seam, and mining is performed by underground methods. Although different type openings may be utilized in another part of the operation, if the drift access continues to be used, the mine is still officially a drift mine.

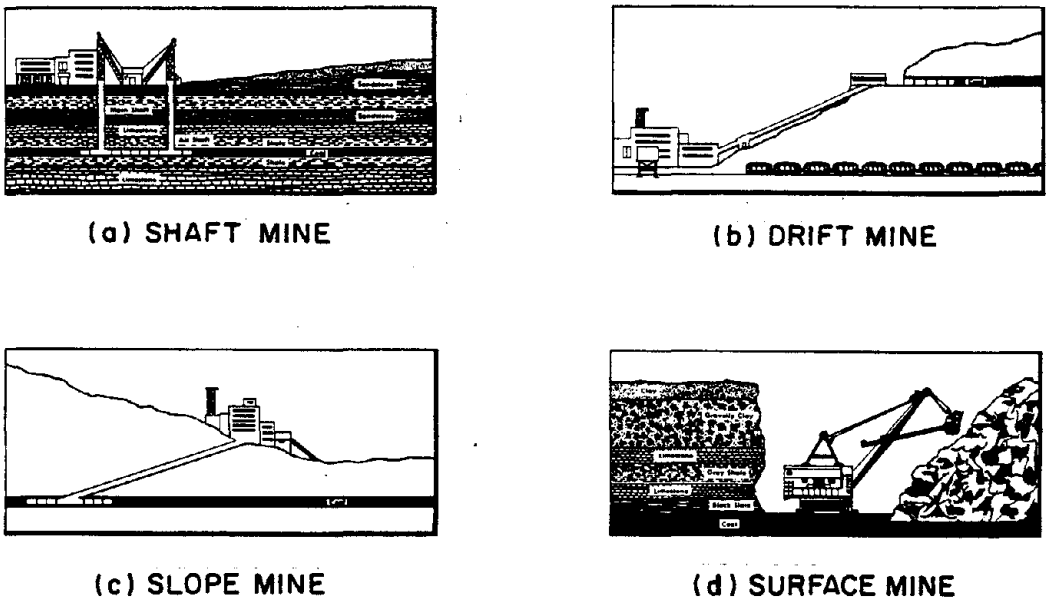


Figure 2.1. Vertical Cross Sections of Representative Mine Types.

Many times, however, deep (i.e., underground) mines cannot be reached from an outcrop. Even if the seam does appear at the surface, it is often divided among several companies (or operators) or the distance to the actual mining area (or "face") is too great to economically move workers. In these cases, to gain access to the seam, vertical or inclined shafts (or both) must be sunk.

A few years ago, most deep mines that were not drift had vertical shafts to hoist both workers and coal; still today, many important underground mines employ only vertical hoisting. Such mines are classified as "shaft" types. The reasons for use include:

1. the mine is too deep for an alternative opening with the economic breakpoint depth being about 1000 ft or
2. the original vertical shaft in old mines is still in excellent condition.

Usually in deep mines, no less than two shafts are provided, their major functions coupled to coal and worker movement plus mine ventilation.

The introduction of continuous belt-conveyor haulage provided an alternative opening for underground mines, the "slope." Presently, a large number of deep mines use slopes for conveyor haulage of coal to the surface, also utilizing the opening for material, equipment, and supplies (movement by hoisting with wire-rope and rails). As the maximum practical incline for a belt conveyor is 30% grade (17° to 18° angle from horizontal), the maximum seam depth is considered around 1000 ft, although there are some slope mines with greater seam depth. Vertical shafts are still used in most slope mines for ventilation or with elevators for people. Vertical movement (as generally opposed to inclined) is the most safe, fast way to move workers into or from a mine.

"Surface mining" methods are selected over underground when the "overburden," the earth above the coal seam, can be economically removed, exposing the coal. Further, surface mining is usually the best choice for seams that are less than 150-ft deep because productivity, safety, and profitability commonly favor these methods.

2.2-1 Underground Methods

Figure 2.2 is a plan view of the general underground-coal-mine technique used in the United States. A system of main "entries," each 16- to 20-ft wide, is developed from the coal-seam access point to the production areas, called "panels" or "sections." "Pillars" of coals are left during development to support the overburden above the entries. "Crosscuts" are mined between the entries. The main entries may remain standing for several years while coal is being extracted from the panels. Haulage of personnel, supplies, and coal, along with ventilation air, dust-suppression water, and electrical distribution are necessary functions of the main entries throughout the life of the mine.

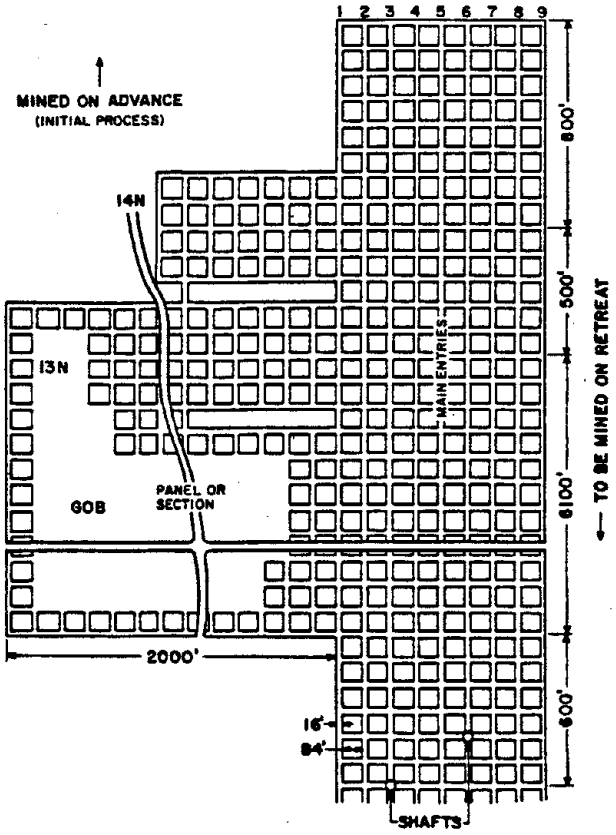


Figure 2.2. Plan View of an Underground Coal-Mine Layout.

The "mining method" is defined by the configuration of openings ("rooms") and pillars in the panel and by the classification of equipment used. The important underground coal-mining methods can be divided into three major categories with variations as follows:

1. room and pillar:
   a. conventional,
   b. continuous;
2. longwall:
   a. retreat,
   b. advance; and
3. shortwall.

Mining machinery is an integral and essential part of each. Often a specific machine performs one of three basic functions: coal extraction, haulage, and roof support. Although there has been a recent substantial increase in longwall and, to a lesser extent, shortwall, the room-and-pillar method, including both conventional and continuous equipment, remains dominant (3). The reason a specific method is selected over another is usually a result of the mine's natural conditions, including: (5)

1. the characteristics of the overburden, roof, and floor, plus

2. grades (i.e., seam dip), water, methane, and seam height.

The method and equipment selected is based on the combination that will provide the safest and most profitable extraction in a given set of natural geologic conditions while complying with state and federal health, safety, and environmental regulations.

Room and Pillar. Before the advent of mechanized mining, coal was drilled and picked by hand, explosives were loaded and shot, then the broken coal was placed by hand onto some form of conveyance for movement from the working area. In the United States, this form of coal mining is considered extremely obsolete, yet the "conventional" mining method represents a direct evolution. Present mining is based on the original "loading machine" (see Figure 2.3) which came into use in the early 1920's.

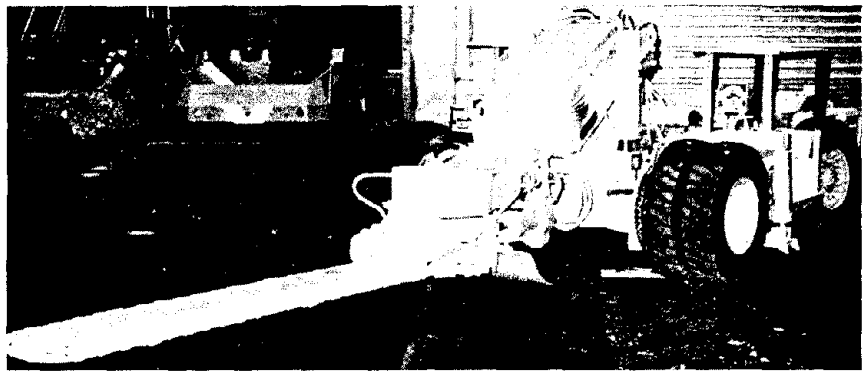
Conventional mining is performed by six distinct operations:

1. "undercutting" the coal face,
2. "drilling" holes in the face for blasting,
3. "blasting,"
4. "loading" the broken coal onto a face haulage system,
5. "hauling" the coal from the face area to a subsequent haulage system, then
6. providing "roof support".

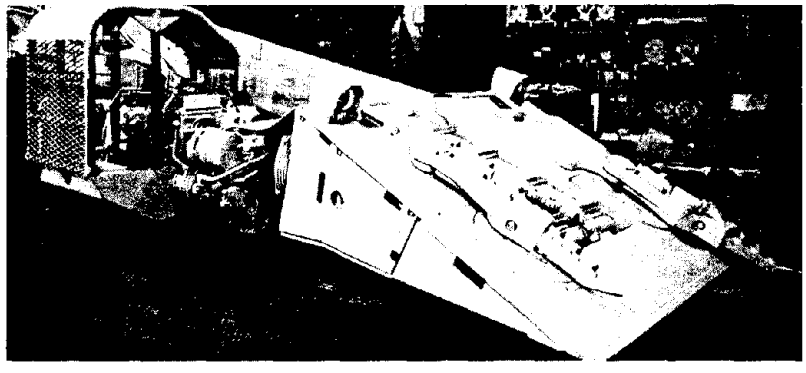
In order, these comprise a "mining cycle" and, after roof support is provided, work again starts at step 1. Because of its continuous nature, ventilation is not included as a separate step in the cycle, but its importance cannot be overlooked. Furthermore, the roof and face are examined carefully after blasting and before each job begins at the face. Mobile self-propelled mining equipment, illustrated in Figure 2.3, perform almost all of the operations.

The "cutting maching", basically an oversized chain saw, is employed to cut a slot at floor level, usually at floor level, called the "kerf". This provides room for coal expansion during blasting. A self-propelled face drill follows the cutter and uses carbide-tipped auger-type drills to place several holes in the face. Blasting can be accomplished by high-pressure air (Airdox) or high-pressure carbon dioxide (Cardox) but is normally done with chemical explosives that are approved to be "permissible" by MSHA. Permissible explosives will not ignite methane and coal dust when used in a proper manner.

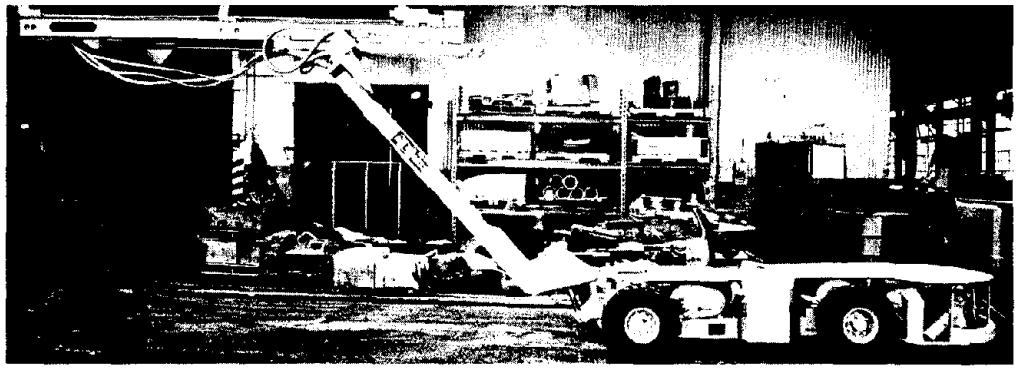
A crawler-mounted loading machine loads the broken coal onto the face haulage vehicle, typically a "shuttle car". The car is equipped with a chain conveyor for moving coal from the load end to the discharge end and then for discharging coal from the vehicle. Shuttle cars almost always work in pairs, moving the coal to rail cars or a conveyor belt (the next stage of materials handling in the mine).



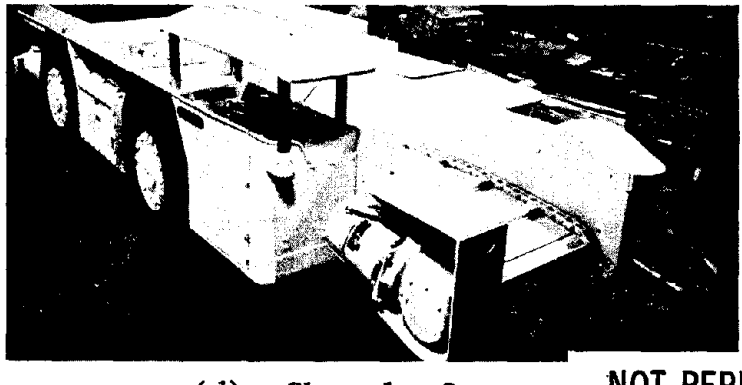
(a) Cutting Machine



(b) Loading Machine



(c) Face Drill



(d) Shuttle Car

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Figure 2.3. Conventional Mining Equipment (courtesy Joy Manu.).

The "roof bolter" (or "roof drill") is a rubber-tired vehicle utilized to secure the roof by first drilling vertical holes then emplacing roof bolts. These bolts can be of either expansion-shell-anchor or epoxy-resin-anchor type. When in place, the result is roof support either by beam strengthening (clamping thin roof layers into a thick beam) or by hanging weak strata to a more competent upper layer. Drilling is often done by rotary action with auger-type bits, the resulting dust being collected through the bit and hollow drill rod by vacuum.

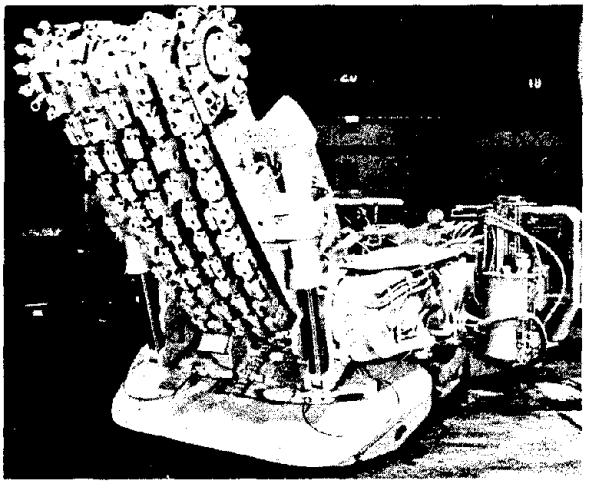
With very minor exceptions, the foregoing machines are electrically driven, powered via trailing cables from the mine power system. The mining equipment is continually moved among several faces in a coordinated plan for maximum production efficiency.

What results from the actual coal removal is a system of coal pillars surrounded by open rooms, hence the mining method term. The mining-operation movement develops towards the property boundaries in the individual mining operations called sections. When the equipment nears the property lines, the operation is turned around. If the surface subsidence is permitted, the pillars are removed (extracted) in an organized plan with adjacent sections. The extracting process is named "retreat".

Continuous Mining. First introduced in 1948, the heart of the continuous coal-mining method is the "continuous miner". It so revolutionized U.S. coal mining that it is now the most popular underground method. As shown in Table 1.1, the continuous miner replaces the conventional room-and-pillar unit operations of cutting, drilling, blasting, and loading. However, the mining functions of haulage and roof support remain, though some continuous miners even perform roof bolting. However, the term, continuous, is, in fact, a misnomer because of legal constraints.

Of the four basic continuous-miner types shown in Figure 2.4, the "ripper chain" is one of the earliest. The machine consists of a ripper head fitted with multi-bit chains which rip coal from the face, and the head is attached to the main frame through a flexible hydraulic mechanism that allows horizontal and vertical movement. Both directions are used to attack the coal face. The cut coal is loaded onto a centrally located chain conveyor by two eccentric gathering arms, the operation being practically identical to that of a coal loading machine. The rear of the conveyor can be moved horizontally or vertically to facilitate loading the face haulage, and the machine chassis is crawler-mounted for mobility.

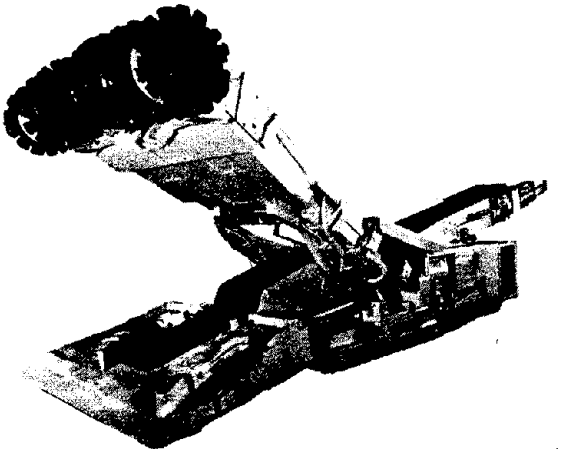
The "boring machine" was introduced almost simultaneously with the ripper. This miner cuts a full-face in one operation with two rotating boring heads and trimming chains (normally on the top and bottom of the cut). The borer, being very bulky, is generally considered a development machine and is used rarely



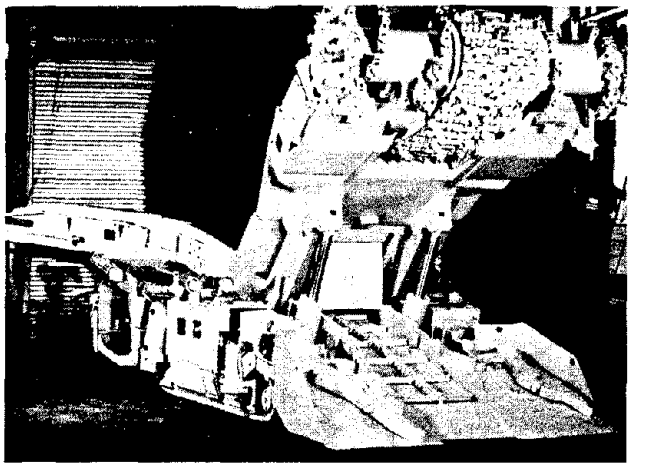
(a) Ripper Chain (Joy)



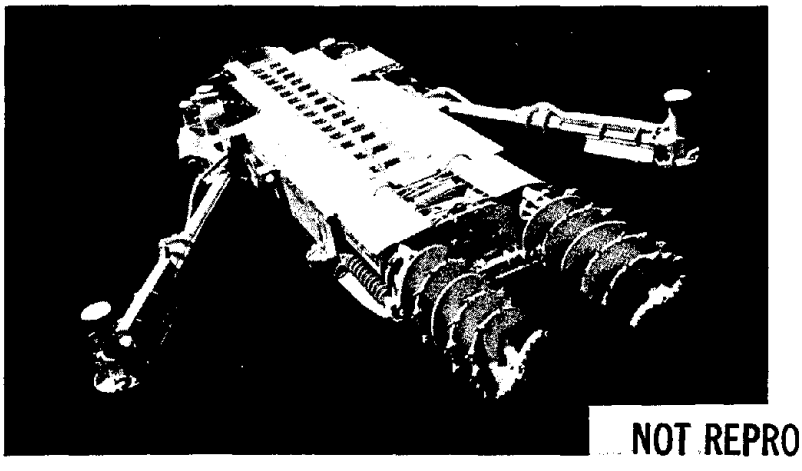
(b) Boring Machine (Joy)



(c) Oscillating-head (Joy)



(d) Fixed-head (Joy)



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(e) Pivot Auger (Fairchild)

Figure 2.4. Basic Continuous Miners.

for pillar extraction. Mobility and conveyance systems are similar to the ripper.

The third basic continuous miner is the "milling head" of which there are two categories: oscillating and fixed. The "oscillating-head" milling machine has a similar frame, conveyor, and loader as the ripper except, in place of the ripper chains, a number of cutting wheels or disks with bits are located at the end of two arms. When cutting coal, the wheels are rotated in a vertical plane, and the arms oscillate the cutting heads back and forth horizontally, Using the crawler (or cats), the machine "sumps" the heads into the coal seam top, then hydraulic rams pull the arms downward so the cutters "shear" coal from the face. (The entire head assembly cannot be swung from side to side, except by using the crawlers.) Generally the same as an oscillating-head machine, the "fixed-head" or "hardhead" continuous miner performs the same mining function. Here, plumb-bob bits are spirally mounted on two rigid heads. The result is a more reliable machine, and the fixed-head arrangement is currently becoming the most popular continuous miner.

"Pivot auger" and "helical auger" miners fit into the fourth basic continuous-miner type. These have been manufactured because of a need for efficient machines in thin-seam mining (less than 36 in. seam height, referred to as "low-coal"). The other continuous miners work extremely well in thicker seams, but attempts to employ the same designs for low-coal have normally been unsatisfactory. Until about 1974, the pivot auger miner was the main thin-seam miner and allowed mining down to 20 in. The

Table 2.1. Comparison of Typical Room-and-Pillar Conventional and Continuous Mining Equipment.

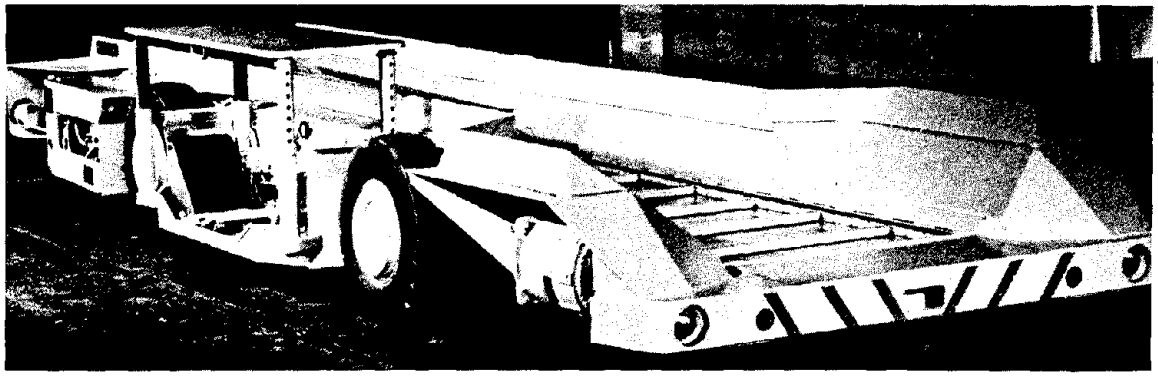
CONVENTIONAL		CONTINUOUS
	1. EXTRACTION	
Cutting Machine Drill Loading Machine Blasting		Continuous Miner
	2. FACE HAULAGE	
Shuttle Cars (2)		Shuttle Cars (2)
	3. ROOF SUPPORT	
Roof Bolter		Roof Bolter

machine cuts coal with twin cutting augers and a lower cutting bar. Maneuvering and face cutting is facilitated by ropes pulling the machine about one of two pivot jacks located at the rear (of the machine). By alternating swing directions and the pivot point, the machine is advanced into the coal.

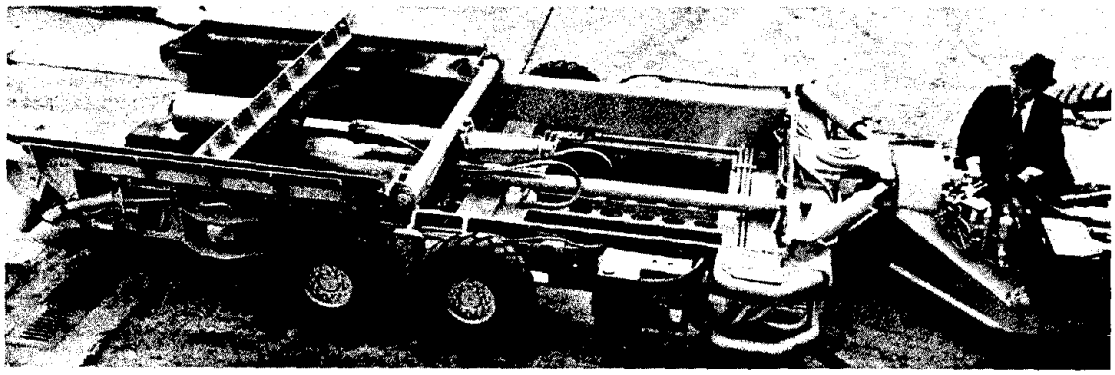
The other popular thin-seam miner uses a single, extendable, helical auger which cuts and loads in a single operation. Sumping and shearing operations are similar to milling machines, but all head actions are performed with hydraulic cylinders. They are practical in seam heights ranging from 30 to 47 in. The operation is often semi-remote controlled by a cable-connected console.

In continuous mining, face haulage is commonly performed by wheeled intermittent units (except in extremely low seams where mobile-chain or belt conveyors are more common). As with conventional mining, these are typically shuttle cars, but articulated ram-dump ("ram-cars"), tractor-trailers, and front-end loaders also find application (they are also used in some conventional sections). These alternatives are shown in Figure 2.5, and the last two units are able to perform functions other than haulage, connected with maintenance, equipment movement, and supplies. There are several continuous-transport systems that have undergone development to eliminate a significant production delay, the nearly constant waiting for intermittent face haulage (3). A couple of these are illustrated in Figure 2.6, of which mobile chain and belt conveyors have predominated from the beginning. Several continuous-haulage designs have been hampered by maneuverability and reliability problems. However, hydraulic transport systems have shown great promise; they operate by pulverizing and slurrying the coal right behind the miner then pumping the slurry to the surface.

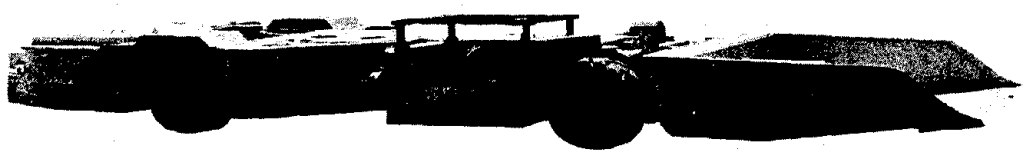
As mentioned, continuous mining, at times, cannot be continuous. There are three primary reasons, all being tied to federal or state regulations. The federal regulations are published under Title 30, Code of Federal Regulations, in the Federal Register. First, work cannot proceed under unsupported roof. With most continuous miners, this means a maximum advance of 20 ft (distance from the cutters to the machine operator) before the machine must be maneuvered for the next cut. Next, ventilation must be maintained to within 10 ft of the face. At that mined depth, the brattice cloth line (directing air flow) or air tubing (forced flow with an auxiliary fan), whichever is used, must be extended. Finally, in some states, methane concentration at the face must be measured at regular intervals, usually 20 min. These constraints bring out another important unit function to underground mining, ventilation. Intermittent haulage units (shuttle car or ram car) also detract from continuous operation even though they are favored over continuous-haulage equipment. Usually ventilation advance and gas checks can be made during change-out periods of the intermittent haulage units.



(a) Shuttle Car (courtesy Joy Manufacturing)

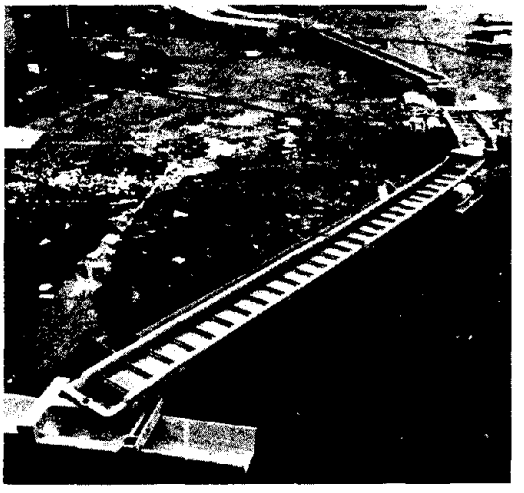


(b) Dump Portion of a Ram-Dump (courtesy Jeffrey Division, Dresser Ind.)

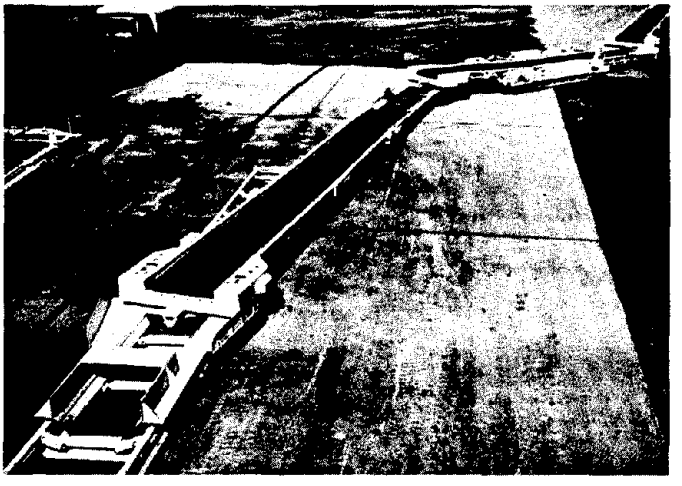


(c) Scoop Tractor (courtesy S and S Corp.)

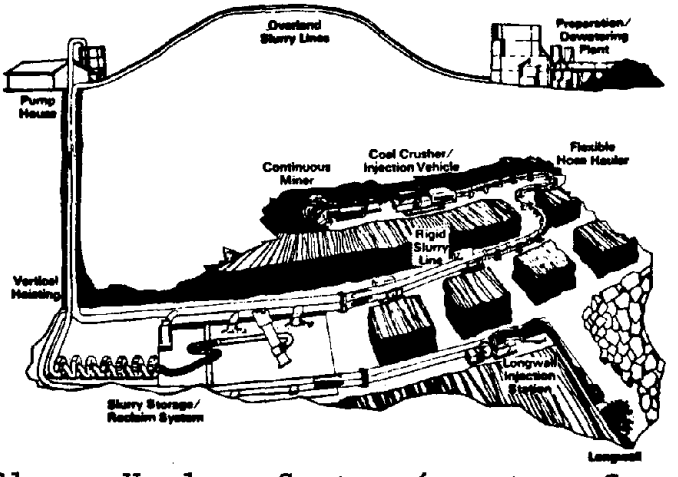
Figure 2.5. Important Intermittent Face-Haulage Units.



(a) Bridge Conveyor (courtesy Jeffery Div., Dresser Ind.)



(b) Cascading Conveyor (courtesy Hewitt-Robins)



(c) Slurry Haulage System (courtesy Conoco)

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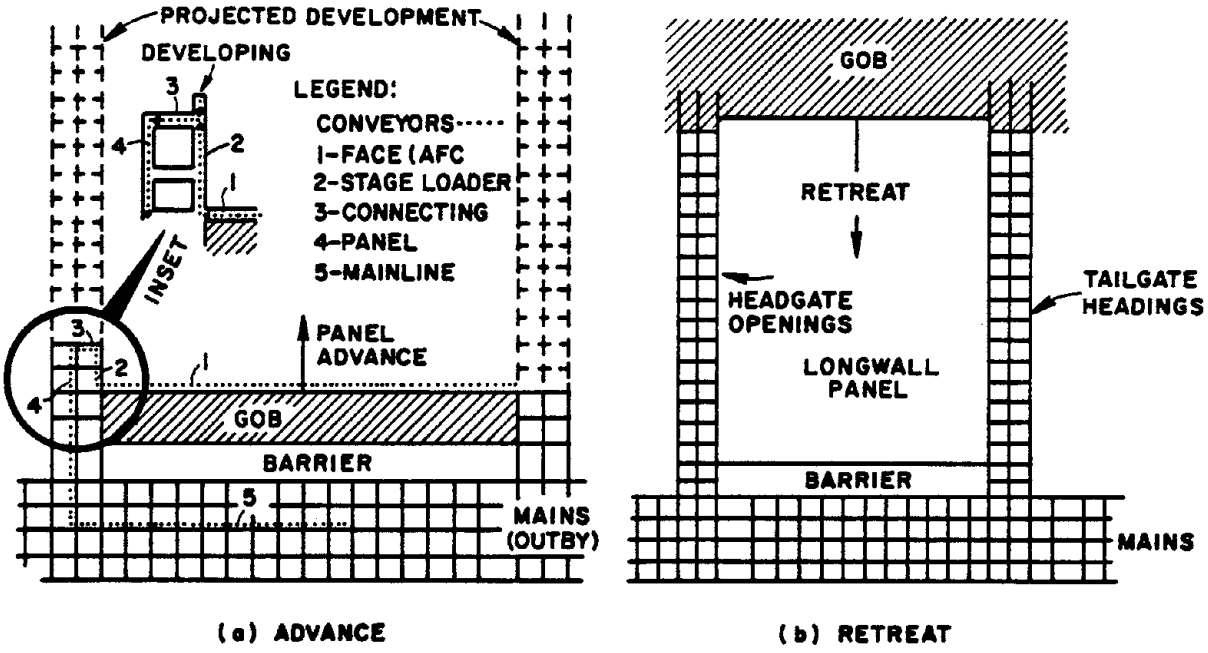
Figure 2.6. Examples of Continuous Face-Haulage Systems.

Longwall Mining. Longwall mining is the most popular underground coal mining technique in Europe; it is undergoing fast acceptance and growth in the United States. In contrast to room and pillar, longwall is capital rather than labor intensive (3). To mine coal, a section of the coal seam is delineated by entries, for haulage and ventilation approximately 300 to 600 ft apart, and an interconnection. The rib of the interconnection is then mined on a longwall, and the roof is allowed to cave immediately as the longwall equipment moves. As shown in Figure 2.7, the direction of mining with respect to the main entries classifies the longwall technique: advancing or retreating. Most popular in the U.S. is the latter.

In the typical "retreating longwall", two sets of room and pillar entries (or gates) are driven away from the main entries. An interconnection is made and the mining equipment installed. The face is then mined back and forth, moving towards the main entries. For "advancing longwall", the equipment is installed in an interconnection adjacent to the main entry, then mining proceeds. The gates are advanced with or just slightly ahead of the longwall equipment. As caving occurs, these openings must be maintained. In some mines, adjacent panels are mined by alternating retreat and advance.

Longwall mining equipment again consists of three basic components (see Figure 2.8): the support equipment, the haulage system, and the mining machine (40). The support equipment consists of hydraulic jacks with roof and floor beams. The jacks are interconnected via the conveyor. These are self-advancing and capable of moving the face conveyor. The roof beam extends up to the face being mined. The haulage system is an armored-chain conveyor with elevated discharge to the next haulage system, often an extensible belt conveyor. Figure 2.9 shows the two basic mining machine categories: the planer (or plow) and the shearer. The "planer" rests on the mine floor immediately ahead of the conveyor. It spalls or picks a thin layer (3 to 6 in.) of coal while being pulled by a chain. The "shearer", however, mines 24 to 30 in. per pass with a rotating drum (similar to the head of a milling continuous miner) which rides on the side rails of the conveyor. The shearer can have one or two drums and also might be "ranging", allowing vertical drum movement.

Shortwall. In plan view, "shortwall mining" is practically the same as longwall, except the face length is normally 150 to 200 ft, and shortwall is not as popular. However, as with most other underground techniques, the major difference involves the mining machinery. Shortwall can be considered a compromise between room and pillar and longwall because the extractive and face-haulage systems are identical to continuous mining while the roof-support equipment functions as in longwall mining (3). A typical layout is shown in Figure 2.10. A standard continuous miner is used to cut about 8 to 10 ft of coal in one pass across



(a) Advance (b) Retreat

Figure 2.7. Plan Views of Advancing and Retreating Longwalls.

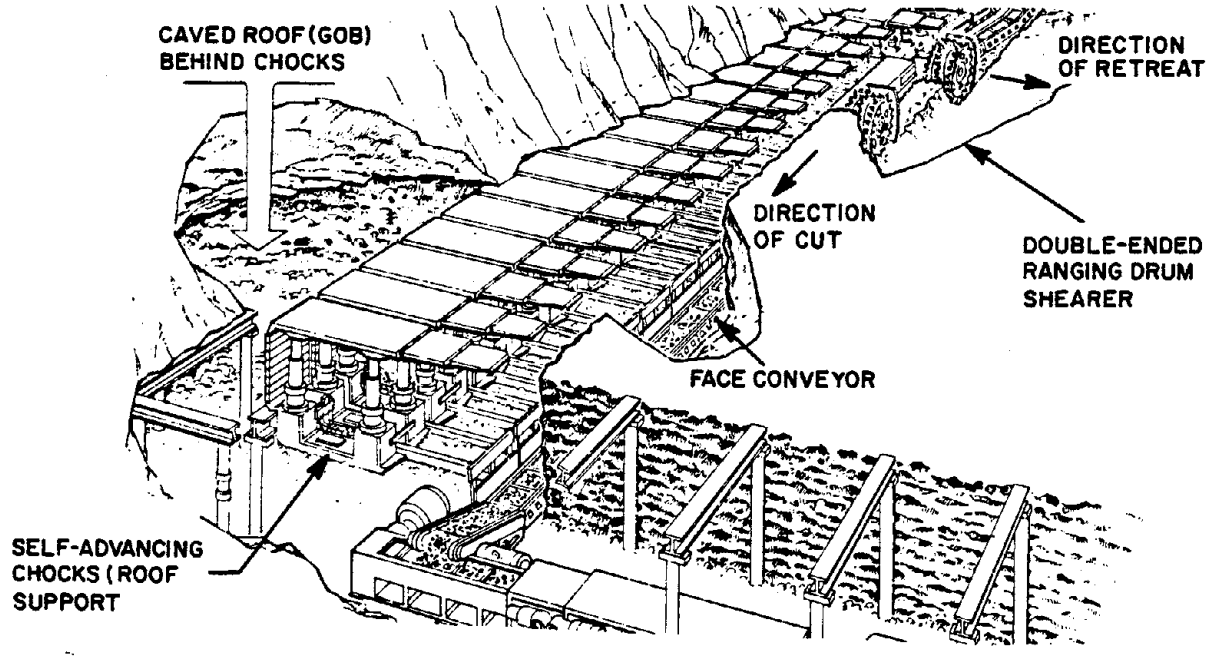
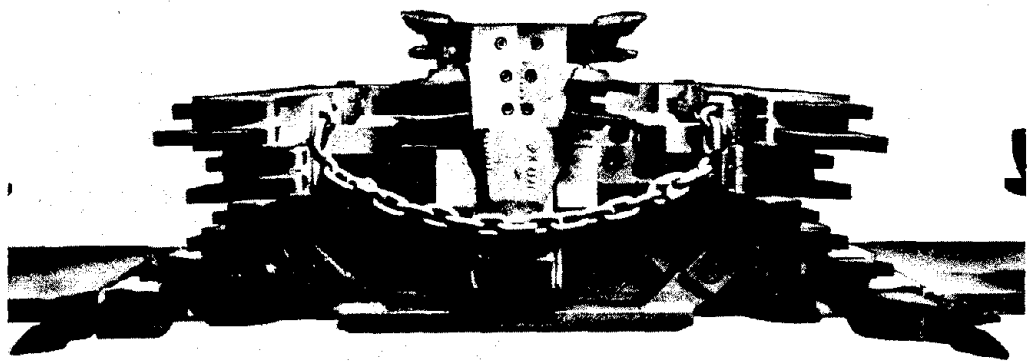
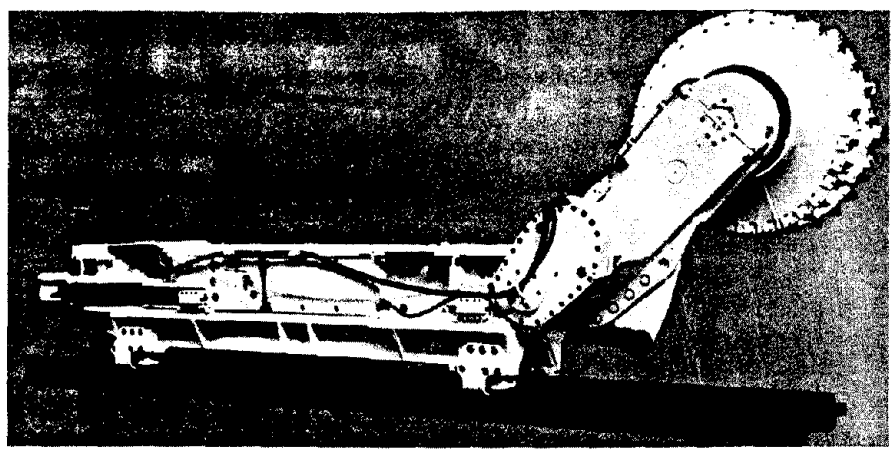


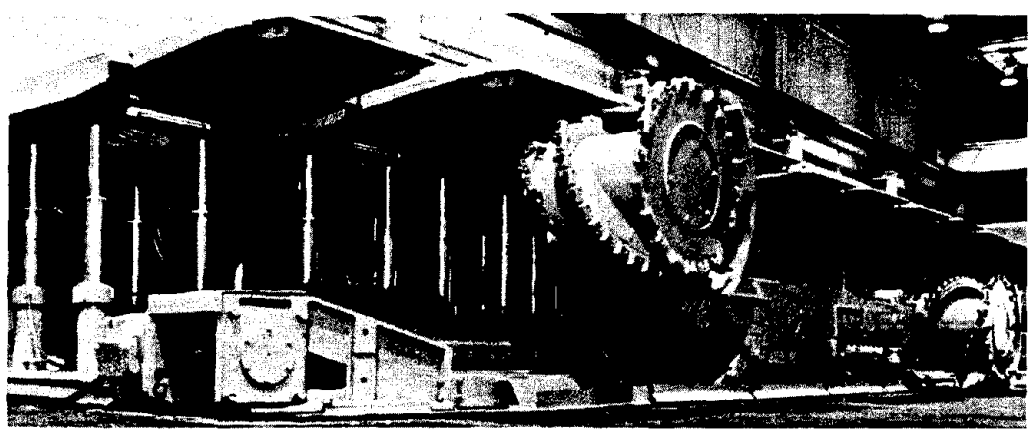
Figure 2.8. Basic Components of Longwall-Mining Equipment (Courtesy of Dowty Corporation).



(a) Planer (Mining Progress)



(b) Single-Drum Shearer (Anderson Maror)



(c) Double-Drum Shearer (Joy)

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Figure 2.9. Basic Longwall-Mining Methods.

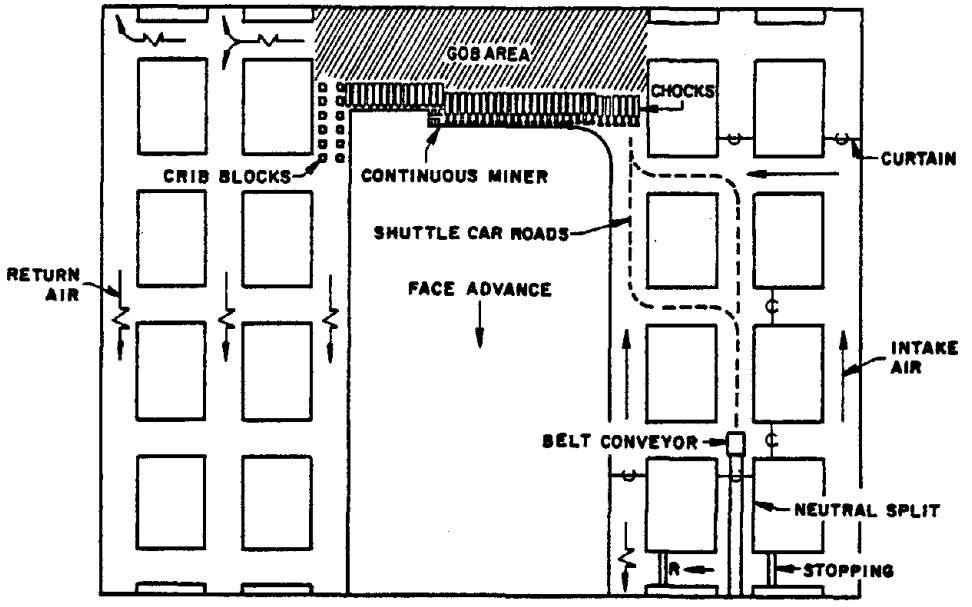


Figure 2.10. A Typical Layout of a Shortwall.

the face. As the miner moves, hydraulic chocks are moved forward (advanced) to support the roof, again allowing the roof to cave behind. After each pass, the miner is trammed in reverse then starts another cut. Instead of the longwall armored-chain conveyor, either continuous (usually cascading or accordian-pleated types) or intermittent (often shuttle cars) units provide face haulage.

2.2-2 Surface Methods

Surface coal-mining methods consist of four basic operations: overburden removal to expose the coal, coal loading, haulage, and reclamation. The mining method is generally classified according to the physical characteristics of the overburden and ore. Some of these characteristics are topography or land contour, overburden thickness, coal thickness, number of coal seams, type of overburden (difficulty of fragmentation), climate, and hydrology. The mining method is also affected by federal and state reclamation requirements. The method that is selected for each specific set of physical conditions is designed to obtain maximum profitability while protecting the health and safety of the workers and minimizing environmental disturbance. The major methods are "contour" and "area" mining.

Contour Mining. "Contour-mining" methods are commonly used in rolling or mountainous terrain typical of area I in Figure 2.11 (3). There are many varieties of contour mining, but the

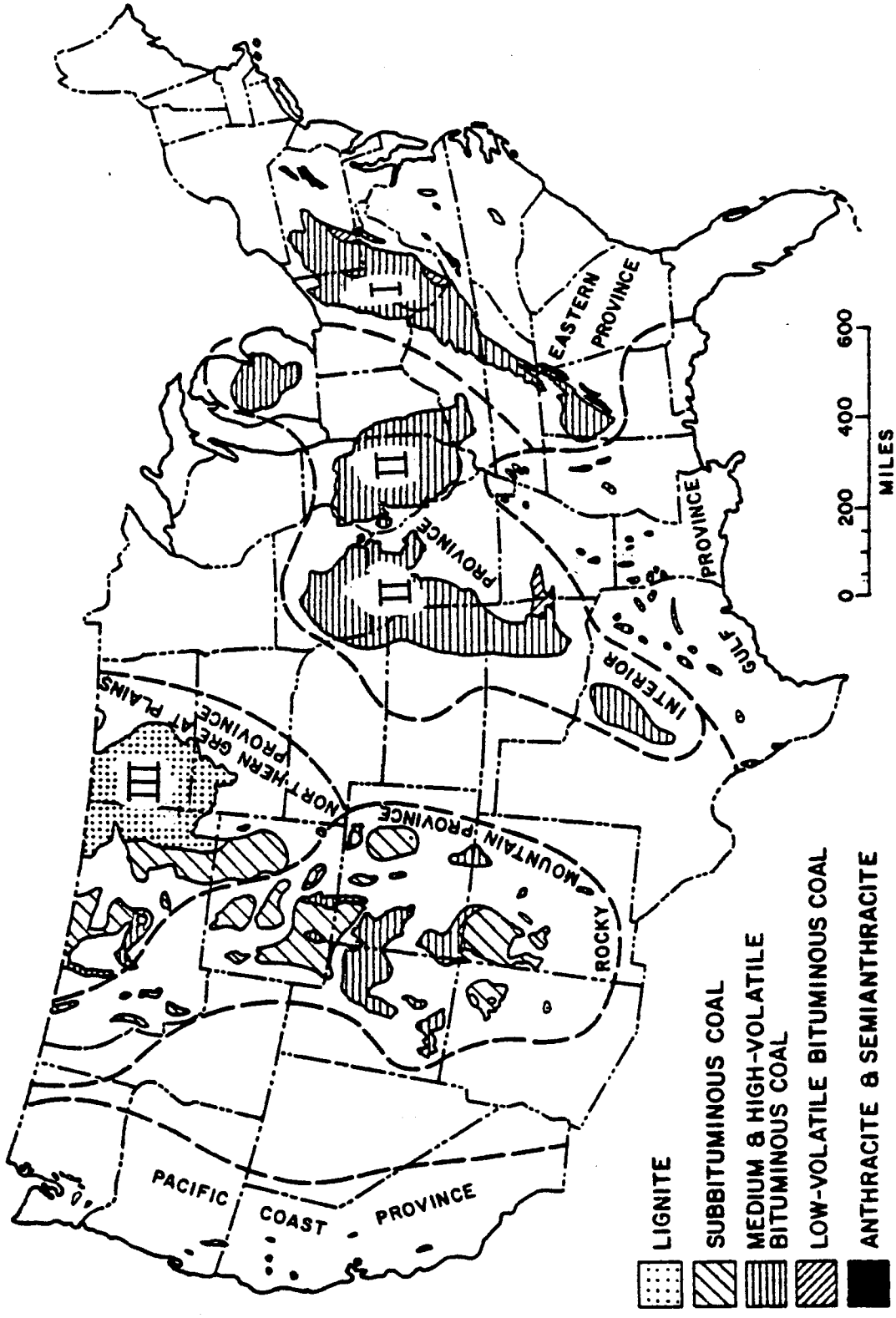


Figure 2.11. Coal Deposits in the United States.

process is shown in Figure 2.12a. First, overburden is fragmented by drilling and blasting, then it is removed by small, diesel and/or electric-powered draglines (shown in Figure 2.13a) or in some instances by diesel-powered front-end loaders and trucks. Scrapers and bulldozers may be used in soft overburden, especially for removing top soil. In conventional contour mining, the overburden is cast on the downslope side as shown in Figure 2.12a to expose the coal seam. However, in the haulback system, shown in Figure 2.14a, overburden is used to fill previously mined cuts after the material from the first cut is stored in an environmentally acceptable area (7). The overburden is graded to match the original land contour by bulldozers, and scrapers replace topsoil prior to revegetation.

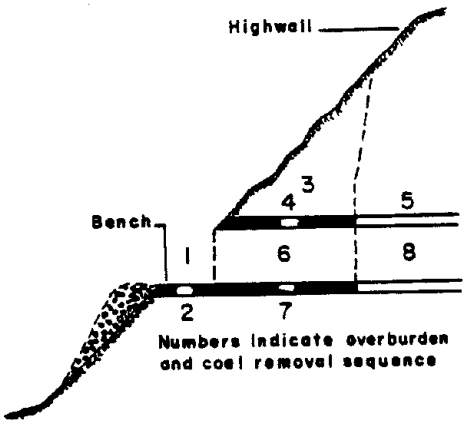
No matter what technique and equipment is used, overburden removal progresses around the hillside at the coal-seam horizon so the pit resembles a contour line on a topographic map. A highwall is left (Figure 2.12a) when the overburden thickness is too great for profitable extraction. If the entire hilltop can be mined and adjacent valleys filled with overburden, the technique shown in Figure 2.16 is employed (7).

Coal loading can be accomplished with a front-end loader or small shovel. In some cases, bulldozers rip the coal prior to loading or, if the coal is extremely hard, it is fragmented by drilling and blasting. In order to improve extraction when a highwall is left, auger machines are used to drill seam-height holes up to 200 ft into the coal.

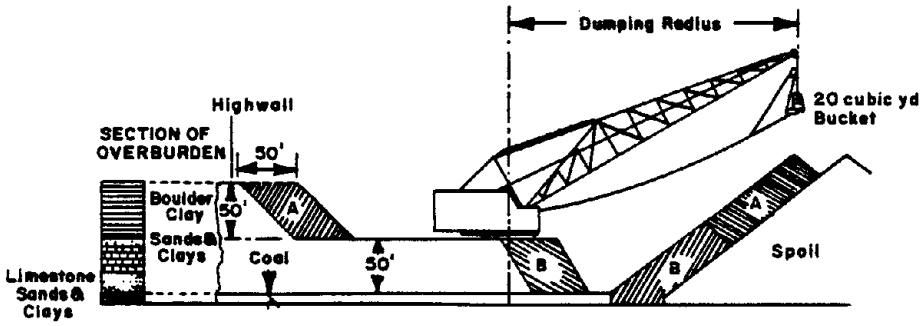
Area Mining. Much larger equipment is used in the "area-mining" method shown in Figure 2.15. In fact, some overburden-removal equipment have more than 30,000 total connected horse-power. Even though diesel-powered auxiliary equipment is prevalent in area as well as contour mining, the magnitude of electrical distribution and utilization is much greater in area mining.

Area mining is common in flatter terrain found in areas II and III in Figure 2.11. As shown in Figures 2.13a and b, either a dragline working on the highwall, or a stripping shovel working in the pit, is used to remove overburden. In soft over-burden, the more continuous "bucket-wheel excavator" shown in Figure 2.13d can be employed, but hard overburden must be drilled and blasted. Then the dragline or shovel casts or spoils the fragmented material into the previously mined pit opposite the unmined highwall as shown in Figures 2.12b and 2.15 (7). Bulldozers regrade the spoil to the original contour before scrapers spread topsoil for revegetation.

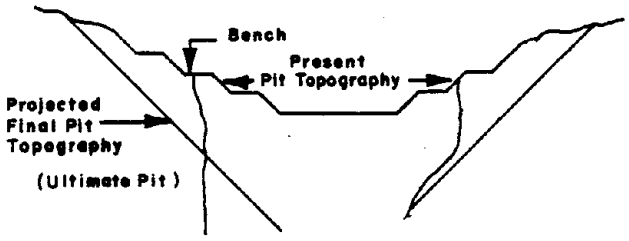
Exposed coal is removed by relatively small power shovels (the maximum bucket size is 18 yd^3) or by rubber-tired front-end loaders. Haulage of coal away from the pit is commonly done with large diesel-powered trucks (around 100-tons capacity).



(a) Cross Section of Contour Mining

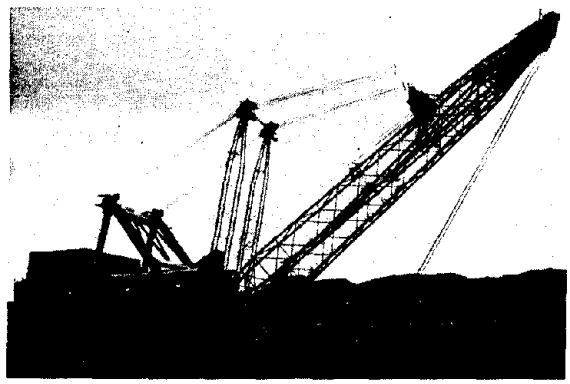


(b) Cross Section of Area Mining with Dragline

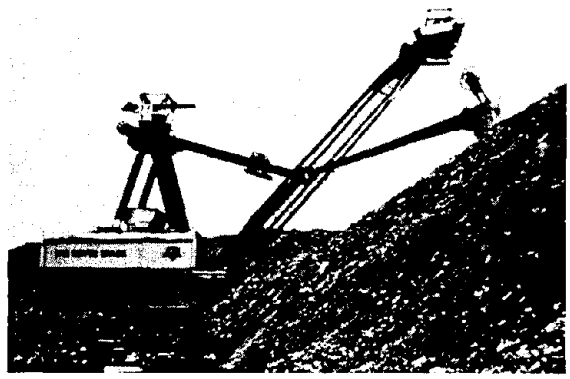


(c) Cross Section of Open-Pit Mining
Showing Step-Wise Benches

Figure 2.12. Cross Sections of Surface-Mining Methods.



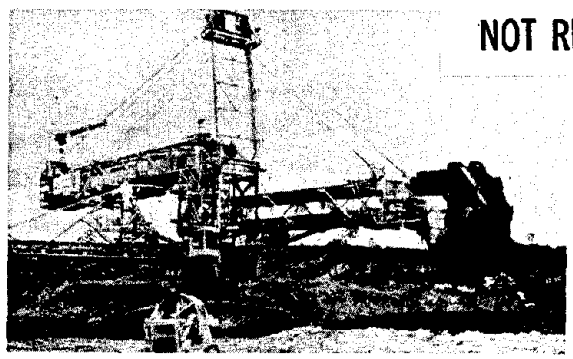
(a) Dragline Beside Pit



(b) Large Stripping Shovel



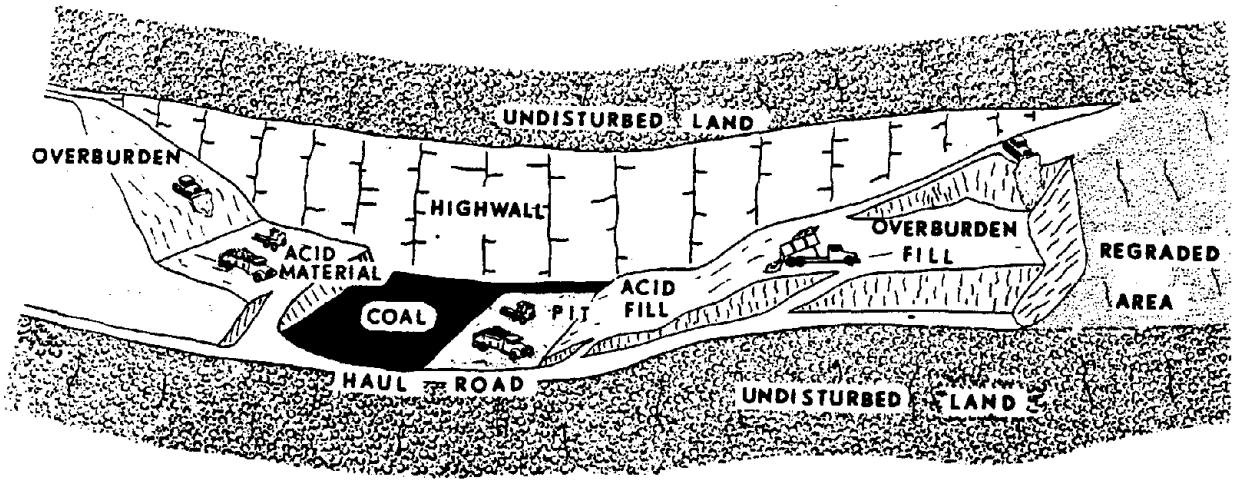
(c) Production Shovel and Trucks



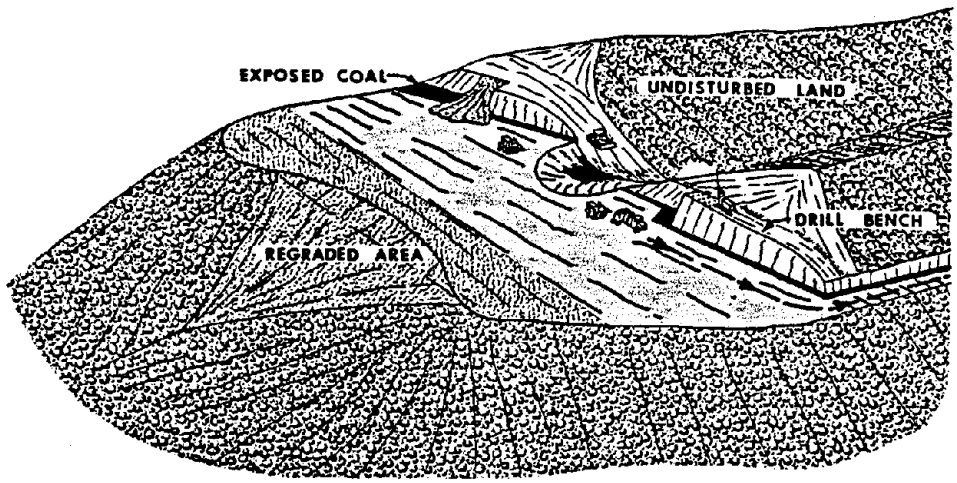
NOT REPRODUCIBLE

(d) Bucket-Wheel Excavator

Figure 2.13. Surface-Mining Equipment.



(a) Contour-Mining Truck-Haulback Technique.



(b) Contour-Mining Hilltop-Removal Technique.

Figure 2.14. Contour Surface Mining.

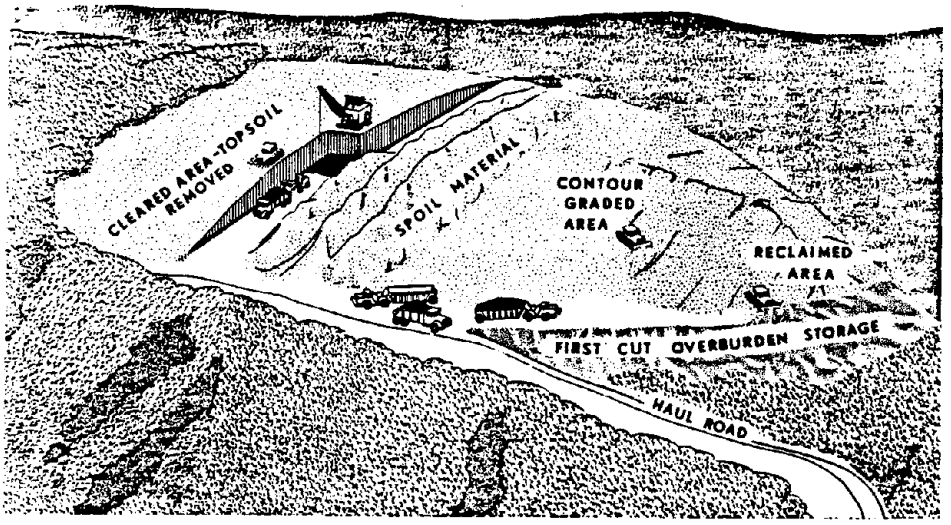


Figure 2.15. Conventional Area Mining.

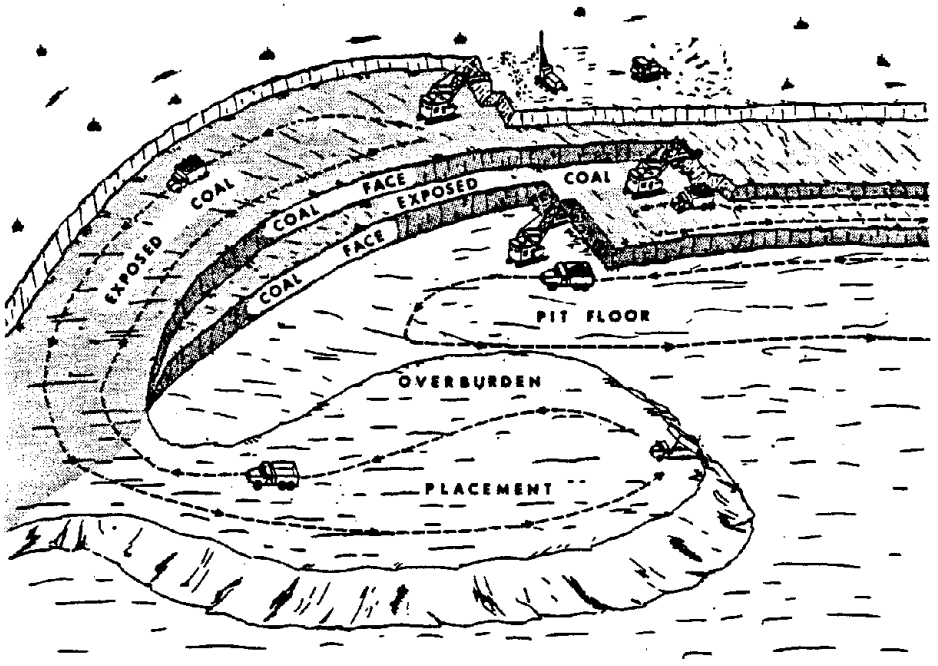


Figure 2.16. Thick-Seam Area Mining.

Especially in area III, where thick coal seams and shallow overburden are encountered, the area-mining technique approaches open-pit methods that are commonly used in metal mining (see Figure 2.12 c). As shown in Figure 2.16 the thick seam is mined on two levels or "benches" and the overburden is returned to the mined-out pit and later graded to a contour compatible with the surrounding terrain (3).

2.2-3 Summary

The preceding information on mining methods has been included to provide just an introduction to those individuals not familiar with mining methods. It should be noted that the techniques given primarily relate to bituminous coal. If more coverage is desired on these or other methods, this chapter's reference list provides many sources (1,2,3,4,5,7). The knowledge of actual mining methods provides a necessary foundation to study mine power systems.

2.3 Electrical Terms

Several of the terms used in the preceding chapter and in the next section are probably common to the reader's vocabulary: volts, current, a-c, conductor, and so on. But what do they actually stand for? Although their total meaning will be covered in the next few chapters, a short explanation of some terms is beneficial now.

"Voltage" is the electrical pressure or force that causes electricity to flow in a "conductor". "Resistance" and "impedance" are measures of the opposition to this flow. "Direct current" (d-c) may be thought of as an uniform flow of electricity ("current") in one direction only, with any change in voltage resulting in a simultaneous change in current. Only two conductors are required, one for supply and one for return. "Single-phase alternative current" (a-c), the type found in homes, is almost as simple. It also requires two conductors, but the flow of current alternates, going first in one direction, then in the opposite direction. Single-phase a-c is used in coal mining primarily for surface and shop facilities and for lighting. However, the power supplied to all a-c mining equipment is "three-phase". Here, at least three conductors are required for power transmission, and three identical sets of single-phase currents are involved, each phase being separated by (or operating at) one third of a full cycle (120°). Three-phase voltages are conventionally referenced by the level normally existing between any two of the three conductors.

2.4 Mine-Electrical History

Before developing an electrical framework, let's explore the complexities of mine electrical power systems by covering a short history of underground then surface coal-mining usage. This will provide many reasons why mine-electrical arrangements (in general) are as they exist today.

Shortly before the beginning of the twentieth century, electricity was first introduced into coal mines in the form of direct current (d-c) for rail haulage. Direct current was used because most systems at that time were powered by d-c generators. Direct current for haulage had a number of advantages. Most outstanding of these was the fact that the d-c series-wound motor had excellent traction characteristics (as it does today). Speed control was simple, being achieved by placing a resistance in series with the motor armature or field circuits. Batteries served as the first power source and provided an extremely mobile vehicle, even if it was constrained on rails. However, keeping the batteries charged was found bothersome so it was not too long until trolley wires replaced them in several mines. Allowing the trolley wire to act as one conductor and the rail as the other provided the simplest kind of power distribution yet known to the mining industry.

Long distances resulted in increased resistance that reduced voltage and power supplied to the motors but, since current drains and distances were relatively small in early mines, this was acceptable. Thus, the d-c system at a voltage of 250 or 550 V became firmly entrenched in coal mines.

The installation of the first electrically-driven coal-mining machine underground, the coal cutter, was made in the early 1920's. Although d-c offered no special advantages, as it was available the machine was equipped with a d-c motor and added to the system. The cutter was almost immediately followed by the loader, and it too was driven by d-c motors. If there was rail haulage in the mine, trailing cables supplied power from the trolley wire and the rail to the machines.

The next significant increase in power consumption came with the introduction of the shuttle car, almost 20 years after the use of the coal cutter began. Actually, when the shuttle car was first invented in 1937, it was battery powered. The addition of an automatic reeling device to handle a trailing cable came later in an attempt to overcome battery deficiencies. Typically, the trailing cables were also connected to the haulage power system, and this equipment, when combined with the cutters and loaders, placed additional stress on the d-c distribution system.

At that time, the horsepower required to operate each piece of electrical mining equipment was rather small, and no one machine used a large amount of current. However, when all the machines were combined, a significant amount was needed and, because all the conductors offered resistance, voltage drops and transmission losses in the distribution system were extensive. Alternating current (a-c) would have been more practical because it could have been easily distributed at a higher voltage, thereby reducing current, voltage drops, and transmission losses. However, many states had stringent limitations on maximum voltage levels, usually around 300 V, and with the restriction, a-c had no advantage over d-c. So direct current continued to be used to operate the successful combination of cutters, loaders, and shuttle cars.

Development in a-c to d-c conversion equipment continued to play an important role in underground-coal-mine power utilization through the preceding development period. Motor generators or synchronous converters were originally employed for conversion purposes. In addition to being heavy and bulky, they could not be operated effectively in a gassy and dusty atmosphere, and maintenance was high. Most installations were thus placed on the surface with borehole connections underground (acceptable for the light covers existing over the shallow mines of that day).

In the same decade as the inception of the shuttle car, mercury-arc-ignition rectifiers began to be employed to provide d-c underground. Without moving parts, maintenance was lower, efficiency higher, and portability greater. Because of a liquid heat exchanger, they were still heavy and bulky and, therefore, these rectifiers were often centrally located in the mine. Thus, distribution into the mine became a-c, but d-c was still distributed throughout most of the mine electrical system. However, the arc tubes did allow a more efficient use of electricity in deeper and larger mining operations than had been possible before.

At about the same time rectifiers came into use, some mines found that haulage of materials by conveyor might be more efficient than by rail. These too were powered by d-c motors, and stress continued to be added to the electrical system.

In the late 1940's when continuous-mining machines began to be used extensively for the first time, d-c was again expected to provide power as had been the case with earlier advances in coal-mine equipment technology. However, continuous miners normally needed more energy input than the sum of all the various conventional-mining equipment they replaced. Because the required high horsepower created high current demand, d-c was found entirely unsatisfactory in most cases. The attendant current demand created enormous voltage drops in the distribution system. Within a short time, the d-c supply system in most mines was separated from the haulage system, but this was still

not adequate. Increasingly-large cable sizes were required to supply the needed power. Cable handling was difficult and, during peak operation periods, voltages at the machines were so far below the values called for that even moderate efficiency was impossible.

The use of three-phase a-c distribution and motors was an obvious answer. However, for at least a decade, some mining companies held off making the change, in many instances because the laws in their states limited the maximum voltages permitted in the mines. Lawmakers were convinced that high voltages were synonymous with decreased safety, and some state laws were not changed until the mid 1960's.

With higher voltages permitted, the desirable economics of a-c employment could be realized, and a swift transformation from d-c to a-c in underground coal mining for distribution and high-horsepower loads was effected. Numerous mine electrical systems, however, were at least partially modified without concern about the compatibility of the changes with the remainder of the system, and various safety and production problems arose. The discussion of these is a main part of many sections later in this report.

Through the conversion, mine power systems generally resulted in two voltage levels: "distribution" and "utilization". Figure 2.17, which shows a very simple mine-electrical arrangement, can be employed to illustrate the consequence. The major power equipment illustrated are the substation, switchhouse, and load center. The "substation" is employed to transform the utility voltage down to distribution levels, most often at "high voltage" (i.e., greater than 1000 V). Power at this voltage is transmitted (or distributed) through conductors from the substation to the load center; hence, the portion is commonly called the "distribution system". The "load center" (or "power center"), actually a portable substation, transforms the voltage to "utilization", typically at "low voltage" (660 V or less) or "medium voltage" (661 to 1000 V). It is at this level, or "face voltage", that power is delivered to the machinery. Although a reference to voltage levels is made, it should be noted that distribution and utilization describe functions of a power system segment, not a specific voltage range. These concepts will be expanded in a following report section.

Originally, primary a-c distribution was commonly made at 2300 or 4160 V. Later, these levels were increased in most mines to 7200 V. Recently some operations have increased the voltage to 12,470 V (or 13,200 V), both for longwall and continuous-mining applications. Each new distribution voltage, it may be noted, was a factor of $\sqrt{3}$ times the previous value ($\sqrt{3}$ (2400) = 4160). To reiterate, the principal reason for increasing the voltage was that, for the same load, current would be correspondingly smaller, and lower distribution losses would result even though the same conductor sizes were used.

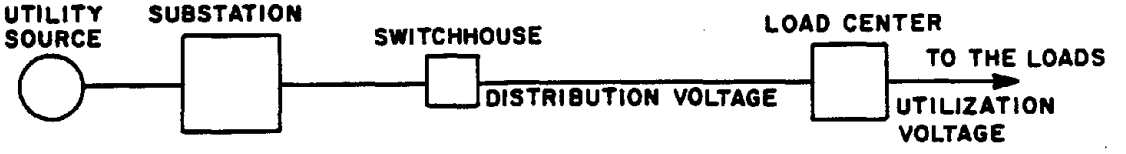


Figure 2.17. A Simple Mine Electrical System Arrangement.

For utilization, 440 Vac was, from the beginning, the most popular. This was despite the fact that after the continuous miner proved so successful, its horsepower was progressively increased with the sometimes misguided idea that a directly proportional increase in coal production would follow. The additional horsepower resulted, as it did with d-c, in an increase in trailing-cable sizes until their weight was almost more than personnel could handle. To compensate, the most common move was to increase the rated motor voltages to 550 Vac. More recently, to further overcome the trailing-cable problems, manufacturers are producing machines with 950-V ($550\sqrt{3}$) motors.

While these changes to a-c for machine operation and distribution were going on, the use of d-c for haulage continued to be advantageous. In the early 1960's, silicon-diode rectifiers with large current capacities became available. Simple, efficient and small, these were ideally suited for use underground and made a-c distribution possible for the entire electrical system except for rail haulage. For example, while continuous miners normally used a-c, part of the supply at the load center was rectified to d-c for powering primarily the shuttle cars. Through it, the benefits of d-c for traction and of a-c distribution and utilization on high-power loads were realized.

The problems associated with underground electrical systems at first glance appear simple. As a result, they were neglected for some time. Systems were often designed and maintained by a seat-of-the-pants approach, to the point where a-c distribution and equipment were installed employing just d-c concepts. Alternating-current systems are more complicated than d-c and call for meticulous planning. If wrong decisions are made, the results can be extremely costly from the viewpoint of safety, production, and economics. A great amount of effort is necessary to maintain an electrical power supply within the requirements of the numerous pieces of mining machinery. Mixing a-c and d-c in the same mine can add greatly to these problems.

The foregoing has only quickly scanned the history of underground-coal-mine electrical systems. As was seen, the mines went from minor usage (the introduction of rail haulage) to almost total dependency on electricity in a period of 50 years. Although not as numerous, surface coal has seen changes as substantial, being centered around an enormous growth of mining-equipment size.

The first mechanization in strip mining occurred in 1877 with the application of an Otis-type steam shovel in a Pittsburg, Kansas mine (8). The early try was rather unsuccessful, but it served as an important step in the evolution of strip-mining machinery. For about 30 years after that point, several successful attempts at applying steam-powered shovels and draglines were made, proving that surface mining of coal was completely practical. In the early 1910's, the advantages of electricity over steam created the first significant introduction of electric-powered shovels.

Whereas d-c series motors were universally employed in underground rail haulage, the first large motors used in surface mining were d-c shunt wound almost directly replacing the single-speed steam engine found on practically all shovels prior to that time (9). They allowed the immediate reduction of the manpower required to run steam machinery. Before long, an important advance in shovel design occurred: application of separate steam engines to power the shovel motions of hoist, crowd, and swing. The change gave increased flexibility through individual control of each operation. The two major shovel manufacturers of the era, Marion and Bucyrus, desired to produce both steam and electrical shovels with similar characteristics (8). As series-wound d-c motors had similar speed-torque relationships to steam engines when used for this type of duty, they were employed to drive each shovel motion.

Because of power generation, initial distribution was d-c; however, technological advances soon made a-c power systems superior. Accordingly, a-c motors were tried with some success. However, by 1927, a-c/d-c motor-generator (m-g) sets and the invention of the Ward-Leonard control concept created abandonment of these efforts. The control system enabled the motor characteristics to be modified as desired within the motor and generator commutator limits (9). As a result, shunt-wound motors were found more favorable than series wound. The m-g sets functioned as on-board power conversion, thereby establishing the use of a-c distribution in the mines.

Motor-generator sets driven by synchronous or induction a-c motors, Ward-Leonard control, and shunt motors established a standard; even now, the combination is used on most mining excavators, especially the larger varieties (10). Some single a-c electric motor drives, with either mechanical-friction or eddy-current clutch systems, have evolved, being used only on smaller machines. These machines, however, are often driven by diesel engines.

Present excavators can be classified into three sizes. For shovels, small types function primarily in general excavation, the intermediate sizes work at bench mining and coal production, and the large machines handle overburden stripping (actual capacity ranges are normally not assigned). Draglines of any size are commonly stripping equipment only. Small and intermediate equipment originally ran on rails, but crawler mountings, giving more mobility, made their first appearance in mining during 1925 (8). Today, small and intermediate-sized shovels and draglines are mounted on two crawlers, while large shovels generally have eight (10). Large draglines (and some intermediate sizes), on the other hand, are walking, featuring a circular base (or tub) to provide low ground-bearing pressure and a walking device for propelling.

Paralleling excavator development was the design of surface-mining drilling equipment. Initially, most drills were pneumatic-percussion types. Because electricity was readily available in mines, some machines were designed with internal motor-driven compressors. In the early 1950's, it was found necessary to manufacture large rotary-drilling equipment to satisfy the blasting requirements of thick, hard overburden (8). The result, being again powered electrically, was extremely successful. These machines combined with excavators, pumps, preparation plants, and mills, make up the prime electrical users in the surface industry today.

The most outstanding change that has happened with electric-powered surface-mining machinery has been in connected horsepower. For example, a 25-yd^3 dragline or stripping shovel was considered enormous in the late 1940's; these machines had maximum total loads of around 2000 hp (8,11). By 1955, 50- to 70-yd^3 excavators were being manufactured with maximum horsepower upped to 4650. Five years later, shovels had reached 140-yd^3 capacity with 12,000 hp of main drive motors (12). In 1976, the largest excavator in service had 30,000 hp in motor-generator-set drive motors (13).

Distribution and utilization voltages also increased to keep pace with the peak load demands of this machinery. For excavators, sometimes mine distribution and machine voltages were (and are) the same. Until the mid 1950's, 4160 and 2300 V were the usual mine levels (11). Then, with the advent of larger concentrated loads, it was found that 7200 V was advisable (14). This level was found unsatisfactory for machines greater than 100 yd^3 when they were introduced; accordingly, 13,800-V mine and excavator voltage became a standard. With machines greater than 200 yd^3 capacity, 23,000-V utilization was established (13). However, even with these substantial increases in distribution, loads up to 1000 kVA continued to be driven at 480 V (14). Production shovels up to

18 yd^3 commonly stayed at 4160 and 7200 V and, in general, 4160 V became standard on machinery with 1500 hp or less. Therefore, if different size excavators were employed at one mine, more than one voltage level in the mine could be specified.

For the sake of brevity, several details have been left out of the preceding discussion, but the reader can probably appreciate the mass of electrical problems that the mining industry has encountered, especially considering the uniqueness of mine power system. Now that the growth of mine-electrical consumption has been covered, the next sections will describe basic power equipment and circuit arrangements.

2.5 Mine Power Equipment

A few pieces of power equipment have already been introduced but only to an extent necessary to describe the concepts of distribution and utilization. The evolution of mine systems has resulted in major items of power apparatus, each serving a specific function. In general, they can be listed as (11,15):

1. generation,
2. main substations,
3. portable and unit substations,
4. switchhouses,
5. distribution transformers and load (or power) centers, plus
6. distribution (conductors and connectors).

A specific mine may not need every item to form its system.

Except for generation, which is beyond the scope of this report, the following paragraphs explain these components so their inclusion in system arrangements can be understood. Complete descriptions of substations, switchhouses, and power centers are presented in Chapter 11, while Chapter 7 is devoted to distribution. Thule and others (16) provide a thorough discussion of power generation and its need in mining.

Substations. If available, common mining practice is to purchase all or most power from utility companies. As these voltages range from 24 to 138 kV, one or more "main or 'primary' substations" are required to transform the incoming levels down to a primary distribution voltage for the mine. In addition to the transformer, substations contain a complex of switches, protection apparatus, and grounding devices, all having a function in safety. Main substations are often permanent installations. The nature of the mining operation and its power needs dictate how many main substations are required and where they should be placed. These may be owned by the utility or the mining company; the decision of ownership is commonly dependent on economics. However, if the total connected load is greater than 1000 hp, mine ownership is often more favored (16).

"Portable substations" and "unit substations" are similar in operation to main units, except they serve to transform the primary distribution voltage to a lower distribution level. In typical employment for strip mining where, for example, a large dragline may require 24 kV while the production shovels and other mining equipment need 4160 V. The term, "unit", means that the substation and power equipment is designed and built as a package.

Switchhouses. "Switchhouses" are portable equipment which protect the distribution circuits. Their internal components are chiefly protection devices, with circuit interruption being performed by load-break switches, oil circuit breakers, or vacuum circuit breakers. The switchhouse may contain more than one complete set of devices; for instance, a double switchhouse which can independently protect two outgoing circuits. This power-equipment category encompasses "disconnect switches"; which are manual devices with the prime function of allowing removal of mine power from the main supply.

Load Centers. At the outermost distribution points are "load centers" and "distribution transformers", equipment which transforms and converts the distribution voltage to utilization. Included are a-c to d-c conversion equipment ("rectifiers"). Load center, also termed a "power center", usually implies an internal "bus" (this word will be defined shortly). Yet, in essence, these are all portable substations, but an individual unit may supply power from one to as many as 20 machines. As with switchhouses, each outgoing circuit has its own set of internal protection components. Load centers are considered the heart of an underground-mining-section power system, and rectifiers convert the distribution voltage to d-c for use on rail trolley and, at times, other systems. In surface mines, load centers supply power to low-voltage auxiliary machinery and loads; there may be no need for this equipment with the mining machinery.

Distribution. The last major power equipment listed is the actual "distribution". This category, often referred to as the mine-power-system's "weakest link", encompasses all the overhead power lines, cables, cable couplers, and trolley lines used to carry power and grounding between the power equipment and eventually to the loads. As a part of distribution, the conductors are usually termed "feeders"; at utilization connected to portable mining machines, "trailing cables".

2.6 Basic Circuit Arrangements

There are five basic distribution arrangements available for mining applications (17):

1. radial,
2. primary selective,

3. primary loop,
4. secondary selective, and
5. secondary-spot network.

All but the last can be found in mining; however, except for trolley-line tie connections and some surface installations, mine power systems are usually radial (18). The use of other arrangements is mainly coupled to a need for more system reliability. "Secondary-spot networks" can be applied to preparation and milling plants, and this is notably the most popular system for large facilities in other industries. This section will cover these basic systems mainly as they are defined by the IEEE (17).

Radial. Without specification, Figure 2.17 has already introduced "radial" type systems. In its most simple form, radial distribution is at utilization voltage as shown in Figure 2.18. Here, a single power source and substation supply all equipment. The single vertical line represents one connection point for all feeders (or all connecting lines) and is termed a "bus". Voltage along the line is considered constant. Radial systems are the least expensive as there is no duplication of equipment; they can be expanded easily just by extending the primary feeders. A prime disadvantage, however, is tied to their simplicity; should a primary component fail or need service, the entire system is down.

An "expanded radial" system, the "load-center radial", is illustrated in Figure 2.19 and is practically the same as that described in the preceding section. Again, two or more voltage levels are established, but the feeders form a tree-like structure spreading out from the source. The advantages of the simple system exist, but additional ones are now available. If the load centers (or distribution transformers) are placed as close as practical to the actual loads, most distribution will be at the higher voltage. This allows decreased conductor investment, lower electrical losses, and better voltage regulation (a concept stated earlier).

Primary Selective. The "primary-selective" system (see Figure 2.20) adds down-time protection through continuity of service. Each substation can receive power by switching from either of two separate primary feeders. These should be selected to carry about 80% of the load, then one feeder can accept a temporary overload (14). Therefore, continued operation is possible if one source should fail. During normal service, each feeder should handle one-half of the load. The system is simple and reliable, but costs are somewhat higher than radial because of the duplication of primary equipment.

Primary Loop. Though found in some mines, the "primary-loop" system, drawn in Figure 2.21, is not considered good practice. It offers the advantages and disadvantages of primary selective, and the cost can be slightly less. However, the

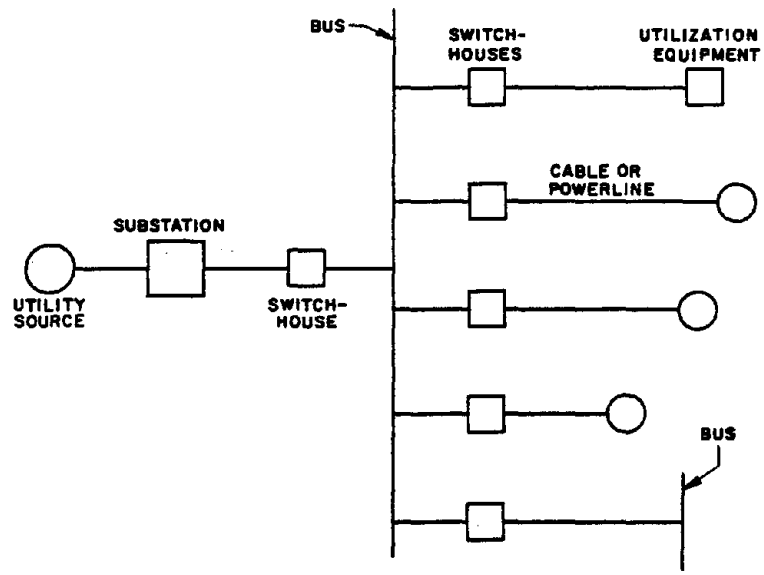


Figure 2.18. A Simple Radial Distribution System.

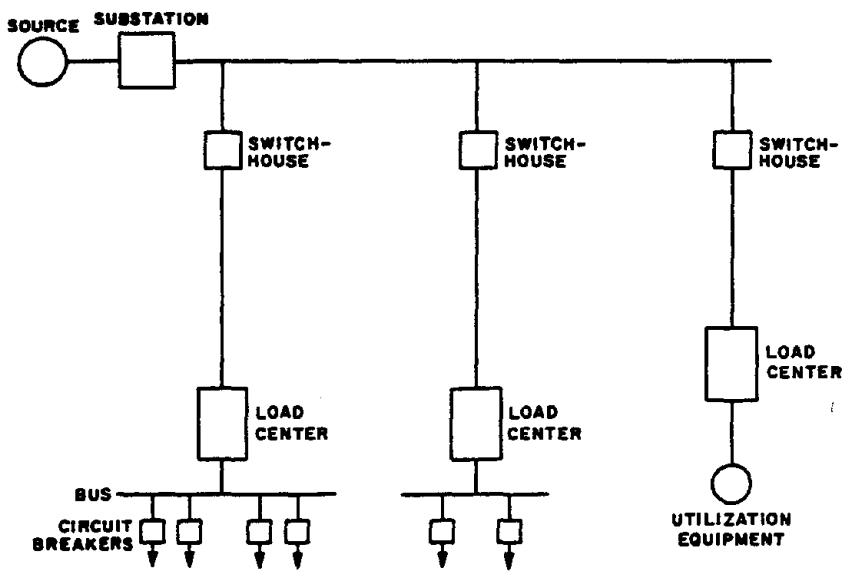


Figure 2.19. A Load-Center Type of Radial Distribution.

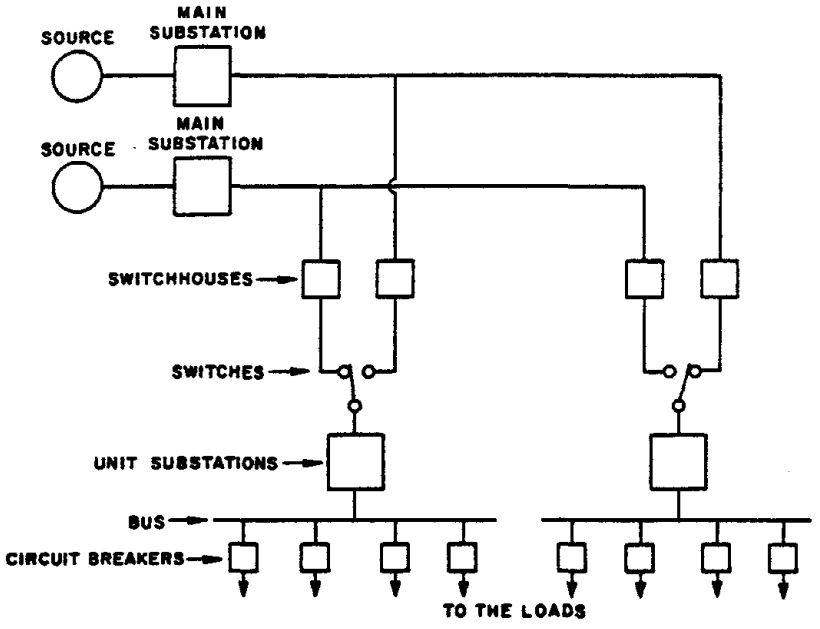


Figure 2.20. A Primary-Selective Distribution System.

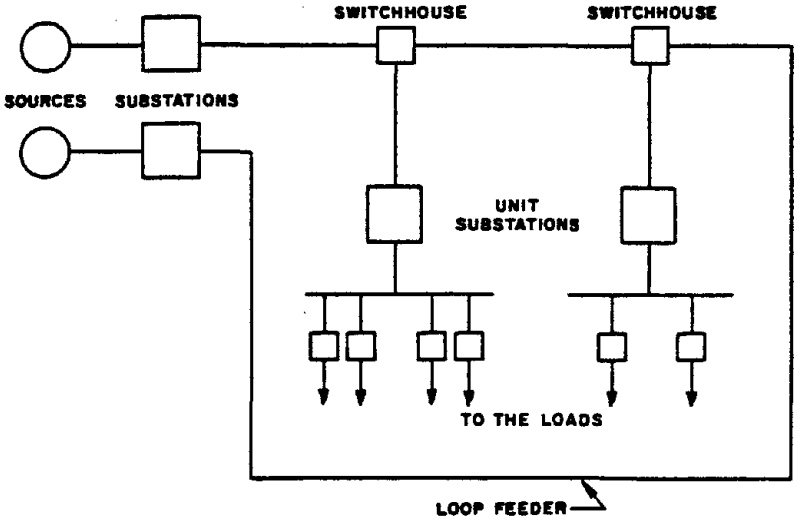


Figure 2.21. Primary-Loop Distribution.

technique can result in dangerous conditions when a primary-feeder failure occurs. For instance, a failed portion can be energized at either side creating an extreme hazard to maintenance personnel.

Secondary Selective. A "secondary selective" system results if a pair of substations are connected through a normally-open secondary tie circuit breaker as shown in Figure 2.22. The arrangement allows greater reliability and flexibility than the preceding techniques. Normally, distribution is radial from either substation. If a primary feeder or substation fails, the bad circuit can be removed from service and the tie breaker closed either manually or automatically. Maintenance and repair of either primary circuit is allowed without a power outage and with only reduced-capacity operation, shedding nonessential loads for the emergency period. The other service-continuity considerations that can be made with secondary-selective systems include (17):

1. oversizing both substations so that one can carry the total load,
2. providing forced-air cooling to the substation in service for the emergency period, or
3. using the temporary overload capacity of the substation and accepting the loss of component life.

Economics often justify this double-ended arrangement if substation requirements are above 5000 kVA (19). ("kVA" is the substation "capacity", the ability to transform power.)

Secondary-Spot Network. In the "secondary-spot network", two or more distribution transformers are supplied by separate primary distribution feeders as illustrated in Figure 2.23. The secondaries are tied together through special circuit breakers, called "network protectors," to a secondary bus. Radial secondary feeders, tapped to the bus, then feed the loads. The arrangement creates the most reliable distribution system available for industrial plants. If a failure occurs in one primary circuit (say, acting as a load to the bus), its network protector can quickly sense the reverse power flow and immediately open the circuit. Total power interruption can only occur with simultaneous mishaps in all primary circuits or a secondary bus-failure. This type of system is expensive, and the reliability gain is not warranted for the majority of mining applications.

It may be obvious that these basic techniques can be combined into hybrid systems. When this is performed, there can be confusion about what is primary or secondary. Ordinarily, how substations are specified dictates the system or subsystem definition. This will be shown in the next two sections.

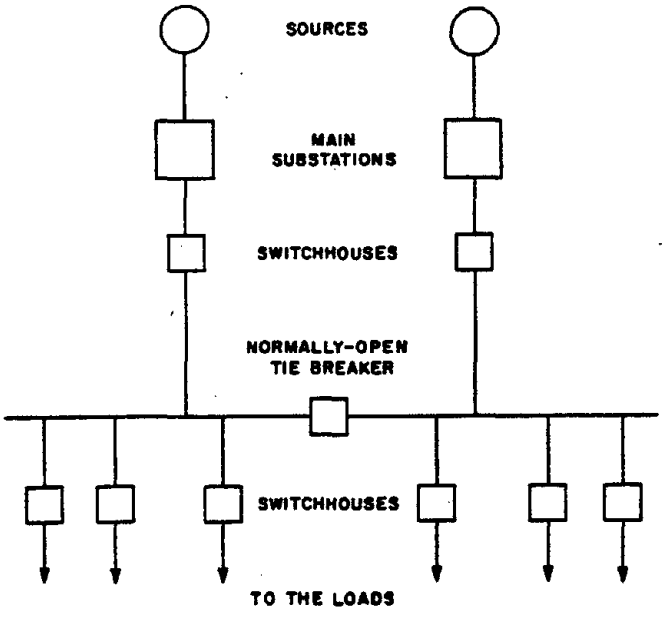


Figure 2.22. A Secondary-Selective System Example.

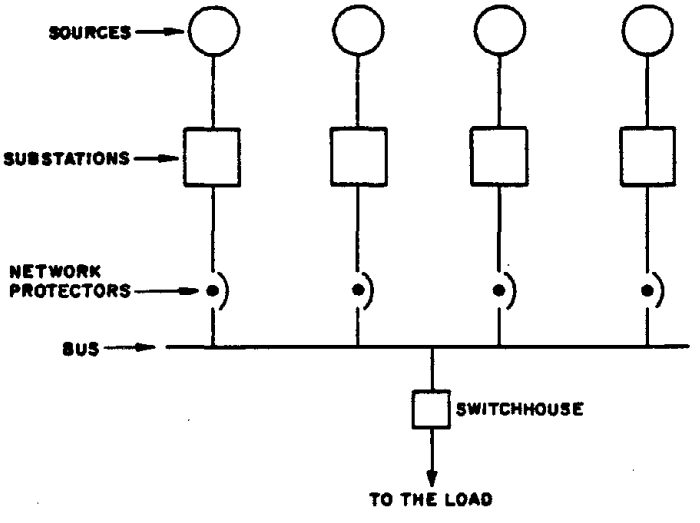


Figure 2.23. The Secondary-Spot-Network Technique.

2.7 Utility-Company Power

As the principal power source for mines are utility companies, an understanding of the utility-system power transmission and distribution is important. Often their systems greatly affect the power available to the mine, including voltage regulation, system capacity during power failures in the mine, and over-voltage occurrences.

Power from a generating station is transformed in a nearby substation to a "transmission" voltage, commonly 69,000 V or more (17). This power is carried on "transmission lines" to major load areas either supplying large industrial users directly or powering the utility's own distribution substations. Distribution substations, again, step the voltage down, this time to a primary-distribution level ranging from 4160 to 34,500 V but most often at 12,470 or 13,200 V (17). These concepts are illustrated in Figure 2.24.

The utility service, therefore, can be any of the following standard values: 138, 115, 69, 44, 33, 23, 13.8, 12.47, 6.9, and 4.16 kV (16). Generally, the voltage delivered ranges from 23 to 138 kV, but also available are 480, 2300, and 7200 V (as well as others). What is available to the mine depends on whether the possible connection is to the power company's transmission system, primary distribution system, or distribution transformer. It is the responsibility of the mining company to select that voltage best suiting its needs. Primarily, the choice depends on the amount of power purchased.

It is not safe to assume that the power company has the capability to serve a large mine complex from their existing primary distribution lines (and sometimes even the transmission system). The problem stems from the nature of mine loads. For example, as previously stated, large excavators in surface mines can require high peak power for a short time followed by regenerative peak power, cycling within the span of 45 s. The fluctuating load may create voltage and frequency variations beyond the limit set for other utility customers. Accordingly, most large draglines and shovels require power from 69- to 138-kV transmission systems to get adequate operational capacity, and the construction of several miles of transmission equipment can result in a sizable cost for the mine's budget.

For the purpose of this report, regardless of where the mine main substation is tied into the utility complex and who owns that equipment, the outgoing circuits of that substation are termed the mine "primary distribution system" (or just "distribution"). The incoming power will most often be referred to as a "transmission system".

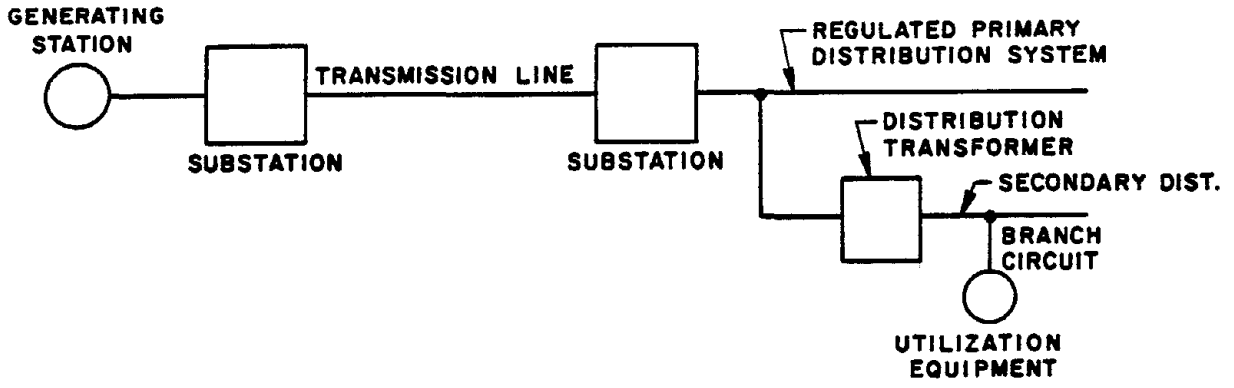


Figure 2.24. Representative Utility Transmission and Distribution.

2.8 Mine Distribution Systems

As mentioned earlier, surface mine power systems have different characteristics than underground. These two basic mining operations are regulated by separate codes and standards, for instance, Title 30, Code of Federal Regulations, Part 75 for underground coal, Part 77 for surface coal and surface facilities of underground coal mines. The latter illustrates an overlap between surface and underground legal demands but, by and large, the system arrangement is specified by mining-operation requirements (i.e., strip mining, longwall, etc.). This section serves as an introduction to "typical" distribution systems, and voltage levels, already given, will be restated to enforce applications.

The mine power system can be divided into three categories depending upon the purpose of a specific portion:

1. subtransmission,
2. primary distribution (or distribution), and
3. secondary distribution (or utilization).

Often, if a subtransmission system is needed, it will have the same general arrangement for any mine. Yet, at distribution and utilization, power-system installations diverge greatly. It should be again noted that distribution and utilization are one and the same for some mines.

Main Substations and Subtransmission. Main substations may range from 500-kVA capacity supplying 480 V to pumps and conveyors to 50,000 kVA servicing a large strip-mining operation and preparation plant (14). Its location is usually an economic compromise between running transmission lines and power losses in the primary distribution system.

After the main substation, power is distributed to the various centers of load in the operation. However, individual loads or complexes, such as preparation plants, belt-conveyor systems, ventilation fans, and other surface facilities, may have large power requirements or be so isolated that primary distribution operation is not practical. In these cases, incoming utility transmission must be extended close to these installations; the extension is designated a "subtransmission system" (16). Other reasons for using subtransmission involve safety.

Subtransmission commonly requires a primary switchyard of high-voltage switching apparatus for power tapping and, for high-reliability needs, dual-bus configurations (a corollary to primary-selective distribution) are employed. Branch circuits are fed through high-voltage circuit breakers to protect the subtransmission line and the utility's system. Arrangements for surface and underground mine subtransmission are given in Figures 2.25 and 2.26. As can be seen, they are practically identical, only the outgoing connections change. Subtransmission circuits (commonly, overhead lines), switchyards, and main substations are almost always permanent installations located in areas unaffected by the mining operation.

Several mining properties are exposed to high lightning incidence; for instance, the primary portions of the power system are often higher in elevation than the surrounding countryside. Therefore, it is necessary and sometimes mandatory to provide a high level of surge protection in the system (16). This can be obtained by surge arresters, masts, and static wires on subtransmission circuits, main substations, and primary distribution plus grounding (tying to earth) of all fences and enclosures (20). Static wires and arresters are only effective if they are properly grounded (see Chapters 6 and 10).

The main substation is where the ground system for the mine is established. This ground is carried along the power lines through overhead conductors or in cables and is connected to the frames of all mobile mining equipment.

Simple Distribution. Mine power distribution, in its most simple radial form, has already been shown in this chapter to consist of a substation, primary distribution, and a load center feeding the mining equipment. The arrangement is very common in small surface and underground operations, for example, punch mines in the southern end of the Appalachian Coal Field. Here, distribution voltage is commonly 4160 V but can be 2300 V in older equipment. In the smallest mines, power is purchased at low-voltage utilization (often 480 V) and fed underground to a "distribution box" to which the mining equipment is connected. Simple radial is, at times, employed in large surface operations

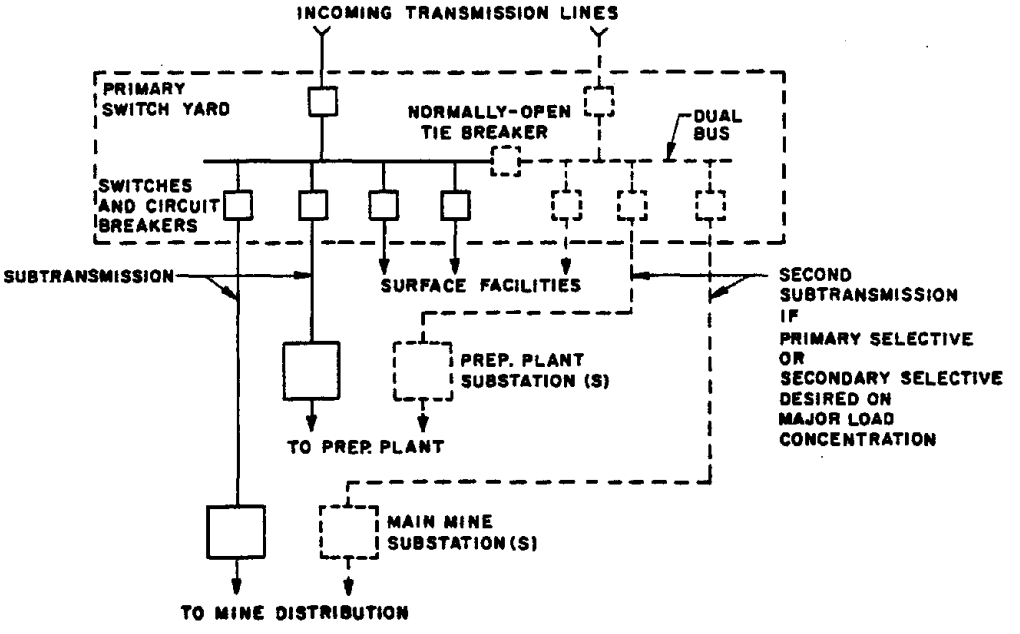


Figure 2.25. Subtransmission for a Surface Mine.

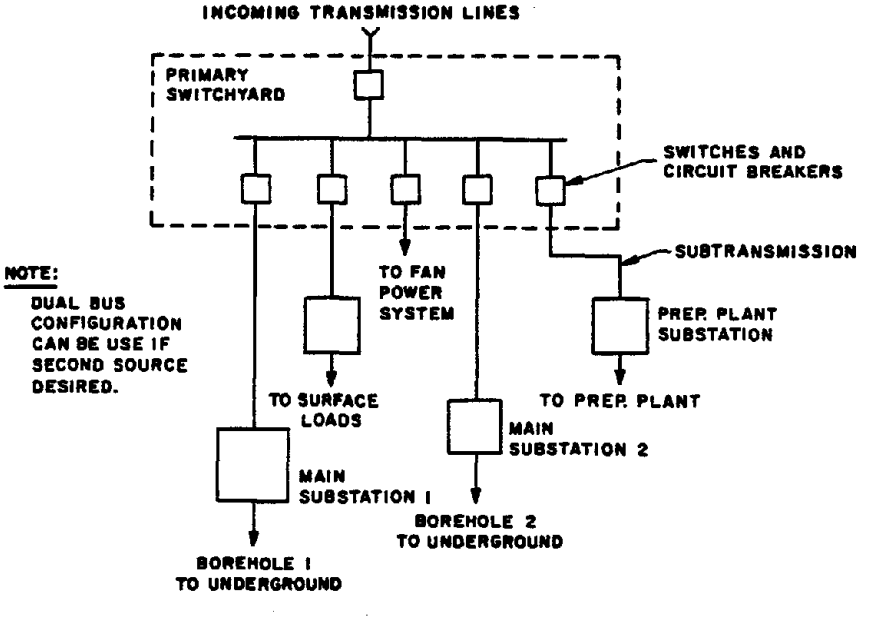


Figure 2.26. Subtransmission for an Underground Mine.

where only one machine must be served or an extensive primary distribution network cannot be established (e.g., as in some contour mines).

Surface-Mining Distribution. The large majority of strip mines employ radial distribution, but secondary-selective and primary-loop designs can also be found. Simplified examples of all three are provided in Figures 2.27 to 2.29, respectively.

With all techniques, a portion of the primary distribution normally establishes a "base line" (in essence, a bus). The base line is located on the highwall, paralleling the pit for the entire length of the cut. Its location is typically 1500 ft ahead of the pit and is moved back as the pit advances (18). Distribution is continued from the base line to the mining equipment, with the connections maintained at regular intervals as much as practical. As the machines move along the pit, the base-line connections are changed to another convenient location.

When secondary-selective operation is utilized, as shown in Figure 2.28, a normally-open tie circuit breaker is placed in the base line as equidistant as possible from the main substations. In very large operations, more than two main substations may be established.

Primary-loop systems have been used in strip mining. It can be noted from Figure 2.29 that the substations actually operate in parallel, considering the base line to be a bus. The substations are sized smaller than would be necessary for a radial system. Notwithstanding, several precautions about this configuration, beyond that already stated, should be taken (11). For one, the substations must be identical if they are to share the load. However, as an unbalance is probable in any system, it is likely that one substation will receive a greater load. Considering the hazards, loop feeding has been considered unsatisfactory practice in other industries. It is shown here mainly because it is used in mining.

The base line can be constructed with either overhead polelines or a cable-switchhouse configuration. These two variations are detailed in Figures 2.30 and 2.31 (18). It can be seen in both that cable distribution almost always brings power into the pit area, and trailing cables connect to the machines. All these cables have shielded conductors.

The overhead poleline plus cable arrangement is more common with older mining operations, especially when utilization is at 7200 V or less (18). Typical spacing between poles (or "line span") is 200 ft. "Drop points" are noted in Figure 2.30 by triangles and are "terminations" between the overhead conductors and the cables. These are mounted on poles (about 8 ft above the ground) at regular intervals of around 1000 to 1500 ft.

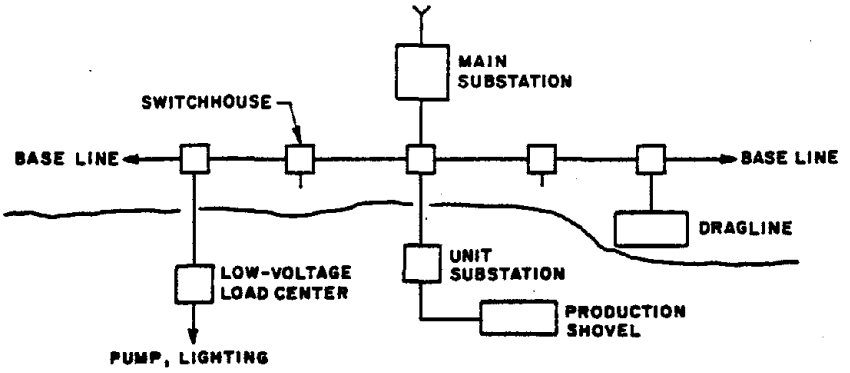


Figure 2.27. A Radial Strip-Mine Distribution System.

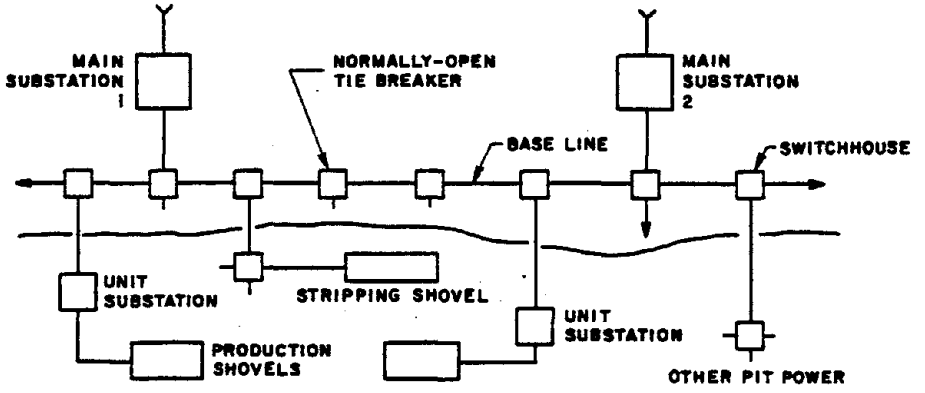


Figure 2.28. Secondary-Selective Distribution in Strip Mining.

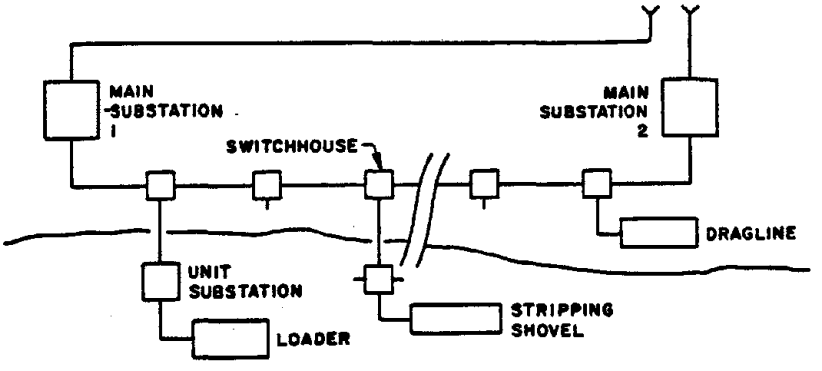


Figure 2.29. Primary-Loop Design for Strip Mining.

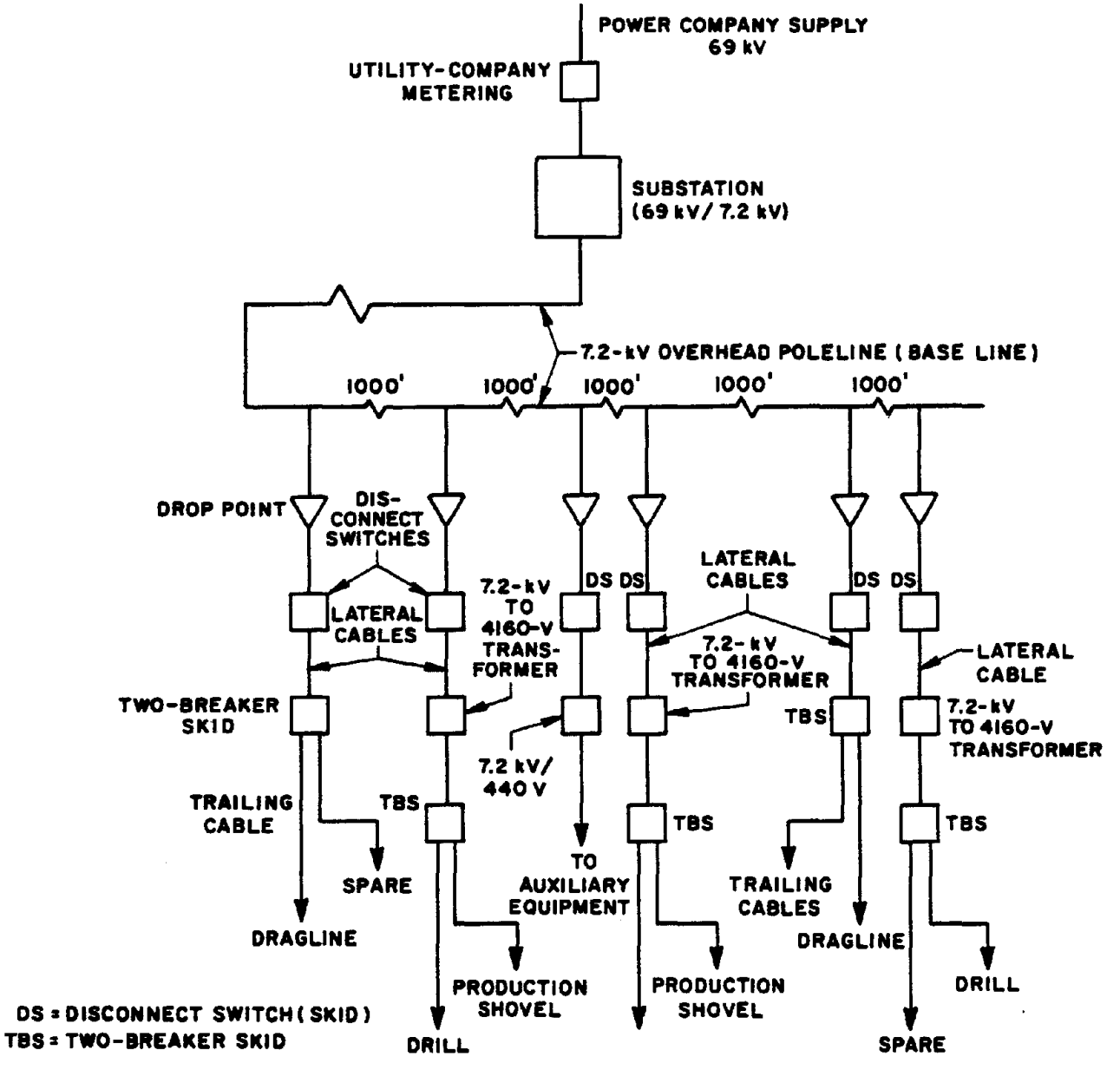


Figure 2.30. Radial Distribution for a Strip Mine with Overhead-Poleline Base Line.

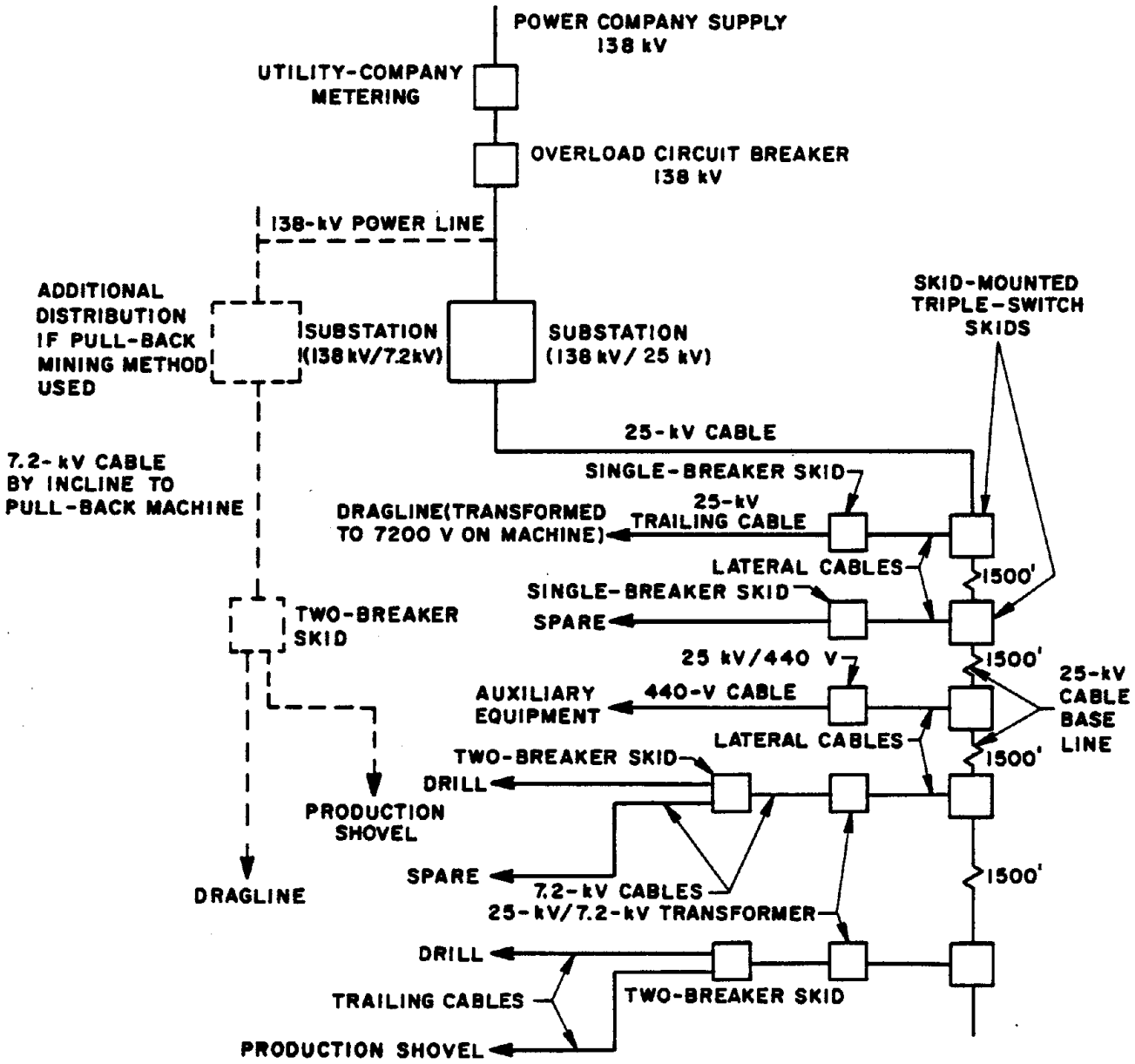


Figure 2.31. Radial Distribution for a Strip Mine with All Cable Distribution.

Cables connected to the drop points deliver power to skid-mounted switchhouses located on the highwall or in the pit. The switchhouses may contain only manual disconnect switches (commonly termed "switch skids" or "disconnect skids"), automatic circuit-protection devices ("breaker skids"), or a combination of both. The skids can be either with flat bottoms ("boat design") or with fabricated runners, depending upon the allowable bearing pressure of the mine terrain. "Couplers," or plug-receptacle pairs, are commonly used for both feeder and trailing-cable connections. The disconnect and circuit-protection functions are required for each distribution load. Double switchhouses (two-breaker skids) are frequently employed for two loads. Unit substations often contain internal circuit protection on the incoming side and, thus, do not require a breaker skid.

Trailing cables are usually 1000 ft in length (although lengths to 2000 ft can be found). When longer cables are necessary to reach a breaker skid, in-line coupling systems can be used. These are commonly mounted on small skids for easy movement. Trailing-cable handling for stripping equipment is often assisted by cable reels mounted on skids or self-propelled carriers. Large excavators can require the self-propelled variety.

The layout for all-cable mine distribution, Figure 2.31, is very similar to that just described. In this case, however, the base line is assembled using cable-interconnected switch-houses. As noted in the illustration, the common approach is to use disconnect skids (with three internal switches) in the base line and separate breaker skids in line with the cables feeding the machinery. Another approach is to combine the single breaker skids into the base-line switchhouses.

Distribution voltage may be 7.2, 13, 23, and to a lesser extent 4.16 kV. Regardless of the level, drills and production shovels usually operate at 7200 or 4160 V (19). Therefore, when higher distribution levels are needed, portable unit substations are commonly used in the pit. (One instance would be when the load created by a large machine is several times that for auxiliary machines.) Another method is to establish two base lines on the highwall for two distribution voltages, as shown in Figure 2.32. Here, a large unit substation interconnects the two base lines. Even in this situation, as can be seen in the preceding drawings, low-voltage unit substations or power centers are often required for 440-V auxiliary equipment.

The primary purpose of any surface-mine primary-distribution scheme is to provide a flexible, easily moved or modified power source for the highly mobile mining equipment. System designs must also be considered an integral part of the total mine

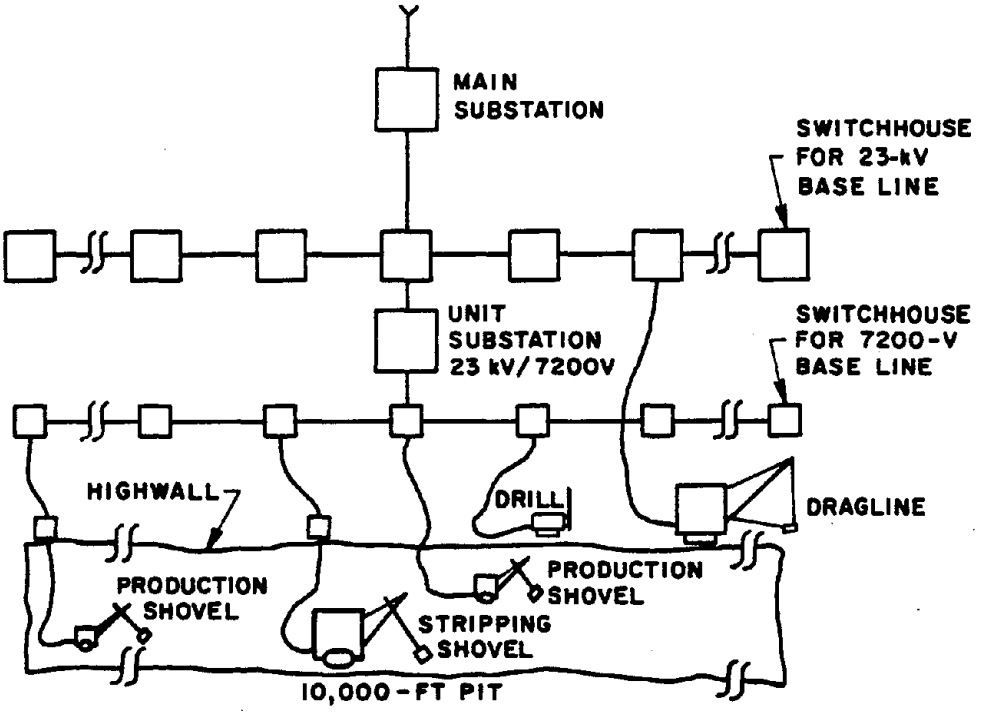


Figure 2.32. A Surface-Mine Distribution System Using Two Base Lines.

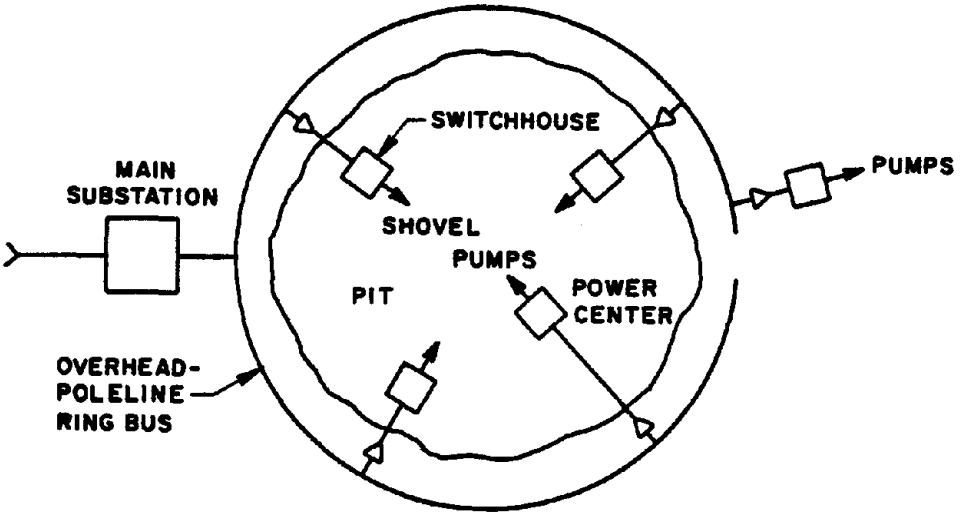


Figure 2.33. An Open-Pit Power-System Example.

operation. Those described have these objectives in mind. As will be seen, the distribution system in any mine, surface or underground, that serves portable equipment is subject to damage by the mining machinery itself. Therefore, the system must be designed with optimum flexibility and personnel safety.

Open-Pit Systems. Open-pit power systems are rather similar to strip mining with one main exception: primary distribution typically establishes a "ring bus" that partially or completely encloses the pit at its periphery. Radial ties to the bus complete the circuit to switchhouses located in the pit. An example is shown in Figure 2.33. Distribution voltage is normally 4.16 kV, but 7.2 (or 6.9) and 13.8 kV are sometimes used. Unit substations are employed if equipment voltages are lower. All portable machinery again uses shielded trailing cables, yet primary distribution is seldom other than overhead powerlines.

Underground Systems. As shown in Figures 2.34 and 2.35, underground mine power systems are somewhat more complicated than those for surface applications. By the nature of the mine and its service requirements, distribution must almost always be radial (Figure 2.34); the freedom of routing distribution that surface mines have is not available. For increased reliability, secondary-selective main substations find application (Figure 2.35). The use of two or more substations and mine feeders with a normally-open tie breaker (as before) above or below ground results in secondary-selective operation. Primary distribution voltage is most commonly 7200 V. However, the older 4160-V systems are still around, and 12,470 V has found increased use in recent years, especially with longwall operations. Substations are very similar to their surface mining counterparts, except for some of the grounding practices. It will be shown in Chapters 6 and 11 that the ground system for the underground mine must be separated from that used for surface equipment.

Power and mine grounding are fed underground in insulated cables through a shaft or borehole for deep mines or a fresh-air entry for drift mines. These cables terminate in disconnect (load-break) switches within 500 ft of the point of power entry into the coal seam. These switches allow total removal of underground power if necessary in an emergency. From the disconnects, which may be a part of a switchhouse, the power is distributed through cables to centers of load in the mine as close to the machinery as practical. All the cables on high-voltage circuits, usually involving only distribution, must have shielding around each power conductor.

Perhaps the prime load concentrations in underground mining are created by the mining sections. Distribution terminates at the section's load center (again, transformer combined with a utilization bus, and protective circuitry), from which several face machines are powered through couplers and trailing cables. Power-system segments for typical continuous and longwall operations are given in Figures 2.36 and 2.37. Rated machine

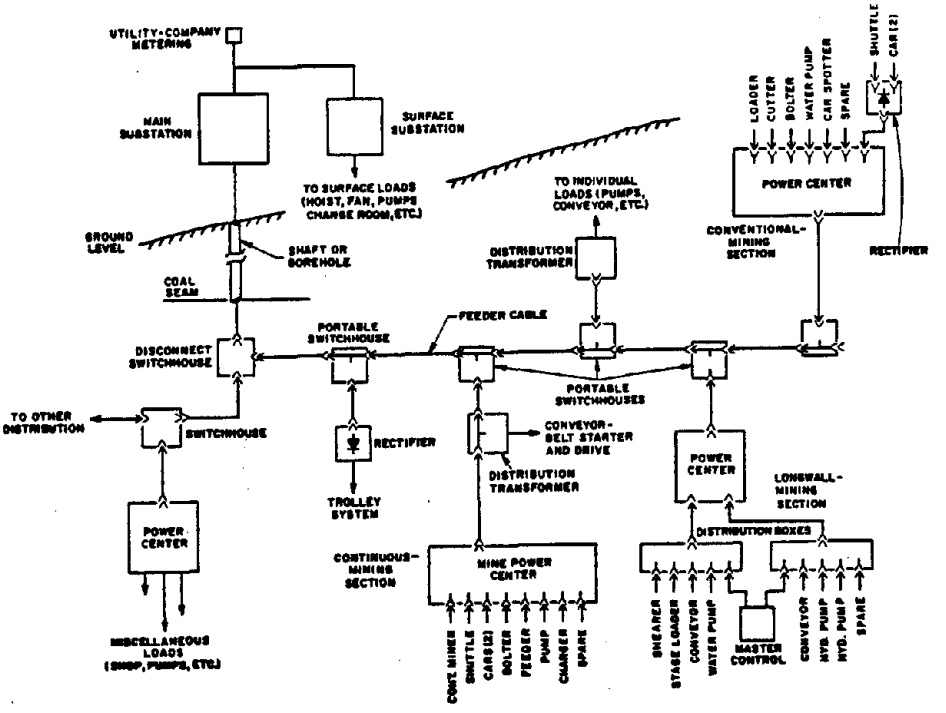


Figure 2.34. A Radially Distributed Underground Power System.

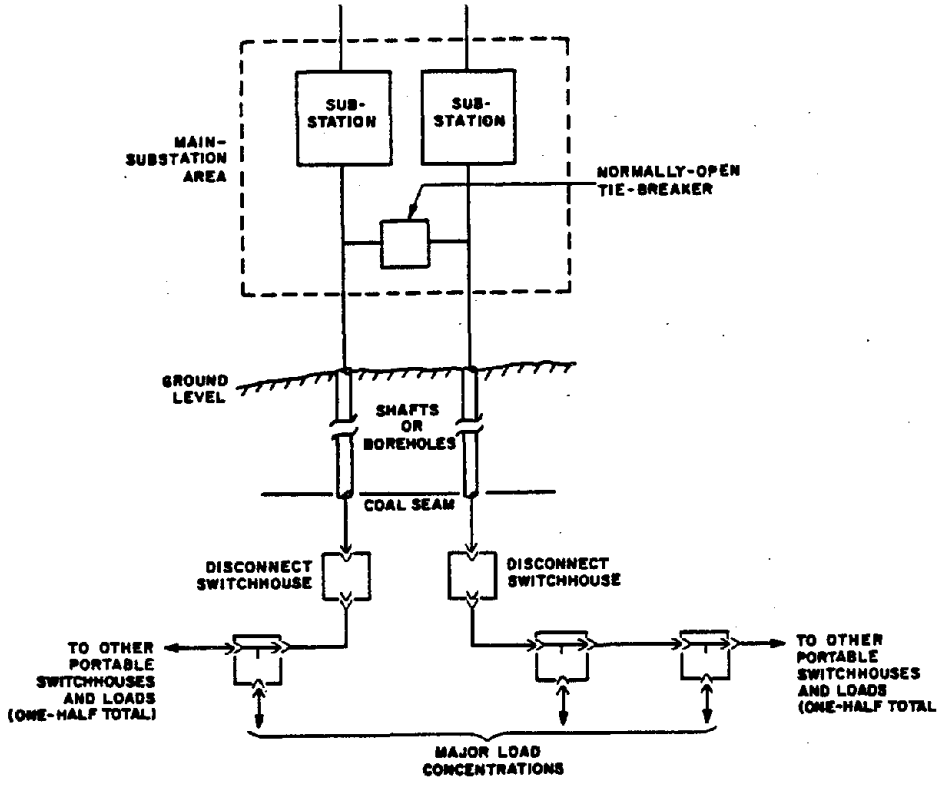


Figure 2.35. Secondary-Selective Distribution in Underground Mines.

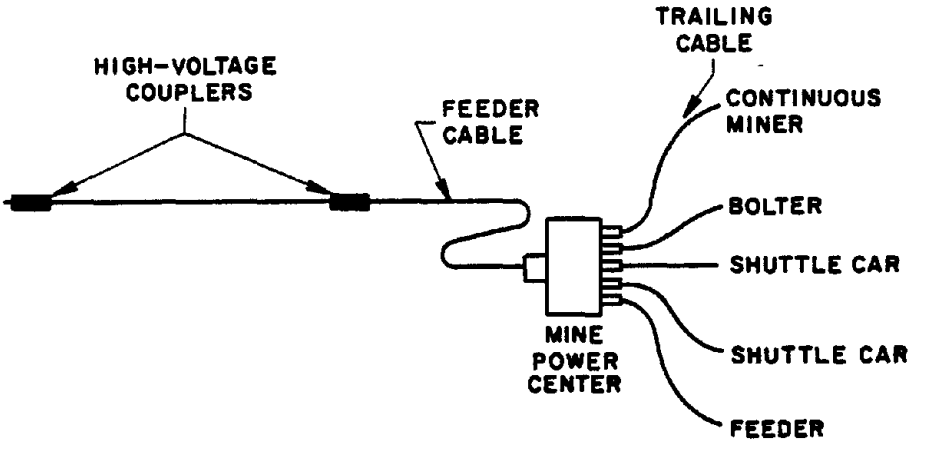


Figure 2.36. Utilization in a Continuous-Mining Section.

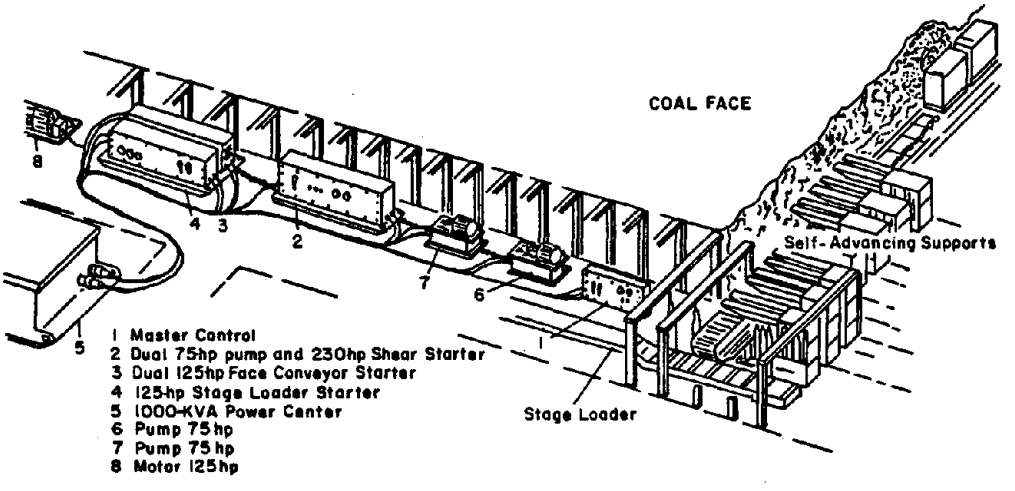


Figure 2.37. The Power-System Segment with Longwall Equipment.

voltage for most installations is 550 Vac, but 250-Vdc and 440-Vac equipment is extensively used. Lately, 950 Vac is becoming quite popular for high-horsepower continuous miners and longwall shearing machines. For the longwall system, power is fed through controls to the various motors. On continuous equipment, the utilization is much like the radial system shown in Figure 2.13.

If belt haulage is used, distribution transformers are located in proximity to all major conveyor-belt drives and are referred to as "belt transformers". After transformation, power is supplied through starter circuitry to the drive motor(s).

With rail haulage, distribution also terminates at rectifiers (again, which contain a transformer and rectifier combination). Rectifiers are located in an entry or crosscut, just off the railway. Direct-current power is then supplied via circuit breakers to an overhead conductor (or "trolley wire") and rail, with rectifiers located at regular intervals from 2000 to 5000 ft along the rail system. A typical rectifier supplies two sections of conductor, and each feeder has its own protective circuitry to detect malfunctions. Furthermore, the trolley conductor is divided into segments, with each segment isolated from adjacent sections. An individually powered trolley-conductor segment is termed a "deadblock". This loop-feeding arrangement is continued throughout most of the haulage system, except for the most inby segment (which is "deadended"). (Note: An alternate method to using rectifiers at the working sections for powering d-c face equipment is a connection (or "nip") to the d-c trolley system.)

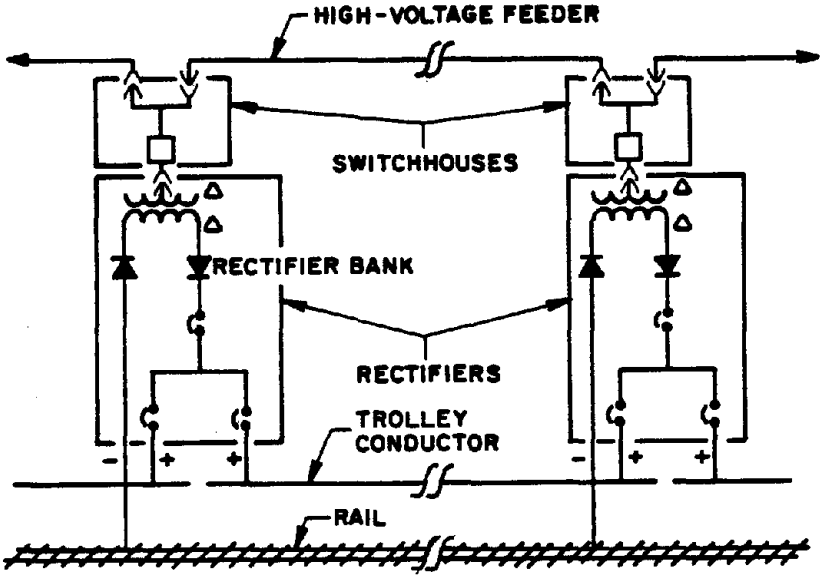


Figure 2.38. Parallel-Feed Haulage System.

Like surface mines, the distribution can also serve large motors directly through switchgear. However, this practice is rare in underground coal.

In the substation, switchhouses, distribution transformers, rectifiers, and so on, each cable and piece of equipment must be protected against many failures that can cause personnel hazards. Primarily by protective relaying, this is built into each system part with redundancy to maximize safety. All power equipment used underground is rugged, portable, sel-contained, and uniquely constructed because of limited space available for installation and operation (13).

Surface Facilities. Large power requirements, that may be necessary for the related surface activities of any mine, include shops, change rooms, offices, ventilation fans, hoisting equipment, preparation plants, and so forth. For safety, these facilities should have an isolated power source (at times, a separate substation), especially if derived from the mine's distribution system. Of the large surface installations, preparation plants deserve special attention in this report.

Preparation Plants. The distribution arrangements almost always employed in preparation plants are expanded radial or secondary selective (22). In both, distribution is at 2.4 to 13.8 kV, with 4160 V the most common. Power is distributed at one of these levels to centers of electric load. Here, the power may be used directly for high-voltage motors, but the voltage is usually stepped-down to supply groups of motors or single high-horsepower motors. Power centers must be totally enclosed in an elevated location. The rooms used may also be pressurized to exclude coal dust.

The most popular voltage for utilization is 480 V. This voltage is used to drive almost all motors throughout the plant, except for high-horsepower demands, such as for centrifugal driers and large fan drives. In these cases, 2300 or 4160 V is commonly employed. These higher voltages may also be preferred for any motor that requires continuity of service or independence from the power-center loads. (Note: 240-V motors are unsatisfactory for typical preparation-plant demands.)

Most modern preparation plants use "group motor control" over individually housed control units. This facilitates maintenance and enables the interlocking of the various motor functions that is required for semi-automatic facilities. All manual controls, indicating lights, and so on are grouped in one central operator's panel to allow easy access and visual indication of plant operation.

Summary. In broad outline, it has been seen that the distribution of purchased power to the mining machinery is accomplished through main substations; switchhouses, unit substations or load centers; and cables or powerlines. However,

as implied, mine power systems are not simple. Many factors, techniques, and components enter into a complete system, and the importance of numerous items listed in Chapter 1 is probably apparent to the reader.

2.9 Concerns

To those not familiar with electrical engineering or mine power systems, the material just covered has perhaps opened many questions. Included might be (just to name a very few):

1. What is protective relaying?
2. What components are in a substation, switchhouses, and load centers?
3. What is grounding and ground systems?
4. How are cables constructed?

If the questions involve areas such as the meaning of series and parallel circuits, the next chapter will be of special interest.

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Chapter 3

ELECTRICAL FUNDAMENTALS

3.1 General

To solve problems in complex electronic circuits or mine power systems, the calculations involve finding currents, voltages, resistances, inductances, impedances, and so on. The solution technique is called "circuit analysis." This serves as the knowledge base on which an understanding of mine electrical systems can be built.

Numerous excellent circuit-analysis textbooks have been produced over the years; many can be employed effectively to cover the subject. Mainly tied to the author's background, the texts produced by Skilling (10), Atwood and Alley (1), plus Hayt and Kemmerly (9) have been extremely valuable in the assembly of the following material. Because practically all fundamental electrical relationships are considered common knowledge, as exemplified by the contents of many electrical-engineering books, the contents of this chapter, other than giving credit to the discoverer, will seldomly be referenced.

The chapter will diverge from classical circuit-analysis presentations by not covering transient effects in circuits. From experience, studying the rate of change of current and voltage existing in a circuit immediately after a change in circuit configuration, commonly confuses individuals and clouds understanding of the most-used segments of circuit analysis. Therefore, although some necessary statements will be made, the subject is delayed until Chapter 10, where it can be combined with practical examples.

The material is not presented as a tutorial. However, if such a need exists, the use of the chapter should be coupled with a problem-oriented book, such as reference 4.

3.2 Basic Electrical Phenomena

Electron Theory and Charge. The nature of electricity is not yet fully understood, but it is well known as a form of energy which can be conveniently converted into and utilized as light, heat, and mechanical power. Like all science, knowledge about it has been developed from observation and experimentation. Theory is the generalization of experimental evidence, and electricity can be associated with the nature and behavior of electrons and electron flow. The combination of these is called "Electron Theory."

The atoms of each element consist of a dense nucleus around which electrons travel in well-defined orbits or shells. The subatomic particles, the building blocks out of which atoms are constructed, are of three different kinds: the negatively charged electron, the positively charged proton, and the neutral neutron. The negative "charge" of the electron, e^-, (-1.6022×10^{-19}C) is of the same magnitude as the positive charge of the proton, e^+, and no charges of smaller magnitude have yet been concretely observed. Thus, the charge of a proton or an electron is taken as the ultimate, natural unit of charge. It is these two particles that are of principal interest in electricity.

Coulomb's Law. The force, F, between two charges, q and q', varies directly as the magnitude of each charge and inversely as the square of the distance between them. This relationship, known as "Coulomb's Law," is represented mathematically by:

$$F = k\frac{qq'}{r^2} \tag{3.1}$$

where,

k = a proportionality constant which depends on the units used for charge, distance, and force.

If force is in newtons, charge in coulombs, and r in meters, then

$$k = 9 \times 10^{-9}\ \mathrm{Nm^2/C^2}.$$

The unit of charge, the coulomb (C), can be defined as the quantity of charge which, when placed one meter from an equal and similar charge, repels it with a force of 9×10^{-9} newtons (N). The charge carried by an electron or by a proton is $e = 1.602 \times 10^{-19}$C.

Voltage and Current. A proton in an atom's nucleus can hold only one electron in orbit around it. When an atom contains less than the normal number of electrons that the proton can attract, the atom has an excess of positive charge and is said to be "positively charged." Atoms having an excess of electrons are referred to as "negatively charged." The net amount of these charges is termed "potential," "electromotive force," or "emf" and is measured in volts. The separation of opposite charges of electricity may be forced by physical motion, or it may be initiated or complimented by thermal, chemical, or magnetic causes or even by radiation.

The potential difference or "voltage," existing between two points, can be measured by the work necessary to transfer a unit charge from one point to the other. The "volt" is the potential between two points when one joule of work is required to

transfer one coulomb of charge. In other words,

$$1 \text{ volt} = 1 \text{ joule/coulomb}.$$

In some metals or "conductors," electrons in the outermost orbit of the atoms are rather loosely bound to their respective nucleus. These are called "conduction electrons," since they can leave the atom upon the application of a small force, thus becoming free to move from one atom to another within the material. In some materials, however, all the electrons are tightly bound to their respective atoms. These are called "insulators;" here, it is exceedingly difficult, if not impossible, to free any electrons. The principal materials used in electrical systems are conductors and insulators.

The application of a voltage across a conductor causes the free electrons within the conductor to move. "Electrical current" is defined by the motion of electrical charge. If the charge in the conductor is being moved at the uniform rate of one coulomb per second, then the constant current existing in that conductor is one "ampere," the unit of electrical current. The amount of current in a conductor can also be measured as a rate of change of the charge flow. Such changing current at any point in time is called "instantaneous current" or

$$i = (\text{the rate of change or charge}) = \frac{dq}{dt} \qquad (3.2)$$

where,

i = the instantaneous current, amperes (A)

q = the flow of charge, coulombs (C)

t = time, seconds (s).

When electricity was first discovered, it was erroneously thought that there was flow of positive charges and, since the laws of attraction and repulsion were known, movement was assumed from positive to negative. The theory was accepted until the discovery of the radio tube, when it was recognized that the flow was movement of electrons in the opposite direction. However, the concept of positive-charge flow was firmly entrenched and remained standard in the United States (as it does today). This report will also use this standard.

3.3 System of Units

As exhibited by the preceding, all material contained in the report is in the International System of Units (SI), with the exception of some calculations in terms of the English or

American Engineering systems for practical considerations. A listing of symbols, units, and abbreviations is available in Table 3.1. The SI incorporates the decimal system to relate larger and smaller units to the basic unit and uses standard prefixes to signify the various powers of ten. Those commonly used are:

pico-	(p-, 10^{-12})
nano-	(n-, 10^{-9})
micro-	(μ-, 10^{-6})
milli-	(m-, 10^{-3})
kilo-	(k-, 10^{3})
mega-	(M-, 10^{6})
giga-	(G-, 10^{12}).

It may be noted that voltage, current, and power are represented by the letter symbols, V, I, and P, each presented in both uppercase and lowercase letters. Uppercase letters represent voltage, current, and power when the variable is constant, as in d-c circuits. In a-c circuit work, uppercase V and I represent effective values, whereas uppercase P represents average power. Lowercase v, i, and p depict instantaneous voltage, current, and power when these quantities are varying with time. Hence, they may be used as instantaneous values of these quantities in an a-c circuit.

Where needed, double-subscript notation is used to describe current and voltage. V_{AB} represents the voltage of point A with respect to point B. I_{CD} represents the current flowing through a circuit element from C to D. Note that in the circuit of Figure 3.1, the voltage V_{AB} causes the current I_{AB} to flow. These meet with the standard for electrical current as positive-charge flow from positive to negative.

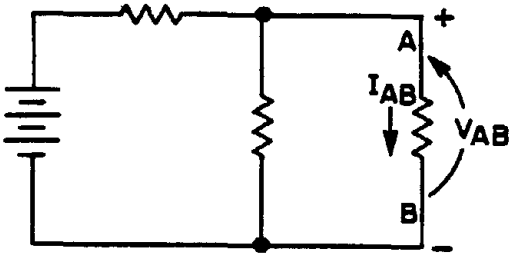


Figure 3.1. A Circuit Element Illustrating Voltage-Polarity and Current-Flow Direction.

Table 3.1. SI Symbols and Units.

Quantity	Qty Symbol	SI Unit	Unit Symbol	Identical Unit
charge	Q	coulomb	C	A·s
current	I	ampere	A	
voltage	V,E...U	volt	V	W/A
electromotive force	V	volt	V	
potential difference	V, Φ	volt	V	
resistance	R	ohm	Ω	V/A
conductance	G	siemens	S	A/V
reactance	X	ohm	Ω	V/A
susceptance	B	siemens	S	A/V
impedance	Z	ohm	Ω	V/A
admittance	Y	siemens	S	A/V
capacitance	C	farad	F	C/V
inductance	L	henry	H	Wb/A
energy, work	W	joule	J	N·m
power (active)	P	watt	W	J/s
power - apparent	S...P_s	voltampere	VA	
power - reactive	Q...P_q	var	var	
resistivity	ρ	ohm-meter	Ω m	
conductivity	γ,σ	siemens per meter	S/m	
electric flux	Ψ	coulomb	C	
electric flux density, displacement	D	coulomb per sq. meter	C/m^2	
electric field strength	E	volt per meter	V/m	
permittivity	ε	farad per meter	F/m	
relative permittivity	ε_r, κ	(numeric)		
magnetic flux	Φ	weber	Wb	V·s
magnetomotive force	F...*F*	ampere (amp turn)		
reluctance	R...*R*	ampere per weber reciprocal henry	A/Wb H^{-1}	
permeance	P...*P*	weber per ampere henry	Wb/A H	
magnetic flux density	B	tesla	T	Wb/m^2
magnetic field strength	H	ampere per meter	A/m	
permeability (absolute)	μ	henry per meter	H/m	
relative permeability	μ_r	(numeric)		

V,E comma indicates alternate symbols

...U dots indicate reserve symbols

3.4 Experimental Laws and Parameters

The basic concepts upon which circuit analysis is built are extremely remarkable because the powerful structure relating to electrical circuits is based on just six experiments. One is Ohm's law, two are named for Kirchhoff, two relate to inductance and capacitance, and one has to do with power. To understand any electrical system, comprehension of these relationships is mandatory, even though all concepts may not be employed in every case.

Ohm's Law. Georg Simon Ohm (1789-1854) discovered that electrical current through most conductors was proportional to the voltage (potential) applied across the conductors. This phenomenon is known as Ohm's law and is expressed mathematically as:

$$v = Ri \tag{3.3}$$

where,

v = the applied potential in volts (V)

i = the current through the conductor in amperes (A)

R = a proportionality constant known as the "resistance" of the conductor, where the unit is the "ohm" (Ω).

No restriction is placed on the form of v and i. They can be constant with respect to time as in d-c circuits; for a-c, they are sinusoidal.

For metals and most other conductors, R is constant; in other words, its value is not dependent on the amount of current, i. In some materials, especially in crystalline materials called "semiconductors," R is not constant, and this situation is useful in diodes, amplifiers, surge arresters, and other devices.

Further experiments by Professor Ohm indicated that the resistance of a piece of metal depends on its size and shape. However, the "resistivity," ρ, of the metal depends only on its composition and physical state. It is an inherent property which opposes current through the conductor just like the frictional resistance of a pipe opposes the flow of water through the pipe. Resistivity can be thought of as a property of the material "at a point." Although its value remains the same for a particular conductor (at all points), the value may vary greatly for different conductors. Further, if the material is not homogeneous, its resistivity can vary from point to point. Resistivity is defined as the resistance of a unit cube of homogeneous material. The concept of resistivity is often used in the grounding and distribution aspects of mine electrical systems, just to name two.

Using the definition, practical resistivity units would be Ω-cm and Ω-inch. However, more accepted units are the Ω-m (SI) and Ω-circular-mill-foot (English). The Ω-m is the resistance of a material one-square millimeter in cross-section with one-meter length. Likewise, the Ω-circular-mill-foot (usually abbreviated just cir-mil-foot) refers to the conductor resistance for a volume 0.001 inch (one-mil) in diameter, one-foot long. For calculating the resistance in this latter case, the cross-sectional area of the conductor is measured in circular-mills (cir-mil or CM), which can be found from:

$$A = d^2 \tag{3.4}$$

where,

A = the cross-sectional area of the circular conductor in cir-mil (CM).

d = the conductor diameter in milli-inches.

Resistivity values of some common conductors are given in Table 3.2.

The resistivity of any specific conductor can be calculated from the material resistivity using the formula,

$$R = \rho\frac{\ell}{A} \tag{3.5}$$

in which

R = the resistance (Ω)

ℓ = the conductor length

A = the conductor cross-sectional area

ρ = the material resistivity.

If ℓ is in m and A is in m^2, then ρ must be given in units of Ω-m.

Electrical resistivity is not constant if the temperature is permitted to change. For most materials, the resistance increases as the temperature increases; carbon is an exception to this rule (negative temperature coefficient, 0.005). If the temperature coefficient is known, the resistance of a given conductor at a given temperature is

$$R = R_o\ (1 + \alpha(t - t_o)) \tag{3.6}$$

Table 3.2. Resistivity of Some Common Materials at 20°C.

Material	Temp. Coeff., α	Resistivity, ρ ohm - m	Resistivity, ρ ohm - cir-mil-ft
Aluminum, commercial	0.0039	2.824×10^{-8}	17.1
Copper, annealed	0.00393	1.724×10^{-8}	10.5
Iron, annealed	0.005	9.5×10^{-8}	57.4
Lead	0.0034	21.83×10^{-8}	132.31
Nichrome	0.04	100×10^{-8}	606.1
Silver	0.0038	1.63×10^{-8}	9.85
Steel, mild	0.002	11.91×10^{-8}	72.17
Tin	0.0042	11.5×10^{-8}	69.7
Tungsten	0.0045	5.5×10^{-8}	33.2

where,

R = the resistance at temperature, t (Ω)

R_o = the resistance at the reference temperature, t_o, usually 20°C (Ω)

α = the temperature coefficient (Ω/°C)

t = the given conductor temperature (°C)

t_o = the reference temperature (°C)

At very low temperatures (about -200°C for copper), the temperature coefficient is no longer constant and changes with temperature; the same is true as the melting point is reached. Therefore, equation (3.6) is not valid for very high or low temperatures.

The symbol illustrated in Figure 3.1 portrays a "resistor" in a circuit, and often its resistance is stated. Again, by definition,

$$R = \frac{v}{i}. \tag{3.7}$$

Sometimes, the element's "conductance," G, is referenced and is defined as the reciprocal of resistance:

$$G = \frac{1}{R} = \frac{i}{v} . \tag{3.8}$$

In circuit analysis, it is occasionally more convenient to use conductance than resistance. Later, the explanation of this symbol will be generalized.

Kirchhoff's Voltage Law. In a simple "series circuit," as shown in Figure 3.2, all apparatus (in this case, three resistors) are connected in tandem to form one single closed loop. Kirchhoff has shown that when several elements are connected in series, the current in the circuit will adjust itself, until the sum of "voltage drops" in the circuit is equal to the sum of "voltage sources" in the circuit. This can be restated as the "sum of all voltages around any closed circuit is zero," which is referred to as "Kirchhoff's Voltage Law." For the circuit shown in Figure 3.2,

$$v_{ab} + v_{bc} + v_{cd} + v_{da} = 0 \tag{3.9}$$

or

$$v_{ab} + v_{bc} + v_{cd} - v_{ad} = 0 \tag{3.10}$$

or

$$v_1 + v_2 + v_3 - v_s = 0. \tag{3.11}$$

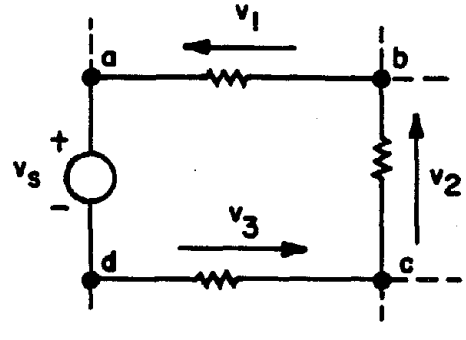


Figure 3.2. A Simple Series Circuit.

Obviously, some of these potential differences could be negative and some positive. This circuit shows only resistances and a voltage source, but the network could contain other kinds of elements and might be as complicated as desired. However, Kirchhoff found that the sum of the voltages around any closed loop in a circuit, such as a-b-c-d, is always zero.

The symbol in Figure 3.2 by v_s represents an "ideal voltage source." Such a source maintains a given voltage across its output (terminals) regardless of the load, but actual voltage sources cannot supply an infinite current if the terminals are "short-circuited" (i.e., tied together so the resistance approaches zero). Therefore, actual sources are usually considered to be ideal voltage sources with an internal resistance connected in series with the source and the output terminals. The assumption is illustrated in Figure 3.3.

Kirchhoff's Current Law. The other law attributed to Kirchhoff specifies that "the sum of all electrical currents flowing toward a junction is zero." Referring to Figure 3.4, if five wires are soldered together at a common terminal and the current in each wire is measured, plus if current towards the junction is called positive (direction shown in the figure) and current outwards is negative (against the arrows), then the sum of the five currents is zero:

$$i_1 + i_2 + i_3 + i_4 + i_5 = 0. \qquad (3.12)$$

As was the case for equation (3.9), this equation implies that some currents must be positive, some negative.

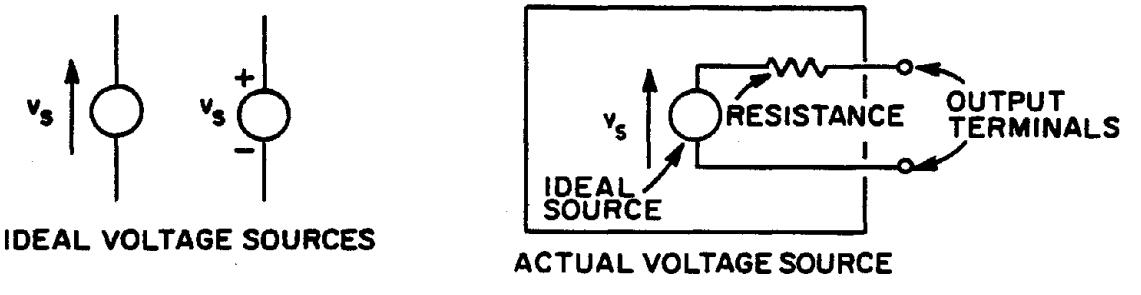


Figure 3.3. Actual and Ideal Voltage Sources.

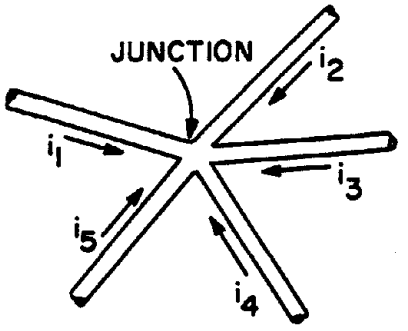


Figure 3.4. Demonstration of Kirchhoff's Current Law.

If two or more loads or apparatus are connected between two common points (or junctions), these elements are said to be in "parallel," as shown in Figure 3.5a. The same is true for Figure 3.5b and, moreover, the two circuits illustrated in Figure 3.5 are identical, just drawn differently. It is important to note that the lines in these and all circuit diagrams usually show no resistance, each is only a connection between elements or between an element and a junction. The similarity in the diagrams can be shown using Kirchhoff's current law. In both, there are only two independent junctions, a and b, and for either point,

$$i_1 + i_2 + i_3 + i_4 = 0. \tag{3.13}$$

The circuit symbol next to i_1 in Figure 3.5 represents an "ideal current source," and a similar situation exists for all practical current sources as was mentioned for practical voltage sources. However, the internal resistance is effectively connected in parallel across the ideal current source. Both ideal and actual current sources are shown in Figure 3.6

Series Circuits. To restate the earlier definition of a series circuit, elements are said to be connected in series if the same current passes through them. Such is the situation for the four resistors shown in Figure 3.7. It would be convenient if there was some resistance, R, that could replace all series resistors. This "equivalent" resistance can be found by returning to Ohm's and Kirchhoff's Voltage laws. By Kirchhoff's,

$$v = v_1 + v_2 + v_3 + v_4$$

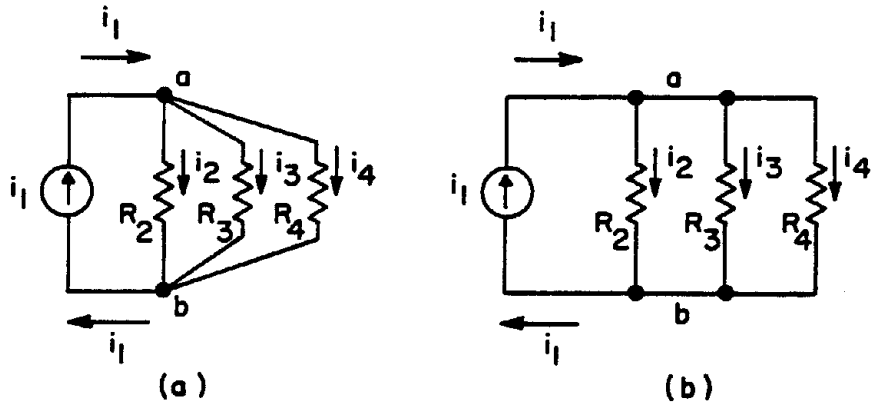


Figure 3.5. Simple Parallel Circuits.

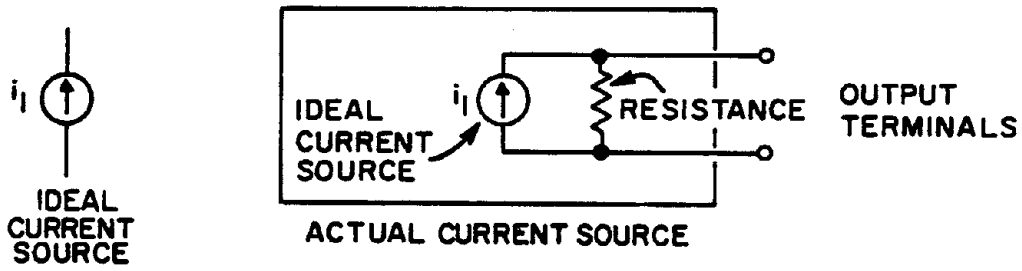


Figure 3.6. Actual and Ideal Current Sources.

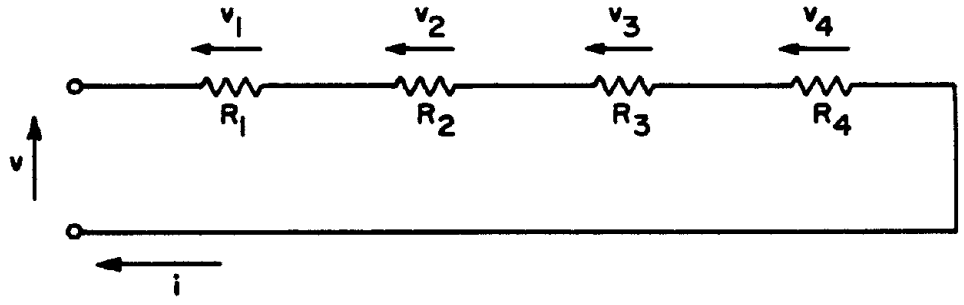


Figure 3.7. A Simple Series Circuit and an Equivalent.

but by Ohm's law,

$$v_1 = iR_1,\ v_2 = iR_2,\ v_3 = iR_3,\ - - - - - - .$$

Therefore,

$$v = iR_1 + iR_2 + iR_3 + iR_4 .$$

For the circuit in Figure 3.7, if the voltage, v, produces the same current, i, through the circuit, then

$$v = iR$$

but

$$v = i\ (R_1 + R_2 + R_3 + R_4)$$

$$iR = i\ (R_1 + R_2 + R_3 + R_4)$$

or

$$R = R_1 + R_2 + R_3 + R_4. \qquad (3.14)$$

Here, R is said to be the equivalent resistance for the previous series circuit. In other words, R is the "series resistance" of that circuit. The same logic applies to all electrical elements in series.

It is often useful to find the voltage drop across just one element in a series circuit. To arrive at an expression, again refer to Figure 3.7. For the current through the circuit, it is obvious that

$$i = i_1 = i_2 = i_3 = i_4$$

but

$$i_1 = \frac{v_1}{R_1},\ i_2 = \frac{v_2}{R_2},\ - - - - - - -.$$

Therefore,

$$i = \frac{v_1}{R_1} = \frac{v_2}{R_2} = \frac{v_3}{R_3} = \frac{v_4}{R_4}.$$

As before, consider R, the equivalent-circuit resistance, and

$$i = \frac{v}{R}$$

Therefore,

$$\frac{v}{R} = \frac{v_1}{R_1}, \frac{v}{R} = \frac{v_2}{R_2}, - - - - - - -$$

or

$$v_1 = \frac{R_1}{R}v, \; v_2 = \frac{R_2}{R}v, - - - - -. \qquad (3.15)$$

In other words, the voltage drop across any one element is equal to the total circuit voltage times the ratio of the element's resistance to the total circuit resistance.

Parallel Circuits. Following the discussion of series circuits, it would be useful to have similar equivalence, voltage, and current relationships for parallel circuits. For the circuit shown in Figure 3.8, the voltage across each circuit element (again, resistors) is the same (a corollary to current through series elements). From this, using the same basic procedure as for series circuits, it can be shown that:

$$G = G_1 + G_2 + G_3 + G_4 + - - - - - \qquad (3.16a)$$

and also

$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \frac{1}{R_4} + - - - - -. \qquad (3.16b)$$

Restated, the total conductance of parallel connected resistors is equal to the sum of all individual conductances. Likewise, the reciprocal of the total resistance of parallel connected resistors is equal to the sum of the reciprocals of the individual resistances. A special case that is very often found occurs when two resistances are in parallel say R_1 and R_2. Then

$$R = \frac{R_1 R_2}{R_1 + R_2}. \tag{3.17}$$

Instead of voltage distribution, current distribution through parallel circuits is of interest. Kirchhoff's current law and, again, Ohm's law can be employed to show that:

$$i_1 = \frac{G_1}{G} i \text{ or } i_1 = \frac{R}{R_1} i \tag{3.18}$$

and so on for the balance of currents.

The preceding paragraphs have been used to show immediate application of Ohm's law plus Kirchhoff's voltage and current laws to circuits having more than one element. The results are extremely valuable in circuit analysis and are extensively used to solve problems. It is important to note now that these concepts are valid when circuits contain components other than resistance. Later, after the balance of fundamental laws and parameters are covered, more applications will be shown.

The Magnetic Field. A.M. Ampere was the first to establish that a conductor through which electric current is passing is enclosed in a magnetic field. The relationship is depicted in Figure 3.9a. After Ampere's discovery, many experimenters tried to reverse the process and create electric current from a magnetic field. Finally, in 1831, Michael Faraday discovered that when a magnet was inserted into a coil of wire, an impulse of

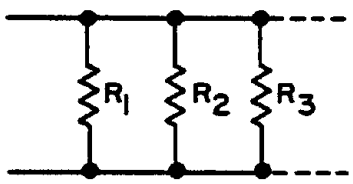


Figure 3.8. A Simple Parallel Circuit.

electrical current would flow through the wire. However, if the magnet was left stationary within the coil, no current was produced. Yet, when the magnet was withdrawn, again a current impulse was observed, but this time it was of opposite direction. The process is demonstrated in Figure 3.10. Faraday visualized that the effect was a result of magnetic "flux lines" cutting or moving through the conductor. Whenever relative motion occurred, an emf was produced in the conductor. This disclosure laid the foundation for electro-mechanical conversion (i.e., converting from mechanical energy to electrical visa versa, as in generators and motors, respectively).

The magnetic field mentioned here is a condition of space. The direction of a magnetic field flux line is the direction of force on a magnetic pole. The flux-line density is in proportion to the magnitude of force on the magnetic pole. Each line represents a certain quantity of magnetic flux (measured in webers), and it is a magnetic-field characteristic that every flux line is a closed curve. The concentric-circle pattern is as shown in Figure 3.9a. These conditions of a magnetic field are employed to develop the relationships, applying to a magnetic devices, which are covered in upcoming report sections.

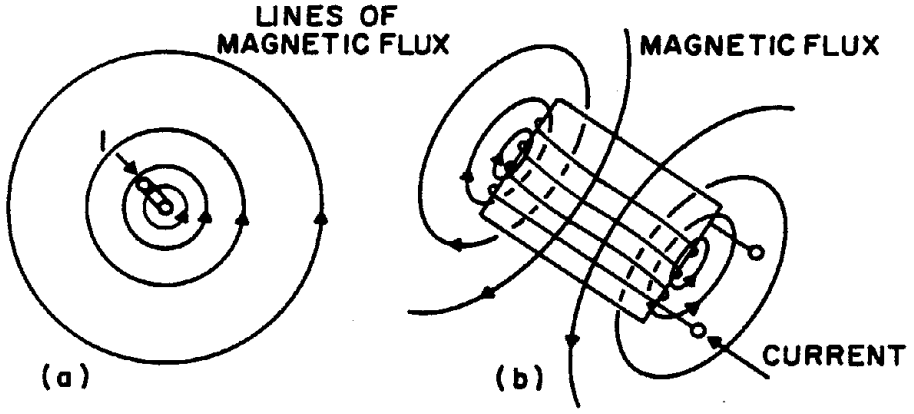


Figure 3.9. Magnetic Flux in a Straight Conductor (a) and a Long Coil (b).

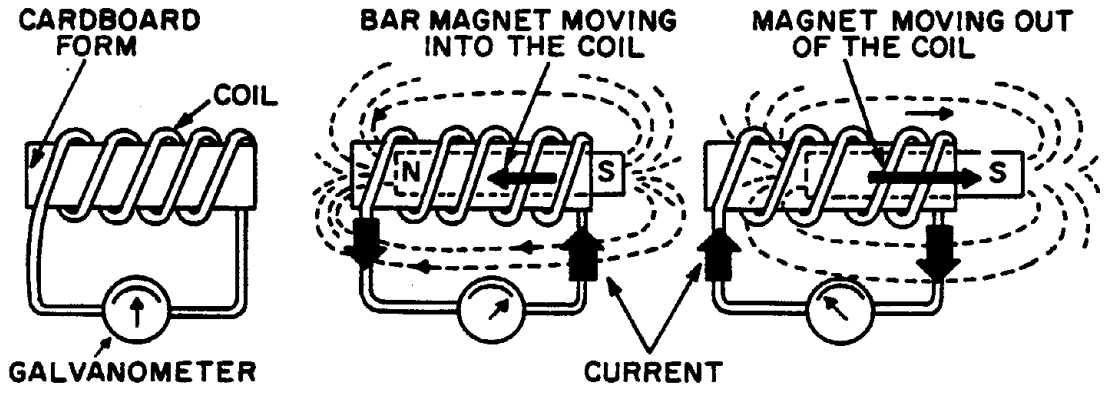


Figure 3.10. Demonstration of Induced Current.

When a wire is wound into a coil, an interesting action occurs. As the magnetic flux builds up around one wire, it tends to cut through adjacent turns of wire. The concept is shown as dashed flux-lines around one winding of the coil in Figure 3.10. Thus, a voltage is induced into the coil windings.

Inductance. Joseph Henry found that electricity flowing in a circuit has a property analogous to mechanical momentum. Current is difficult to start but, once started, it tends to continue. This is a fact for any element from a simple conductor to the most complex. Faraday explained the phenomenon by visualizing the magnetic field in space around the conductor. In terms of the coil in Figure 3.10, the voltage induced in the other windings is proportional to the "rate" at which the magnetic flux lines are cutting through the coil. Yet, the magnetic flux is proportional to the current in the coil. The induced voltage is such that at every instant, it opposes any change in the circuit current. For this reason, the induced voltage is called a "counterelectromotive force," cemf. The interrelation is so important that it has the status of physical law, known as "Lenz's Law."

The property that prevents any change of current in the coil is called "self-inductance;" hence, the coil is known as an "inductor." The greater the induced voltage, the greater is the opposition to the change in current flowing. Therefore, the cemf produced by a specific change of current is a measure of circuit inductance. Expressed as a formula:

$$v = L \text{ (rate of change of current)}$$

or

$$v = L \left(\frac{di}{dt}\right) \tag{3.19}$$

where,

v = the voltage across the coil (V)

L = the proportionality constant known as inductance measured in henries (H)

i = the current through the coil (A).

As noted, inductance is given the symbol, L, and is measured in units called henries in honor of Joseph Henry. A circuit has an inductance of one-henry when a current change of one-ampere-per-second causes a cemf of one-volt to be induced in the coil. The term, di/dt, represents the rate of change of current, i, in the coil.

When two separate coils are placed near each other, as shown in Figure 3.11, the magnetic field from one coil can cut through the windings of the second coil. A change in the current in coil 1 can produce an induced voltage in coil 2. The current-voltage relationship is expressed as follows:

$$v_2 = L_{21} \text{ (rate of change in } i_1)$$

or

$$v_2 = L_{21} \left(\frac{di_1}{dt}\right). \tag{3.20}$$

Similarly, if the current in coil 2 is changing, it induces a voltage in coil 1:

$$v_1 = L_{12} \text{ (rate of change in } i_2)$$

or

$$v_1 = L_{12} \left(\frac{di_2}{dt}\right). \tag{3.21}$$

L_{12} and L_{21} are called "mutual inductances" and are again expressed in henries. These will increase if the coils are brought closer together and decrease as the coils are separated further apart. Two magnetically coupled coils are usually called a "transformer." It is a fact, although not by all means obvious, that the two mutual inductances of a pair of magnetically coupled circuits are equal, or

$$L_{12} = L_{21}. \tag{3.22}$$

The self-inductance of an actual coil is a function of both the coil configuration and the total number of turns. Further, because the magnetic flux may induce currents in adjacent conductors, the environment in which the coils are placed may also have an effect. A large number of inductance equations are available in handbooks and other reference books, each valid for a given coil configuration. Consequently, only a few which give approximate inductance values are given here to demonstrate the parameters that effect inductance.

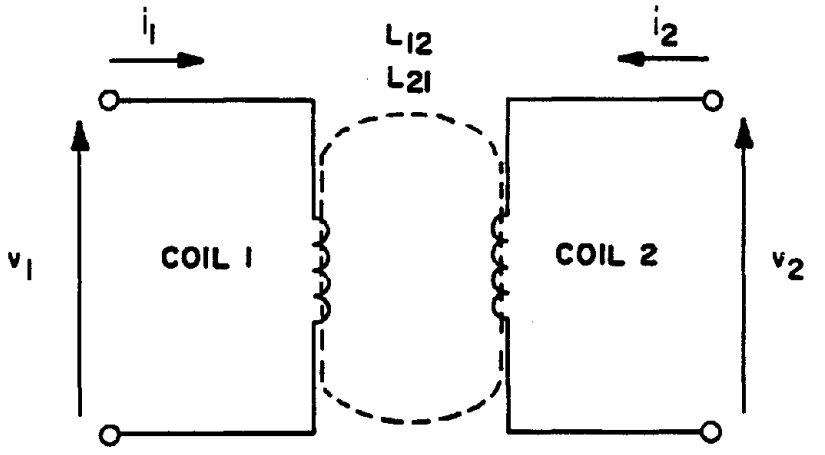


Figure 3.11. Two Coils Demonstrating Mutual Inductance.

For a long coil as shown in Figure 3.12, the inductance is

$$L = \frac{\mu N^2 A}{\ell} \tag{3.23}$$

in which

L = the self-inductance (H)

μ = permeability in henries per meter (H/m), for air, $4\pi \cdot 10^{-7} = 12.566 \cdot 10^{-7}$

N = turns of the coil

A = coil cross-sectional area (m^2)

ℓ = coil length (m).

The cross section need not be circular, but the formula is only approximate because it assumes all flux lines link all turns of the coil (which cannot happen at the coil ends). However, the formula gives good results for long coils and does reveal the following important relationships.

1. Coil inductance is proportional to the square of the number of turns.
2. Inductance is proportional to the core permeability.
3. Inductance is proportional to the cross-sectional area of the core.
4. Inductance decreases as the length increases.

For a shorter single-layer circular solenoid (coil), the inductance is approximately:

$$L = \frac{\mu N^2 A}{\ell + 0.45d} \tag{3.24}$$

where

d = the coil diameter, wire center-to-center (m).

For a toroidal coil of rectangular cross section (see Figure 3.13),

$$L = \frac{\mu N^2 h}{2\pi} \ln\left(\frac{d_2}{d_1}\right) \tag{3.25}$$

where

d_1, d_2 = the inner and outer diameters as shown (m)

h = the thickness (m).

Note that "ln" indicates the natural logarithm, logarithm to the base e. Figure 3.12 also illustrates the two symbols used to indicate inductance; the one on the right is most commonly found in power-circuit diagrams.

Capacitance. When two conducting surfaces are separated by a "dielectric" or insulating material, an effect known as "capacitance" is observed. If two electrical conductors are at different potential, there is some storage of charge upon them. A "capacitor" is a device included in a circuit for the purpose of storing or exchanging electrical charge. Further, when capacitance is present, a charge is observed to flow into the capacitor which is proportional to the voltage applied. This can be expressed as:

$$q = CV \tag{3.26}$$

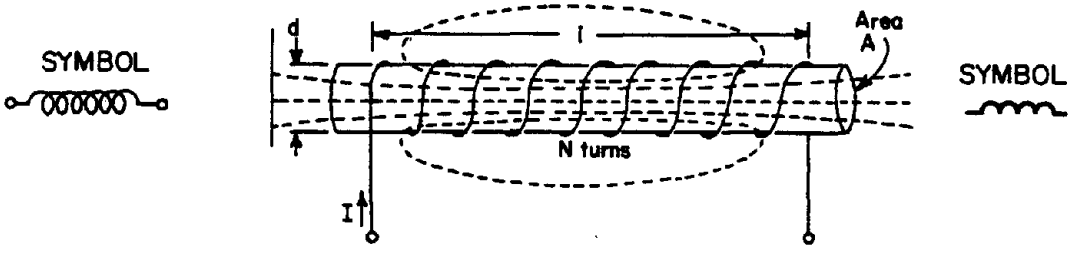


Figure 3.12. Long-Coil Inductance and Inductor Symbols.

where

q = the stored charge in the capacitor (C)

v = the applied voltage (V)

C = the proportionality constant called capacitance, the units are farads (F).

To analyze circuits, a relationship between the voltage applied and the current flowing into (and from) the capacitor is more useful. Current is the rate at which charge flows ($i = dq/dt$). It therefore holds, that for a given capacitance,

$$i = C \text{ (the rate of change of v)}$$

$$i = C\left(\frac{dv}{dt}\right) \tag{3.27}$$

where

i = the current flowing into the capacitor (A)

v = the voltage across the capacitor (V).

This is very similar to formula 3.19 and, using the discussion in that section, capacitance can be defined as that electrical-circuit property which tends to oppose any change in voltage. The capacitance (of a capacitor) depends on the size of the conductors (or plates), their proximity, and the nature of the material between them. For most dielectric materials, C is constant.

Equations 3.26 and 3.27 have algebraic signs consistent with the arrows in Figure 3.14. The symbol shown is for capacitance; note that a positive-terminal voltage produces positive current and, hence, positive charge.

If the voltage across a capacitor is desired, equation 3.27 can be integrated, resulting in

$$v = \frac{1}{C}\int_0^t idt + V_0 \, . \tag{3.28}$$

This equation represents the change in voltage across the capacitor from some arbitrary reference time, called t = 0, to a later time, t. V_0 is the potential across the capacitor at time, t = 0. The term, $\int_0^t idt$, is the voltage change across the capacitance from time, t=0, to time, t = t. From the formula, if the voltage across the capacitor remains constant (as in d-c circuits), no current will flow into or out of the capacitor.

Electric Field. Anywhere in the neighborhood of an electrical charge (for example, between the plates of a capacitor), there is an electric field. The direction of this field is by definition the direction of the force on a positively charged exploring particle (a particle free to move within the electric field). The strength of the field, E, is proportional to the magnitude of the force. If the charge of the exploring particle is q, then the force is

$$F = qE \tag{3.29}$$

where

F = the force on the particle (N)

E = the strength of the electric field (V/m).

Electric-field flux lines are visualized as issuing from positive electric charge and terminating on negative charge as shown in Figure 3.15.

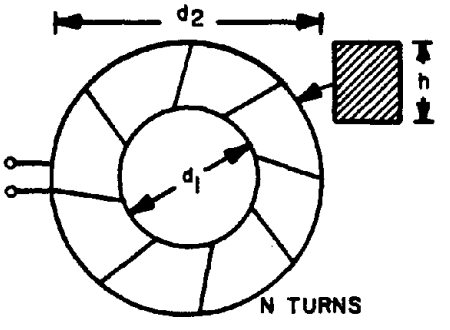


Figure 3.13. A Toroidal Coil.

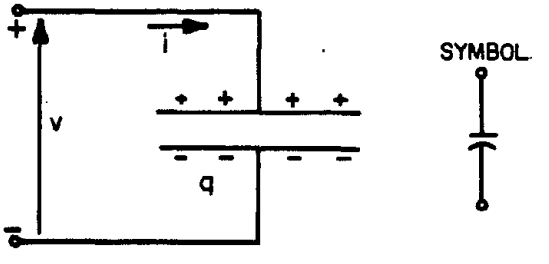


Figure 3.14. Charge, Voltage, and Current Relationships of a Capacitor.

Voltage or potential difference is by definition the integral of electric-field strength or

$$v = \int E \cdot ds . \tag{3.30}$$

A simple application of this concept can be demonstrated from Figure 3.15. If the electric field between the two parallel plates is constant, the voltage between the plates is

$$v = E \cdot s . \tag{3.31}$$

Assume that a positively charged particle, q, is released from the positive plate in Figure 3.15, the particle being within the electric field and free to move. If it moves, work is performed on it by the electric field. The amount of work can be found by employing the mechanical formula

$$w = F \cdot s \tag{3.32}$$

in which

w = the work done (J)

F = the force on the particle (N)

s = the distance the particle moves (m) .

Since

$$F = qE \tag{3.29}$$

work is

$$w = qE \cdot s \tag{3.33}$$

but

$$v = E \cdot s \tag{3.31}$$

so

$$w = qv. \tag{3.34}$$

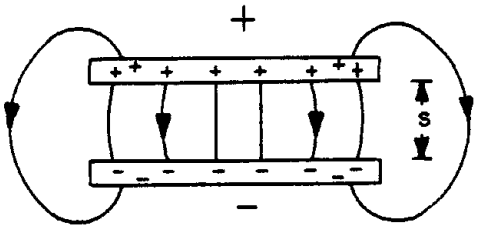


Figure 3.15. Electric Lines of Force Between Two Parallel Charged Plates.

Therefore, when electricity moves from one potential to another, the work done is equal to the product of the amount of electricity and the potential difference. In the next section, this concept is applied to a common electrical component.

Instantaneous Power. Consider the resistor shown in Figure 3.16. A charge, dq, is free to move in the resistor from the point "s" to "s + ds." It moves the distance, ds, in time, dt, and is impelled by the electric field in the region, E.

The electric field exerts a force on the charge, dq, while it moves through ds or,

$$F = dq \cdot E . \tag{3.35}$$

The work done in this section of the resistor during time, dt, can be expressed

$$dw = F \cdot ds = dqE \cdot ds. \tag{3.36a}$$

Power is work per unit time (in other words, the rate of doing work), or for this section of the resistor,

$$dp = \frac{dw}{dt} = \frac{dqE \cdot ds}{dt} \tag{3.36b}$$

where

p = power in watts (W).

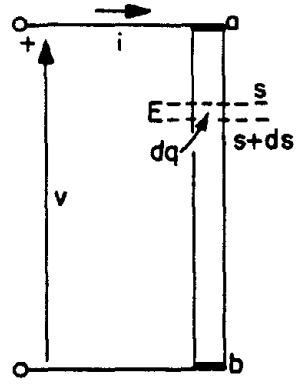


Figure 3.16. A Resistor Used to Demonstrate Instantaneous Power.

However, the current through the resistor is the rate at which charge flows ($i = dq/dt$); therefore,

$$dp = iE \cdot ds. \tag{3.37}$$

Current is constant throughout the resistor and not a function of distance, s. The potential difference across the region, ds, is

$$v = \int E \cdot ds, \tag{3.30}$$

and the power across the whole resistor, from a to b, is then

$$p = \int_a^b iE \cdot ds = i \int_a^b E \cdot ds = iv. \tag{3.38}$$

Formula 3.38 represents only instantaneous power consumed by the resistor, or the power occurring at only one instant in time. This is an extremely important formula as it forms the basis for most power relationships.

Idealization and Concentration. The foregoing has established the elementary laws and parameters that can be applied to investigate electrical circuits. Practical circuits found throughout a mine (or, in fact, anywhere else) are composed of wires, coils, and electrical devices in various complexities. Before these fundamentals can be employed, it is necessary to translate the practical world into an ideal and simple world. The translation is called "idealization" and is, in essence, the construction of a model. Here, electrical effects that create insignificant results are eliminated. For instance, two adjacent conductors in a coil always exhibit capacitance but the capacitance might be so

small that the stored charge is negligible. Yet, for many situations, the resistance and inductance must remain.

For every conductor or component in a circuit, resistance, capacitance, and inductance is distributed throughout the entire length or breadth of the portion. It would be much simpler to apply the preceding relationships if these circuit parameters were lumped or "concentrated" into separate circuit elements. For most circuit analysis needs, fortunately, these indeed can be consolidated.

To illustrate the most fundamental aspects of idealization and concentration, refer to Figure 3.17a, which shows a voltage generator connected to a coil of wire and a resistor in series. Figure 3.17b gives the translation. The distributed resistance and inductance of the coil have been lumped into R_L and L, its capacitance has been ignored (following the aforementioned reasoning). The resistance of the resistor and its lead wires has been concentrated into one value, R. Finally, the voltage generator is represented by an ideal voltage source and an internal series resistance. Of importance are the lines shown in Figure 3.17b; these serve only to connect components and exhibit no electrical properties or effects.

Another example can be expressed from Figure 3.18a. Here, a load center is shown connected to a shuttle car through a trailing cable. Again, Figure 3.18b gives the translation. The distributed resistance, inductance, and capacitance of the trailing cable have been represented by the lumped R_{tc}, L_{tc}, and C_{tc}. Such models can be developed for all portions of a mine distribution system. In this case, although the cable capacitance is rather small, it is shown here to emphasize that it may not always be negligible. The shuttle-car motor is depicted by the symbol shown (obviously, the same as a source, for reasons that will be given later); in a later chapter, motors will also be given resistance, inductance, and capacitance models.

After constructing the circuit representation, or "schematic" as it is most often called, the relationships covered previously in this chapter can be used to solve for currents and voltages within that circuit. A differential equation will usually result but, if the circuit contains only resistance, the only necessary expression is Ohm's law. Such is the case for most d-c circuit analysis.

3.5 Direct-Current Circuits.

Current. As already covered, electrical current consists of the motion of electrical charges in a definite direction. The direction and magnitude of current can vary with time and accordingly, all currents can be classified into one of three basic types:

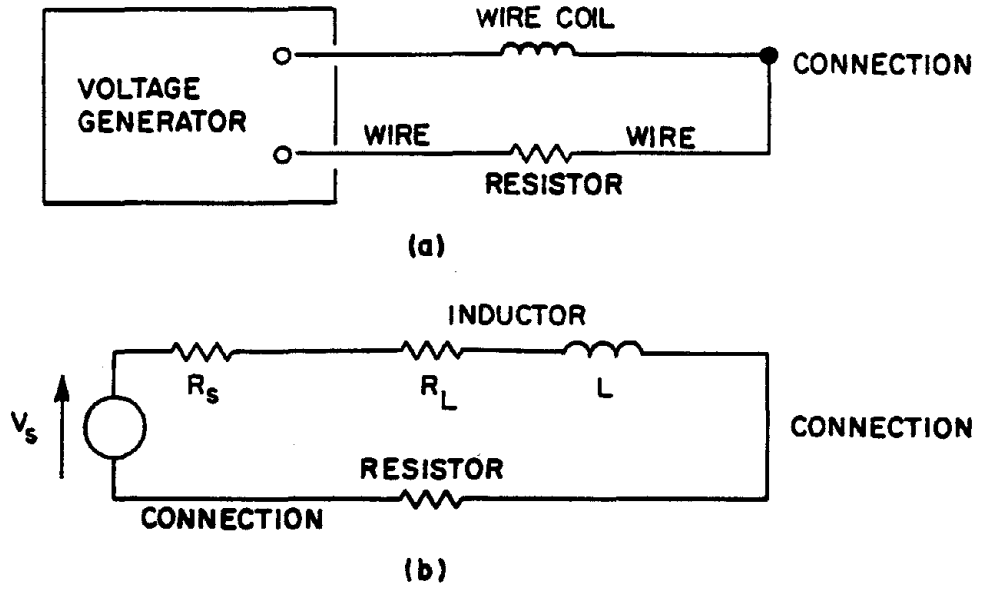


Figure 3.17. A Simple Example of Idealization and Concentration.

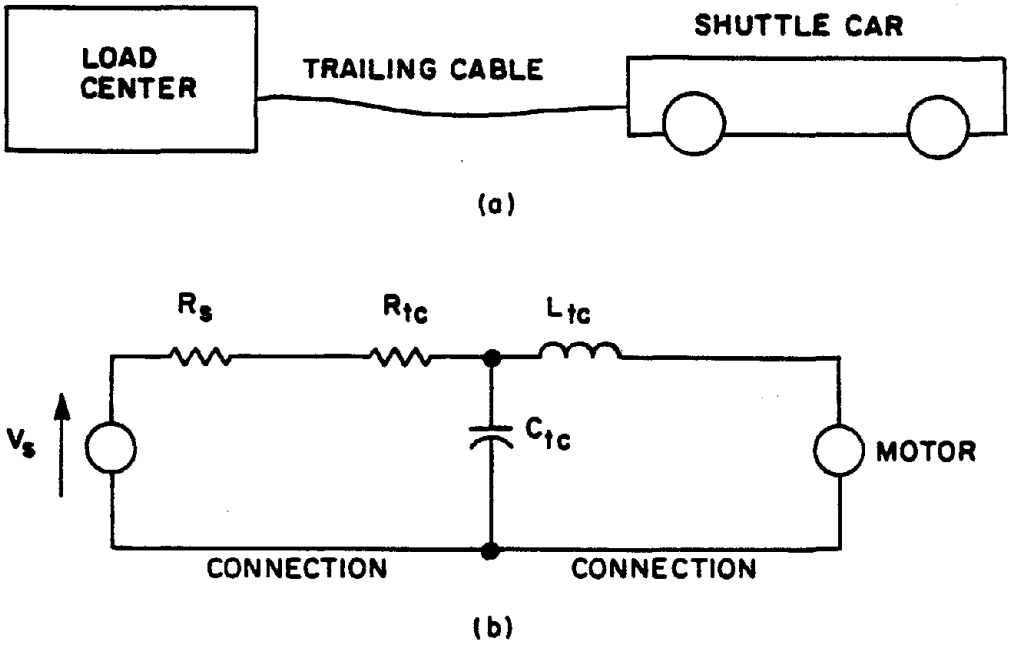


Figure 3.18. Modeling of a Load Center, Trailing Cable, and Shuttle Car.

1. direct current (d-c),
2. alternating current (a-c) or sinusoidal current, and
3. time-varying current.

Although a description was given in Chapter 2, a rigorous definition of direct current is "a continuous flow of electricity (electrical charge) in one direction at a steady-value." In other words, voltage, V, and current, I, have uniform values. Beyond this, the term direct current is also applied to ordinary (or practical) currents that are approximately steady.

This section will explore the analysis of d-c circuits. The importance of such knowledge should already be obvious to the reader because of the extensive mining use for haulage. Direct current is also the most used form of power to drive electronic components. The study of d-c analysis, at this time, allows the application and extension of the fundamental electrical laws and parameters without having the effort clouded by complex-current relationships. The following chapter sections will therefore cover time-varying and sinusoidal currents to further examine electrical-circuit phenomena.

Direct Current and Circuit Elements. Figure 3.19 gives the basic elements of resistance, inductance, and capacitance, each having a voltage and current as shown. By examining the effect of d-c on these, a powerful simplification of complex circuits can be understood. For the resistor, as before, the voltage-current relationship is Ohm's law:

$$V_R = IR \tag{3.39}$$

For the inductor, the voltage across the element is:

$$V_L = L\frac{dI}{dt}$$

but, because I does not change,

$$\frac{dI}{dt} = 0$$

and

$$V_L = 0. \tag{3.40}$$

Likewise for the capacitor, the current through the element is

$$I_C = \frac{dV}{dt}$$

but again,

$$\frac{dV}{dt} = 0$$

$$I_C = 0. \qquad (3.41)$$

Therefore, inductance and capacitance phenomena are not present under pure direct current. In other words, the capacitor appears as an open circuit, while an inductor resembles a conductor showing only resistance. An example of this simplification is available in Figure 3.20. The left-hand circuit shows all circuit elements but, under d-c, the effective circuit is given on the right. The result is a simple series-resistance arrangement, and the only voltage-current relationship necessary for analysis is again Ohm's law.

Series and Parallel Resistance. The expressions to find the equivalent resistance of parallel or series resistances are as before: for series,

$$R_e = R_1 + R_2 + R_3 + \ldots\ldots + R_n$$

for parallel,

$$\frac{1}{R_e} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \ldots\ldots\ldots + \frac{1}{R_n}$$

using Ohm's law,

$$V = IR_e = I(R_L + R_1)$$

or

$$I = \frac{V}{R_e} = \frac{V}{R_L + R_1}.$$

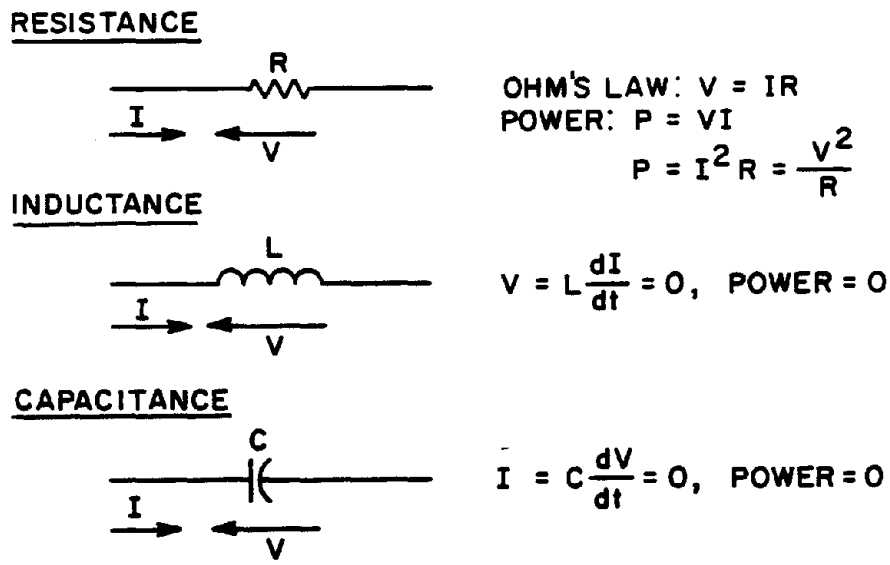


Figure 3.19. Basic Elements of Resistance, Inductance, and Capacitance.

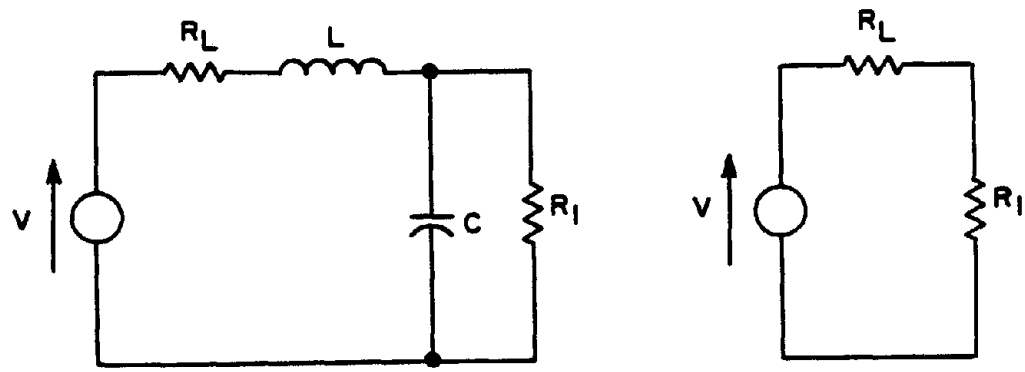


Figure 3.20. Simplification of a Direct-Current Circuit.

Hence, the current through or the voltage across the circuit can be found. By employing the previously given formulas, the voltage-current relationships for each circuit part can be determined.

This concept can be elaborated considering Figure 3.21, which shows a "series-parallel circuit" where an element of the circuit may be in parallel or series with other elements. Arrangements such as this can be solved first by combining all parallel portions. The objective is to gradually reduce the circuit to an equivalent series arrangement. The series circuit can then be replaced by a single equivalent resistance. For instance, the circuit in Figure 3.21a can be changed to Figure 3.21b, noting for the parallel combination:

$$\frac{1}{R_2'} = \frac{1}{R_2} + \frac{1}{R_3} \text{ or } R_2' = \frac{R_2 R_3}{R_2 + R_3}.$$

Figure 3.21b is then reduced to 3.21c for the series combination:

$$R_e = R_1 + R_2' = R_1 + \frac{R_2 R_3}{R_2 + R_3}.$$

Afterwards, if V is known,

$$I_1 = \frac{V}{R_e}.$$

Further, the current and voltage distributions can be determined by

$$I_2 = I_1\left(\frac{R_2'}{R_2}\right) \text{ and } I_3 = I_1\left(\frac{R_2'}{R_3}\right)$$

$$V_1 = \left(\frac{R_1}{R_e}\right)V \quad \text{and} \quad V_2 = \left(\frac{R_2'}{R_e}\right)V$$

or

$$V_1 = R_1 I_1 \quad \text{and } V_2 = R_2' I_1.$$

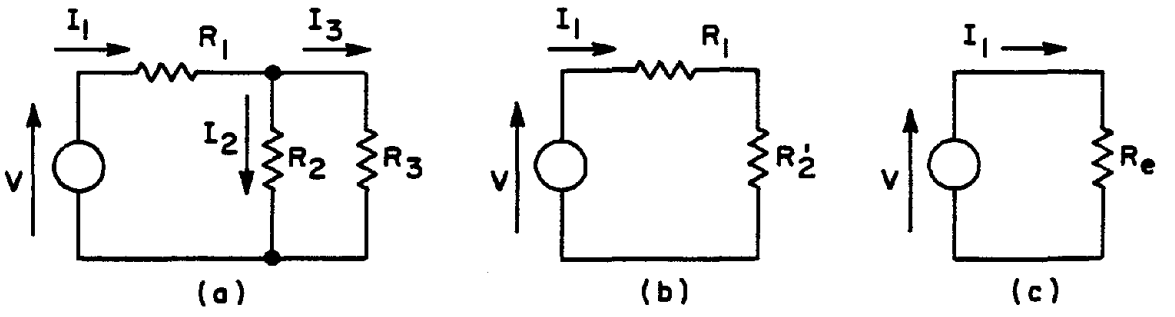


Figure 3.21. Simple Circuit Reduction.

Therefore, all voltages and currents in Figure 3.21 can be found. In summary, the main process used is the substitution of a single resistance for several series-parallel resistances. In concept, the same terminal resistance (R_e) implies equivalence and results in identical current and voltage delivered from the source. This process of solution is formally known as "circuit reduction."

The power consumed by all or part of the circuit can be found by applying equation 3.38:

$$P = VI \tag{3.42}$$

Noting Ohm's law, V = IR, two other convenient power expressions are

$$P = (IR)I = I^2R \tag{3.43}$$

and

$$P = V\left(\frac{V}{R}\right) = \frac{V^2}{R}. \tag{3.44}$$

These three expressions can be used to find the power loss ("I^2R loss") due to conductor resistance before current is delivered to a load, as well as the power used by that load.

Wye-Delta Transformations. Any of the circuits now covered can be reduced to a "two-terminal network," simply a network with two terminals as provided in Figure 3.22a. The circuit receives power from an external source and can contain resistance,

inductance, and capacitance. Such networks are called "passive." For d-c, resistance is only of interest and can be found knowing the terminal voltage and current by

$$R = \frac{V}{I}.$$

Numerous circuits can be represented by a two-terminal arrangement. Many circuits cannot, including a great number in mine power systems; however, several of these can be resolved into the "three-terminal network" given in Figure 3.22b. Even though with three terminals there now exist three voltages and three currents, the concept of circuit equivalence still holds (i.e., voltages and currents are identical, the circuits are equivalent).

For three-terminal networks, there are two basic-circuit configurations: the "wye" (Y, sometimes called a "star," but wye is standard) and the "delta" (Δ). These are shown in Figure 3.23. It is sometimes advantageous to replace or substitute three wye-connected resistances with another set delta-connected or vice versa.

By using equivalence of input currents and voltages for wye and delta circuits, "delta-wye (or delta to wye)" and "wye-delta transformations" can be derived. Thus, for equivalence of Figure 3.23a and b,

$$R_{ab} = \frac{R_a R_b + R_b R_c + R_c R_a}{R_c} \qquad (3.45)$$

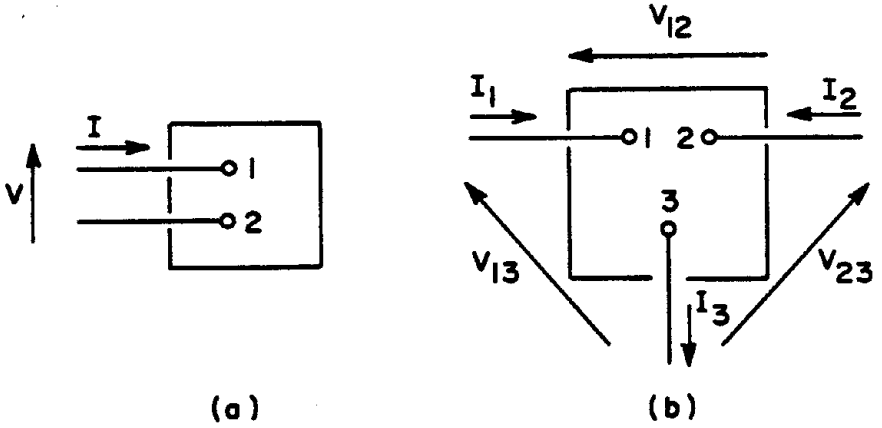


Figure 3.22. Two- and Three-terminal Networks.

$$R_{bc} = \frac{R_a R_b + R_b R_c + R_c R_a}{R_a} \tag{3.46}$$

$$R_{ca} = \frac{R_a R_b + R_b R_c + R_c R_a}{R_b}. \tag{3.47}$$

In other words, the delta is equivalent to the wye if the resistances of the delta are related to the wye by equations 3.45, 3.46, and 3.47. Accordingly with three-terminals, a,b,c, containing wye-connected, R_a, R_b, R_c, the circuit performance is uneffected by replacing them with a delta-connected R_{ab}, R_{bc}, R_{ca}. Likewise, for equivalence of delta-to-wye sets,

$$R_a = \frac{R_{ab} R_{ac}}{R_{ab} + R_{bc} + R_{ca}} \tag{3.48}$$

$$R_b = \frac{R_{ab} R_{bc}}{R_{ab} + R_{bc} + R_{ac}} \tag{3.49}$$

$$R_c = \frac{R_{ac} R_{bc}}{R_{ab} + R_{bc} + R_{ac}} . \tag{3.50}$$

These transformations are useful in allowing three-terminal circuit reduction; they allow substitution when a network does not contain either series or parallel elements. The circuit or circuit portion may not outwardly appear as three-terminal, and perhaps the two most often found examples are given in Figure 3.24, the "π" and the "T". These are actually delta and wye circuits drawn in a slightly different fashion.

It will be shown in Chapter 4 that delta and wye circuits are the two most important configurations for power systems. These transformations will be called upon there.

It has already been shown that when circuit elements are not all in series or all in parallel, but present some series and parallel arrangement, the elements can be handled in groups to reduce the circuit to an equivalent resistance. This important kind of circuit analysis has been called circuit reduction. Now that delta-wye and wye-delta transformations have been introduced, the substitution process can be employed to solve networks that contain elements neither in series nor parallel. A prime example is the common "bridge circuit" shown in Figure 3.25. The bridge

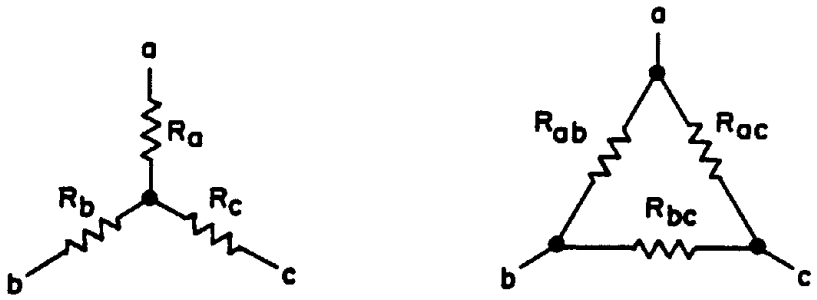


Figure 3.23. Wye and Delta Circuit Configurations.

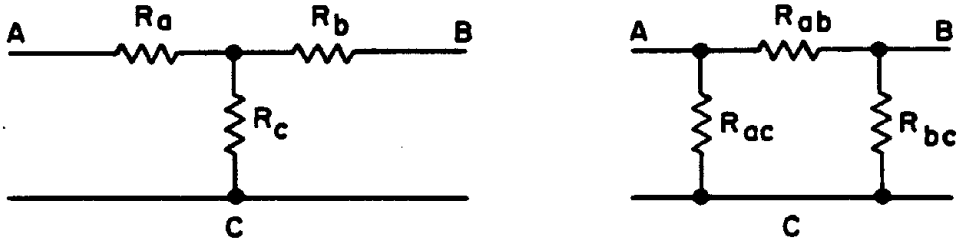


Figure 3.24. "T" and "π" Circuit Configurations.

is one of the most used configurations in electrical instrumentation. The objective is to find all available currents and voltage-drops in the network, and an overall solution approach is illustrated in Figure 3.26.

Through a delta-wye transformation, the elements connected to points a,b,c in the original circuit are converted to a wye configuration. The result gives the simple series-parallel arrangement in Figure 3.26b. This is then reduced, as before, to the series circuit in Figure 3.26c which can be easily combined into one equivalent resistance. After total circuit current is solved using Ohm's law, Kirchhoff's current and voltage laws, and the voltage and current distribution formulas can be employed to find currents through the voltage drops across each circuit element.

A large amount of circuit analysis can be handled by circuit reduction but as circuits become more complex this process becomes cumbersome. There are solution approaches that are more systematic and the next two sections provide two of these. Regardless, circuit reduction should always be used when it produces results more easily than when other methods are employed.

Circuit Equations. Before more general solution methods can be identified, the meaning of some words need to be made more clear. A "node" is the position or point in a circuit where two or more elements are connected. When three or more elements extend from a node, the node is called a "junction." A "branch" is a circuit portion existing between two junctions and may contain one element or several in series. A "loop" also called a "mesh" is a single closed path for current. Figure 3.27 illustrates all these circuit parts.

Only Ohm's law and Kirchhoff's current and voltage laws form the basis for the following techniques. The analysis principle will produce "n" simultaneous equations. Therefore, it must be remembered that the solution of "n" unknowns requires "n" independent equations. Importantly, it is always possible to write as many equations as there are unknowns. For loop equations, the unknowns are currents, and the method will use Kirchhoff's voltage law; for node equations, voltages are unknown, and Kirchhoff's current law will be employed to find them.

Loop Equations. In loop analysis, it is only necessary to determine as many different currents as there are independent loops (i.e., equations are constructed by defining independent loop currents). For example, consider Figure 3.28. The current, I_1, flowing out of source, V_1, and through R_a will be around loop 1. The current flowing from source, V_2, and through R_c will be around loop 2. Although not essential, these directions follow the general convention of assigning all reference loops clockwise. Other directions can be taken, for instance, with currents flowing out of a source positive terminal, but it is imperative that after

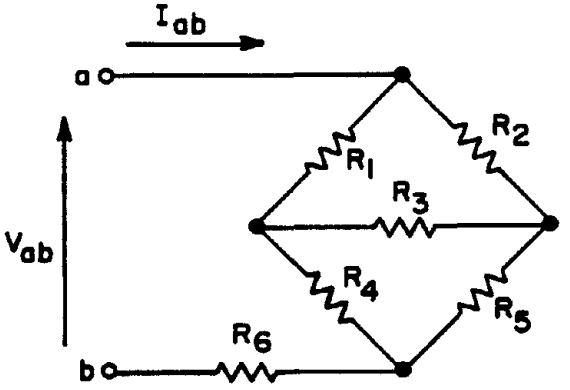


Figure 3.25. The Common Bridge Circuit.

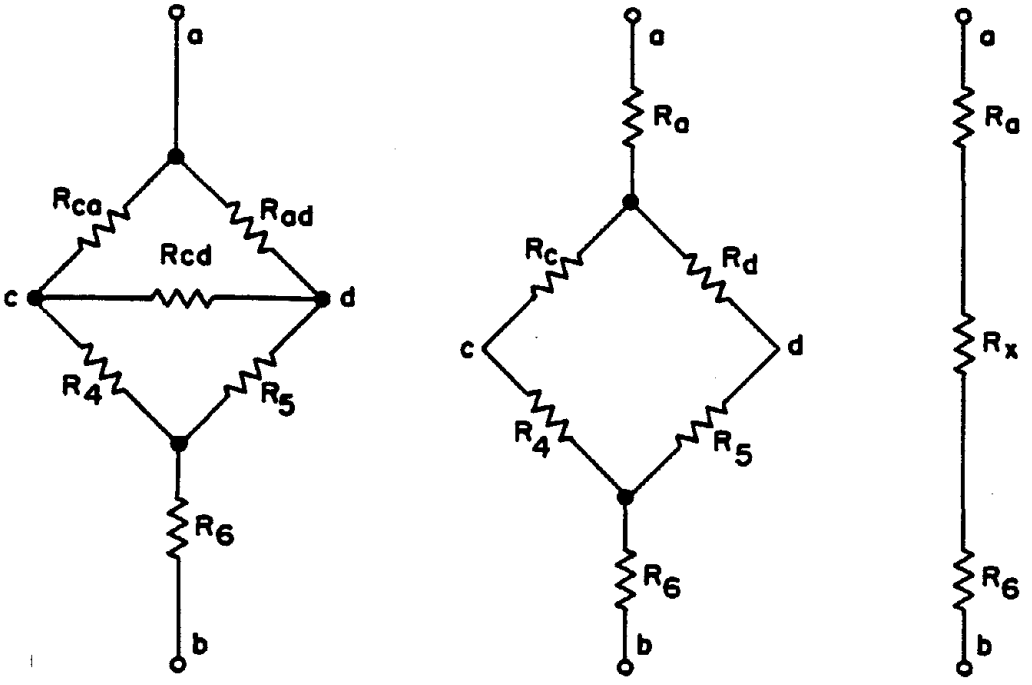


Figure 3.26. Circuit Reduction of a Bridge Circuit.

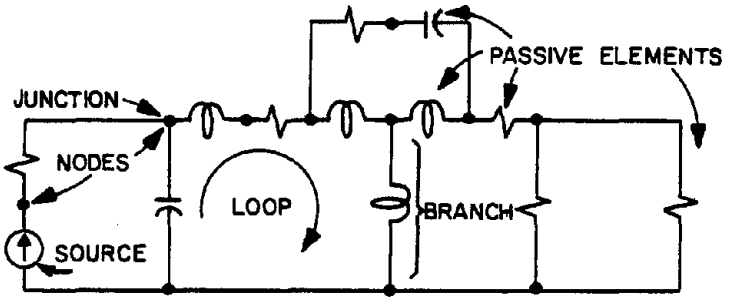


Figure 3.27. Circuit Illustrating the Definition of Parts.

the loop is assigned, the use of currents within a specific loop remain consistent.

Notice in Figure 3.28 that both I_1 and I_2 flow through R_b. Depending on the loop direction (i.e., the direction defined by I_1 or I_2), the total current through R_b is either I_1-I_2 or I_2-I_1. Thus, if I_1 and I_2 can be found, the current through each circuit element can be determined.

The first task in loop analysis is to use Kirchhoff's voltage law to write equations about each current loop, stating that the sum of voltages about each loop equals zero. For loop 1,

$$0 = -V_1 + R_aI_1 + R_b(I_1-I_2). \tag{3.51}$$

Notice that R_aI_1 equals the voltage drop across R_a and $R_b(I_1-I_2)$ is across R_b. In the latter case, the voltage can be taken as $R_bI_1-R_bI_2$, considering that the voltage produced by I_2 opposes that produced by I_1. Likewise, for loop 2,

$$0 = -V_2 + R_cI_2 + R_b(I_2-I_1). \tag{3.52}$$

By rearranging equations 3.51 and 3.52,

$$(R_a + R_b)I_1 - R_bI_2 = V_1 \tag{3.53}$$

$$-R_bI_1 + (R_b + R_c)I_2 = V_2, \tag{3.54}$$

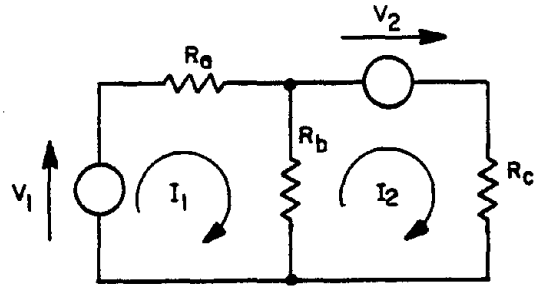


Figure 3.28. Circuit Demonstrating Two Independent Loops.

which are two simultaneous equations with two unknowns, I_1 and I_2. These can be solved easily by simultaneous methods.

It should be noted that one additional loop equation could be written, that for the loop containing both V_1 and V_2. However, this will not provide another independent equation. Information concerning the maximum number of independent equations available will follow shortly.

To further enforce the concept of loop analysis, again consider the common bridge circuit redrawn in Figure 3.29 to include current loops. There now exists three possible independent loops; therefore, three loop equations can be written. For loop 1,

$$R_1(I_1 - I_2) + R_4(I_1 - I_3) + R_6I_1 - V_{ab} = 0 \qquad (3.55)$$

for loop 2,

$$R_1(I_2 - I_1) + R_2I_2 + R_3(I_2 - I_3) = 0 \qquad (3.56)$$

and loop 3,

$$R_4(I_3 - I_1) + R_3(I_3 - I_2) + R_5I_3 = 0. \qquad (3.57)$$

Again, rearranging,

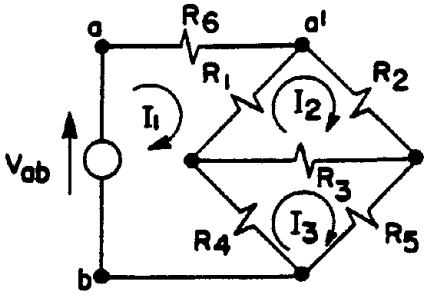


Figure 3.29. A Bridge Circuit Demonstrating Loop Analysis.

$$(R_1 + R_4 + R_6)\ I_1 - R_1 I_2 - R_4 I_3 = V_{ab} \qquad (3.58)$$

$$-R_1 I_1 + (R_1 + R_2 + R_3) I_2 - R_3 I_3 = 0 \qquad (3.59)$$

$$-R_4 I_1 - R_3 I_2 + (R_3 + R_4 + R_5) I_3 = 0 \qquad (3.60)$$

which are three simultaneous equations with three unknowns, I_1, I_2, and I_3. The proper combination of these currents will yield the current through each branch of the circuit. The process, again, was to employ Kirchhoff's voltage law with the purpose of finding unknown currents.

Equations 3.58 through 3.60 are not a unique set, as other loops about the bridge will produce the same valid results. Generally, a particular choice of loops can enhance a desired result; for instance, if only the current through R_3 of Figure 3.29 is desired, establishing only one loop current through that resistance would create a more direct solution.

As circuits become more complex and the number of possible loops increase, a method of determining the number of required equations is useful. By counting the number of branches and junctions in the circuit, the following expression provides the necessary number of loop currents:

number of equations = branches - (junctions - 1).

For Figure 3.29, there are six branches and four junctions (following the preceding definitions); therefore, the number of equations needed equals 6 - (4-1) = 3, as has been shown with equations 3.58, 3.59, and 3.60.

Node Equations. In the preceding, Kirchhoff's voltage law established the method of loop equations. Kirchhoff's current law did not receive any attention, yet it was satisfied. Such can be demonstrated with Figure 3.29 by taking any junction and summing the currents through it. For junction a', considering the currents through R_1 and R_2 flow from the point,

$$I_1 - I_{R1} - I_{R2} = 0$$

or

$$I_1 - (I_1 - I_2) - I_2 = 0$$

hence,

$$I_1 - I_1 + I_2 - I_2 = 0.$$

In node analysis, Kirchhoff's current law is used directly and the unknowns are voltages across branches.

The technique by which these voltages are referenced or measured provides a simplifying procedure to a circuit being analyzed. Each junction or "principal node" in a circuit is assigned a number or letter. Voltages then can be measured from each junction to one specific junction, called the "reference node." In essence, the reference node is dependent on all other nodes in the circuit. Node analysis consists of finding the voltages from each junction to the reference node.

The procedure can be demonstrated easily with the simple two-node circuit shown in Figure 3.30. I_a, R_b, and R_c are known. The existing junctions are A and 0, and 0 is taken as reference. The voltage of A to 0 is then V_{A0}, and Kirchhoff's current law is used to write an equation for point A:

$$I_a - I_b - I_c = 0 . \qquad (3.61a)$$

By Ohm's law,

$$V_{AO} = I_b R_b$$

$$V_{AO} = I_c R_c.$$

Therefore,

$$I_a - \frac{V_{AO}}{R_b} - \frac{V_{AO}}{R_c} = 0 \qquad (3.61b)$$

since, $1/R = G$,

$$I_a - V_{AO}G_b - V_{AO}G_c = 0. \qquad (3.62)$$

Equation 3.63 can be further solved for the unknown, V_{AO}.

During the process, an equation was written for each junction, excluding the reference node. In general, for node analysis, the number of required equations is therefore always one less that the number of junctions in a circuit.

To further illustrate node analysis, consider Figure 3.31, a three-junction circuit. If junction 0 is taken as the reference node, V_{AO} and V_{BO} are the unknown voltages. The reference node, which establishes a reference potential across the bottom of the circuit, is normally assumed at zero potential. Accordingly, the double-subscripted voltages are unnecessary, and unknown values can be simply called V_A and V_B. Further, as zero potential is often referenced to earth or "ground," a most convenient reference, Figure 3.31 can be redrawn as shown in Figure 3.32. Here, where each element was connected to the reference node, a "ground" symbol is shown; hence, each of these circuit elements is "grounded."

Now, applying Kirchhoff's current law to junctions A and B,

$$I_a - I_c - I_b = 0 \qquad (3.63a)$$

$$-I_e - I_d + I_c = 0. \qquad (3.63b)$$

By Ohm's law, $I_b = V_A G_b$, $I_d = V_B G_d$, and

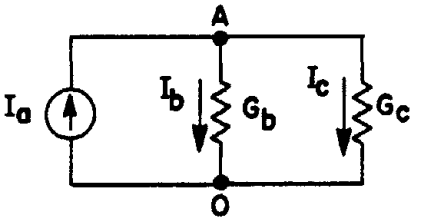


Figure 3.30. A Simple Two-Node Circuit.

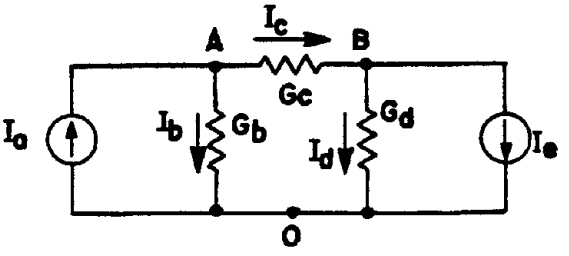


Figure 3.31. A Three-Junction Circuit.

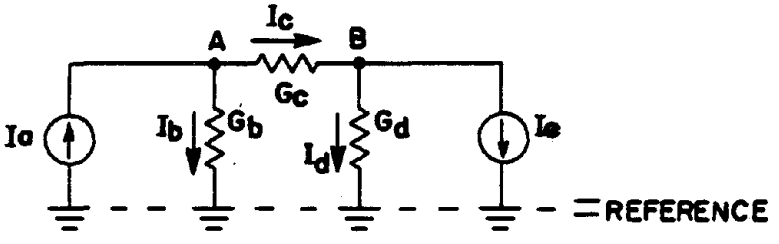


Figure 3.32. A Three-Junction Circuit with Grounds.

$$I_c = (V_A - V_B)G_c. \tag{3.64}$$

The last expression is evident because, by Kirchhoff's voltage law, the voltage across G_c is the potential at junction A minus that at junction B. Therefore,

$$I_a - (V_A - V_B)G_c - V_A G_b = 0 \tag{3.65}$$

$$-I_e - V_B G_d + (V_A - V_B)G_C = 0 \tag{3.66}$$

or

$$(G_b + G_c)V_A - G_c V_B = I_a \tag{3.67}$$

$$-G_c V_A + (G_c + G_d)V_B = -I_e, \tag{3.68}$$

which are two simultaneous equations with unknowns, V_A and V_B.

The same procedure can be applied to circuits with more nodes, but the foregoing examples have shown only current sources that are known. Node analysis can also be used with voltage sources or known voltages; such is the case with Figure 3.33. For instance, the current through G_a,

$$I_a = (V_A - V_B)G_a$$

likewise,

$$I_c = (V_C - V_B)G_c.$$

The analysis procedure then continues as before. Mixed voltage and current sources can be handled in much the same manner, realizing that the current source establishes the current through the branch in which it is contained.

With both loop and node analysis available, a decision must be made to which technique best suits the solution of a circuit. Simply, the one to select is that providing the fewest equations to finally resolve. Importantly, circuit reduction may still lead

to the most efficient procedure for some circuits and, therefore, it should always be considered.

Network Theorems. Practically any circuit can be analyzed using either circuit reduction, loop equations, or node equations. In addition, there are several theorems that may allow simplification of certain circuits so one of these three methods can be applied more easily, just as delta-wye transformations assisted in circuit reduction. The most commonly used theorems with the same basic purpose are:

1. Substitution,
2. Superposition,
3. Reciprocity,
4. Source Transformation,
5. Maximum Power Transfer,
6. Thévenin's, and
7. Norton's.

The first, "Substitution," has been extensively used already in the circuit-reduction report segment and simply states that "equivalent circuits produce equivalent results." The following paragraphs entertain the rest.

Superposition. The "Superposition Theorem" relates that "for a linear, bilateral network with two or more electromotive sources (voltage or current), the response in any element of the circuit is equal to the sum of responses obtained by each source acting separately with all other sources set equal to zero." Although the word "bilateral" is new, it does not create problems in d-c analysis since circuits under d-c are all essentially bilateral. This property will be further defined later.

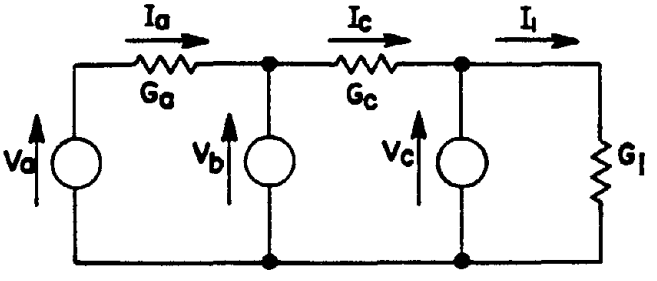


Figure 3.33. A Voltage-Source Circuit Demonstrating Node Analysis.

The meaning of this theorem can be illustrated using Figure 3.34a, a network with two voltage sources. Superposition relates that:

1. first one source is set equal to zero (i.e., by removing it from the circuit), and the currents produced by the other source are found;
2. then the second source is set equal to zero, and currents caused by the first source are found;
3. by summing both findings, the results are the currents with both sources operating.

In other words, by letting $V_2 = 0$ as in Figure 3.34b, through circuit reduction,

$$R_{e1} = R_1 + \frac{R_2 R_3}{R_2 + R_3}$$

$$I_{1(1)} = \frac{V_1}{R_{e1}}$$

$$I_{3(1)} = \left(\frac{R_2}{R_2 + R_3}\right) I_{1(1)}$$

$$I_{2(1)} = -\left(\frac{R_3}{R_2 + R_3}\right) I_{1(1)}.$$

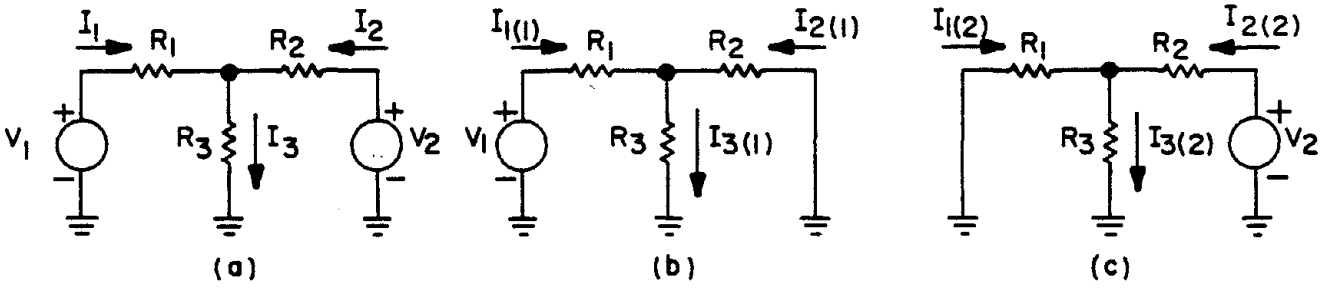


Figure 3.34. Circuit for Superposition Theorem Demonstration.

The second part of the double subscripts are used only to signify that the currents are owing to Source 1. The negative sign in the last expression above is because of the assumed current direction in the illustration. Next step is letting $V_1 = 0$, restoring V_2 (see Figure 3.34c),

$$R_{e2} = R_2 + \frac{R_1 R_3}{R_1 + R_3}$$

$$I_{2(2)} = \frac{V_2}{R_{e2}}$$

$$I_{3(2)} = \left(\frac{R_1}{R_1 + R_3}\right) I_{2(2)}$$

$$I_{1(2)} = -\left(\frac{R_3}{R_1 + R_3}\right) I_{2(2)}$$

Finally, the sums of steps 1 and 2 yield

$$I_1 = I_{1(1)} + I_{1(2)} \tag{3.69}$$

$$I_2 = I_{2(1)} + I_{2(2)} \tag{3.70}$$

$$I_3 = I_{3(1)} + I_{3(2)} \tag{3.71}$$

which are the currents with both sources in operation as in Figure 3.34a. The process is adaptable (and perhaps more useful) with circuits having more than two voltage or current sources. As in node analysis, with current sources, the unknowns in each step are voltages. Nevertheless, superposition allows considering many sources separately; thus, it is of great benefit in the analysis of circuits.

Reciprocity. The "Reciprocity Theorem" specifies that "in a linear, bilateral, passive circuit, if a single source in one branch produces a result in another branch, the same source in the other branch produces the same result in the first." Figure 3.35 demonstrates the concept. If V_1 produces I_1 in the branch

shown (Figure 3.35a), then moving V_1 to that branch produces I_2 (where V_1 originally was, see Figure 3.35b), the currents I_1 and I_2 are equal. Likewise, the dual form of Reciprocity relates a current source to the voltage produced. The great advantage gained from this theorem is that a source may be moved to a more convenient place for analysis.

Source Transformation and Maximum Power Transfer. Thévenin's, Norton's, Source Transformation, and Maximum Power Transfer theorems are coupled with two subjects covered earlier: ideal and practical sources. Before covering these theorems, definitions should be expanded.

An "ideal voltage source" has been described as a device whose terminal voltage is independent of the current through it. As no such device exists practically, a resistance is assumed in series with an ideal source to model a practical voltage source. Such is the case in Figure 3.36a, which could represent a 12-V automotive storage battery. As shown in Figure 3.36b, the internal resistance, R_v, compensates the output voltage, V_L, for varying load currents, I_L, drawn by changing the load, R_L. For small current, the practical source approximates an ideal one but, under heavy duty (i.e., high-current and low-load-resistance), the output voltage drops substantially. Using Ohm's and Kirchhoff's voltage laws,

$$V_L = \left(\frac{V_s}{R_v + R_L}\right) R_L \tag{3.72}$$

$$I_L = \frac{V_s}{R_v + R_L}. \tag{3.73}$$

V_s equals the voltage of the ideal source, which can be found by measuring the terminal voltage with no load resistance. The internal resistance, R_v, can be determined by applying a known R_L and measuring V_L.

Similarily, Figure 3.37 illustrates a model of a practical current source, where R_i is the internal shunt resistance as before. The graph illustrates this resistance's effect; as the load resistance increases, terminal current decreases. Now using Kirchhoff's current law, it can be shown that

$$V_L = \left(\frac{R_i R_L}{R_i + R_L}\right) I_s \tag{3.74}$$

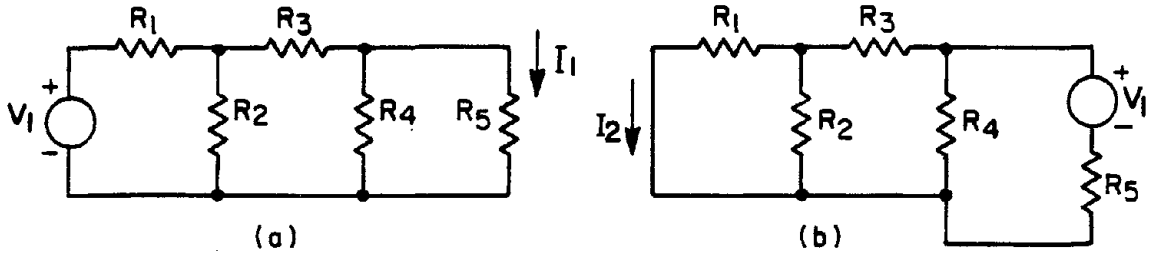


Figure 3.35. Demonstration of the Reciprocity Theorem.

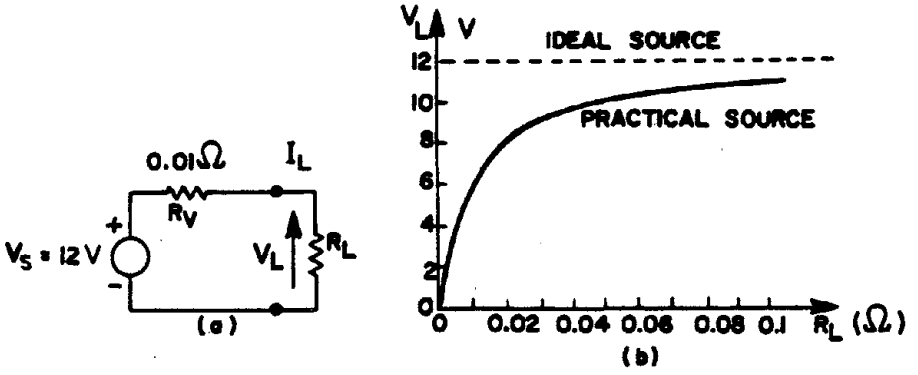


Figure 3.36. Practical Voltage-Source Model.

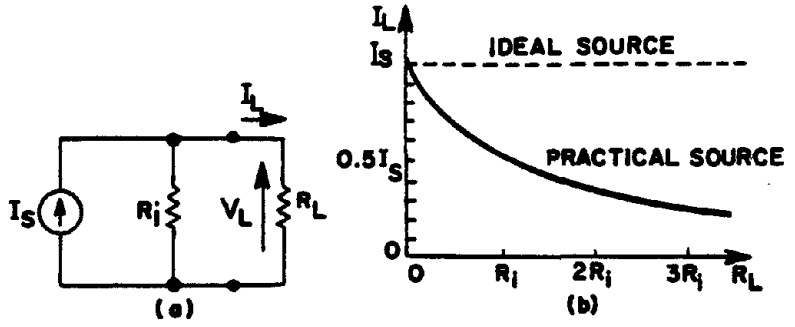


Figure 3.37. Practical Current-Source Model.

and

$$I_L = \left(\frac{R_L}{R_i + R_L}\right) I_s . \tag{3.75}$$

The output of the ideal current source, I_s, can be found by short-circuiting the output terminals and measuring the resulting current. Then, R_i can be calculated by measuring V_L and I_L with a known load, R_L. Shorting the terminals of a source is usually not wise, because it could damage the real-world source (not to mention being often an unsafe practice).

However, I_s can be determined through "Source Transformation," which uses the fact that "two sources are equivalent if each produces identical terminal voltage and current in any load." Therefore, for equivalence of practical voltage and practical current sources, equations 3.72 and 3.73 must equal 3.74 and 3.75, respectively (obviously, both sets are interrelated). In other words, for load current,

$$I_L = \frac{V_s}{R_v + R_L} = \frac{R_i I_s}{R_i + R_L} . \tag{3.76}$$

If equation 3.76 is valid for any load, R_L, it must hold that

$$R_v = R_i = R_s \tag{3.77}$$

$$V_s = R_s I_s \tag{3.78}$$

where

R_s = the internal resistance for either equivalent practical source

V_s = the output voltage of the ideal voltage source

I_s = the output current of the ideal current source.

This relationship is shown in Figure 3.38, and the two circuits shown will be named shortly. Source Transformation states that if one source is known, it can be replaced with the other. Note however, even if two practical sources are equivalent, the power which the two internal ideal sources supply and internal resistances absorb may be quite different. Notwithstanding, this substitution permits assistance in writing network equations.

Constant-current sources are more convenient for node equations, and constant-voltage sources for loop equations. In addition, the exchange of particular sources may permit direct circuit reduction.

Since load resistance can vary from zero to infinity, there must exist some value of resistance that will receive the maximum power that is available from a particular source. It can be proven, using the concepts just presented that "an independent voltage source in series with a resistance, R_s, or an independent current source in parallel with a resistance, R_s, delivers maximum power to a load resistance, R_L, when $R_L = R_s$." This is called the "Maximum Power Transfer" theorem.

Thévenin's and Norton's Theorems. Consider the active network (one that delivers power) with two output terminals as shown in Figure 3.39a. The internal configuration may be anything, but the elements must be linear. The internal sources can be either constant voltage or constant current.

When all internal sources are operating normally and no loads are connected, the voltage across the output terminals (open-circuit voltage) equals V_o. With all the ideal sources set to zero (short-circuited), a resistance, R_o, can be measured at the terminals.

"Thévenin's theorem" states that if such an active network is attached to any external network (Figure 3.39b), it will behave as if it were simply a single ideal-voltage source, V_o, in series with a single resistance, R_o (see Figure 3.39c). This specifies that the active circuit will appear as the foregoing practical voltage source.

The theorem is important because it relates that any linear circuit, where the internal components are unknown, can be considered as a constant voltage source in series with a resistance. Any circuit reduced to this form is called a "Thévenin Circuit."

The correlary to Thévenin's theorem is "Norton's theorem." Consider the same linear active network, this time shown in Figure 3.40a with an internal resistance as before but with internal sources operating normally, the output terminals are short-circuited, and a terminal current is measured. Norton relates that if such an active network is attached to any external network, it will behave as a single ideal current source, I_o, in parallel with a single resistance, R_o (Figure 3.39c, i.e., a practical current source).

Thévenin's and Norton's circuits are obviously related by Source Transformation and, if one is known, the other can be constructed. The equations relating the two are shown in Figure 3.41. These theorems are most often employed when a series of

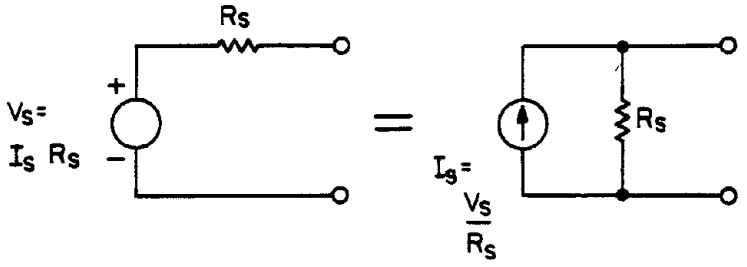


Figure 3.38. Source Transformation.

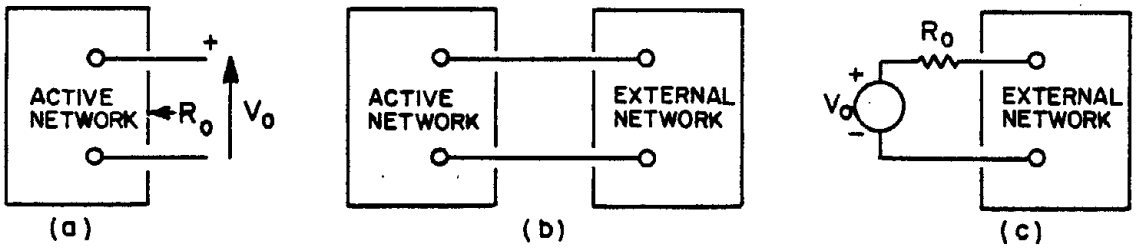


Figure 3.39. Thévenin's Theorem.

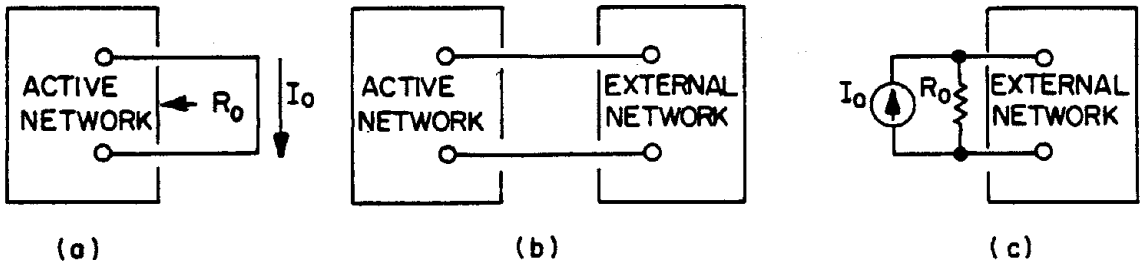


Figure 3.40. Norton's Theorem.

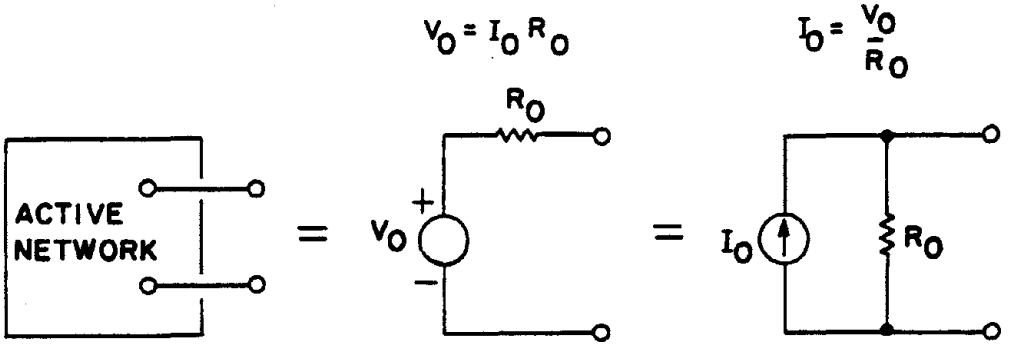


Figure 3.41. Comparison of Thévenin's and Norton's Circuits.

calculations involves changing one part of a network while another part is kept constant. This greatly helps simplify complex computations such as power system short-circuit currents.

Summary. This report segment started by applying the fundamental laws and parameters to circuits under the influence of d-c. Expanding upon these laws, several circuit-analysis techniques and theorems were covered. Because only d-c was considered, the circuit element of interest has been only resistance. As will be shown shortly, most of the foregoing is also valid for circuits acting under current forms other than d-c where, however, inductance plus capacitance may enter into the picture.

3.6. Time-Varying Voltages and Currents.

Forms. Time-varying voltages and currents are considered as the name implies: their magnitude may not be constant with time. As a consequence, the instantaneous value of the voltage and current waveform, v and i, must be considered (v and i are functions of time, as they were originally in this chapter). In general, their characteristics can take on any form from constant to the most complex; Figure 3.42 presents just a minor sampling time-varying waveforms to enhance their general nature.

As with d-c, the process of circuit analysis with time-varying current and voltage is to first form a model of the circuit then apply the fundamental laws and relationships. Unlike d-c circuits, a differential equation usually results. To illustrate the effect of time-varying and current on circuit elements, this section will first consider a special waveform, steady alternating-current (a-c). The importance of a-c to mine power systems has been presented in Chapter 2.

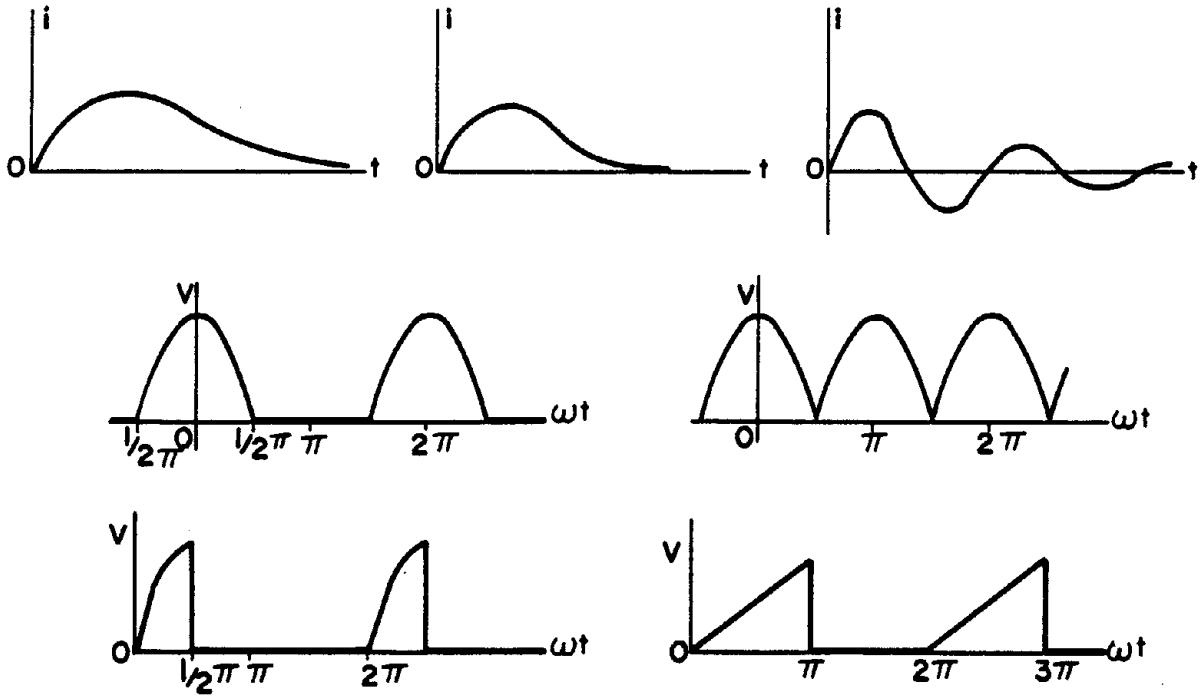


Figure 3.42. Some Time-Varying Electrical Waveforms.

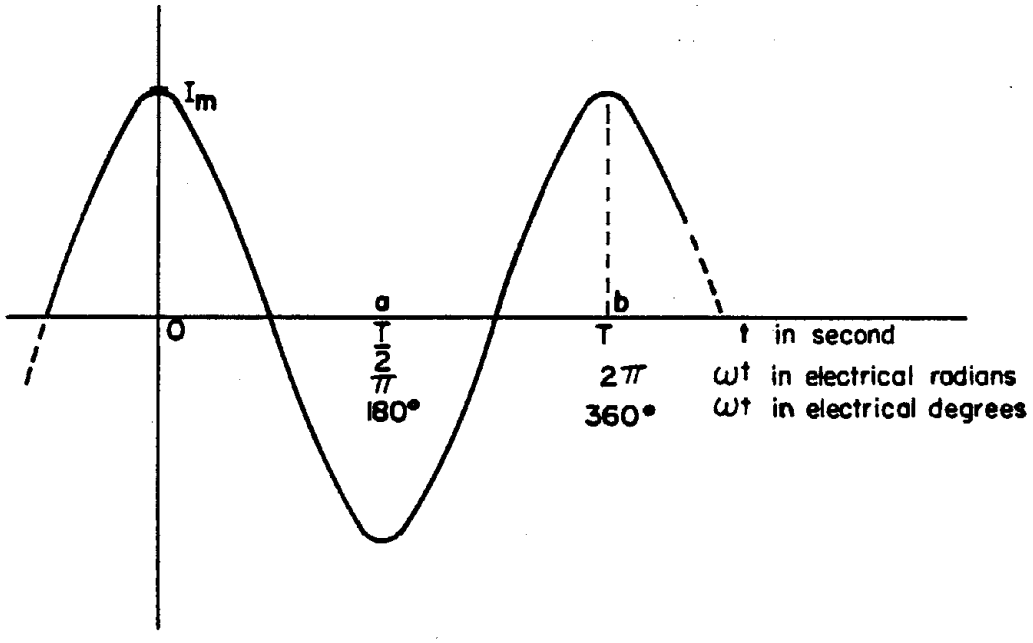


Figure 3.43. A Sinusoidal Alternating-Current Waveform.

Steady Alternating Current. A waveform example of steady (or sinusoidally) alternating current is provided in Figure 3.43. The repetitive nature of this sinusoidal function can be expressed mathematically as:

$$i = I_m \cos(\omega t) \tag{3.79}$$

in which

i = the current at any time, t (A)

I_m = the crest or maximum value of current, a constant, (A)

ω = the radian frequency (rad/s).

The term, "sinusoid," (or sine-wave) is used collectively to include cosinusoidal (or cosine-wave) expressions. The above equation could also use a sine function, but the cosine is employed for convenience when referring to current.

It can be noticed in Figure 3.43 and equation 3.79 that the instantaneous value of current repeats itself every 2π radians or 360° (i.e., the waveform goes through one complete "cycle" every 2π). From this, the number of repetitions per second is $\omega/2\pi$ which is defined as the "frequency," f, of the waveform or

$$f = \frac{\omega}{2\pi} \tag{3.80}$$

or

$$\omega = 2\pi f. \tag{3.81}$$

The units of frequency are hertz, abbreviated Hz (one hertz is equal to one cycle-per-second, cps, an expression whose use is obsolete). The common power frequency in the United States is 60 Hz, for which $\omega = 377$ rad/s (or just simply $\omega = 377$).

A more general form of a-c is

$$i = I_m \cos(\omega t + \theta) \tag{3.82}$$

where

θ = the "phase angle."

Instead of expressing the phase angle in radians (say, $\pi/6$), angular degrees (30°) are customarily used. By adjusting θ, the sinusoid can be moved left (increasing θ) or right (decreasing θ). Such movement is illustrated in Figure 3.44.

Using the earlier thought of differential equations resulting through circuit analysis, let's apply steady a-c to pure resistance, inductance, and capacitance to observe what happens.

Alternating Current Through Resistance. Figure 3.45a shows a resistor of resistance, R. If the current through this element is

$$i = I_m \cos(\omega t), \tag{3.79}$$

by Ohm's law, the voltage developed across the resistor is

$$v = Ri$$

or

$$v = R(I_m \cos(\omega t)) = V_m \cos(\omega t) \tag{3.83}$$

where

$V_m = RI_m$ = the maximum or crest value of the voltage waveform (V).

Figure 3.45b shows both voltage and current as functions of time. At every instant, v is proportional to i, and v and i are said to be "in phase." When two sinusoidal waves are compared in this manner (for phase), both must be sine waves or cosine waves; both must be expressed with positive amplitudes and have the same frequency.

Alternating Current Through Inductance. Suppose that current through the pure inductance of Figure 3.46a is again as in equation 3.79. The voltage across the element is

$$v = L\frac{di}{dt}$$

or

$$v = L\frac{d}{dt}(I_m \cos(\omega t))$$

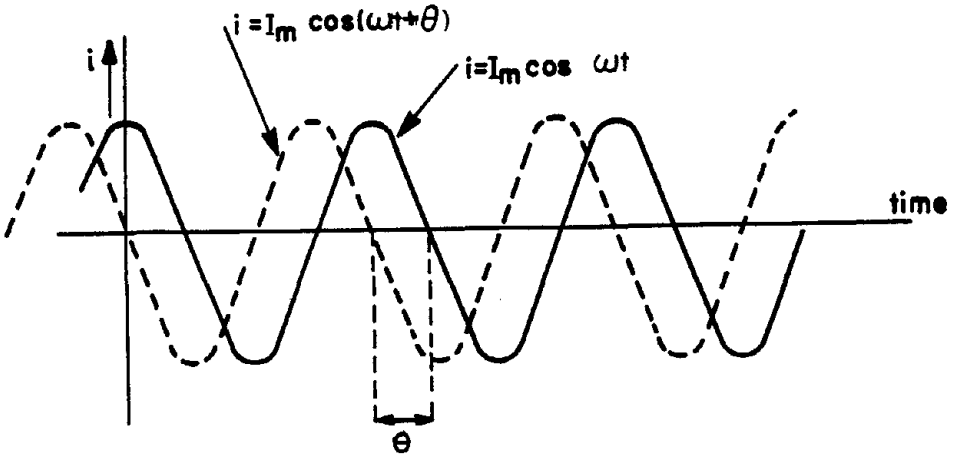


Figure 3.44. Steady Alternating-current Showing Phase Shift.

or

$$v = LI_m \frac{d\cos(\omega t)}{dt} .$$

Differentiating,

$$v = -\omega LI_m \sin(\omega t)$$

or

$$v = \omega LI_m \cos(\omega t + 90°) = V_m \cos(\omega t + 90°) \qquad (3.84)$$

where

$V_m = \omega LI_m$ = the maximum or crest voltage.

The term, ωL, is used so frequently that it is provided a special name "inductive reactance," and is designated "X," where

$$X = \omega L = 2\pi fL \qquad (3.85)$$

and

$$V_m = I_m X. \qquad (3.86)$$

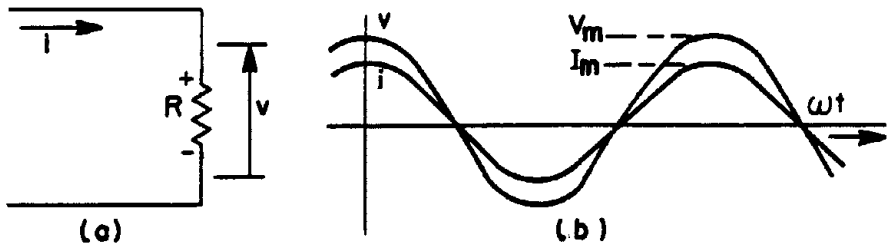


Figure 3.45. Steady Alternating Current Through Resistance.

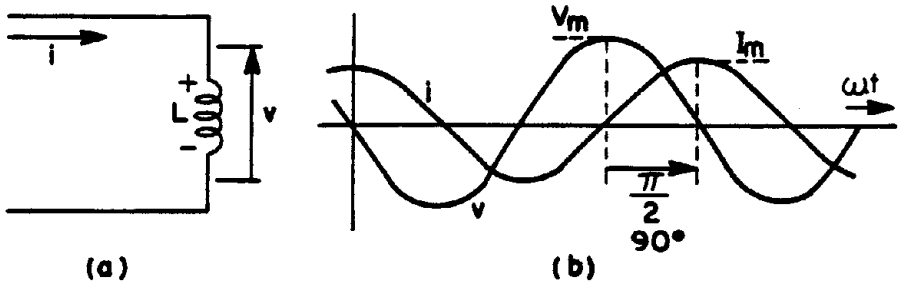


Figure 3.46. Steady Alternating Current Through Inductance.

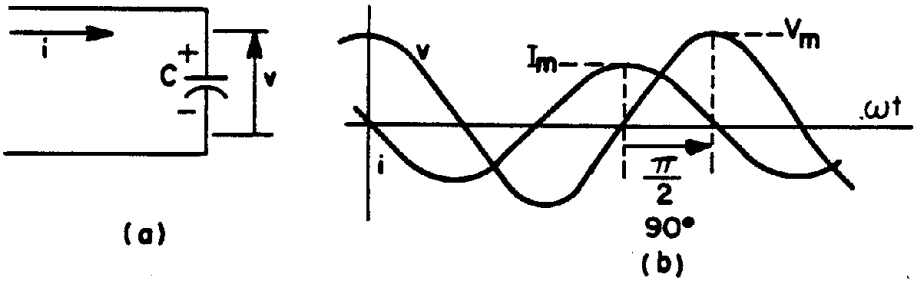


Figure 3.47. Steady Alternating Current Through Capacitance.

Figure 3.46b compares equations 3.79 and 3.84 (i and v as functions of time). It can be seen that the current crest is reached at a later time than the crest voltage. Here, the current waveform is said to "lag" the voltage waveform by 90°. The phase angle in this case (90°) is called "lagging."

Alternating Current Through Capacitance. Consider the capacitance shown in Figure 3.47a, and let the voltage across it be:

$$v = V_m \cos(\omega t). \tag{3.87}$$

The current through the capacitor is then

$$i = C\frac{dv}{dt}$$

or

$$i = C\frac{d}{dt}(V_m \cos(\omega t)).$$

Differentiating,

$$i = -\omega C V_m \sin(\omega t)$$

or

$$i = \omega C V_m \cos(\omega t + 90°) = I_m \cos(\omega t + 90°) \tag{3.88}$$

where

$I_m = \omega C V_m$ = the maximum or crest current through the capacitor.

As with the inductive reactance, ωC is also provided a special name, "capacitive susceptance," and symbol, "B." Thus,

$$B = \omega C = 2\pi f C \tag{3.89}$$

and

$$I_m = B V_m. \tag{3.90}$$

The current, voltage waveform relationship (see Figure 3.47b) is the reverse of the inductance situation; the current waveform is now "leading" the voltage waveform by 90°. Likewise, the phase angle is called leading.

The importance of current and voltage waveforms being compared for lagging and leading phase angles will be brought out later in the chapter.

Time-Varying Equations. The preceding development has considered voltage and current to be steady sinusoids, but what if they are allowed to have any form. To illustrate the consequence, the fundamental laws and parameters can be applied to the simple series RL, RC, and RLC circuits shown in Figures 3.48, 3.49, and 3.50, respectively.

For the series RL circuit, by Kirchhoff's voltage law,

$$v = v_R + v_L.$$

Substituting in the relationships for voltages across resistance and inductance,

$$v = iR + L\frac{di}{dt}. \tag{3.91}$$

Now for the series RC circuit,

$$v = v_R + v_C.$$

Applying the elementary laws,

$$v = iR + \frac{1}{C}\int_0^t idt + V_0. \tag{3.92}$$

The differential equations 3.91 and 3.92 are valid for any voltage and current, no matter what form. V_0, as before, is the initial charge on the capacitance.

Considering Figure 3.50, the series RLC combination,

$$v = v_R + v_L + v_C$$

thus,

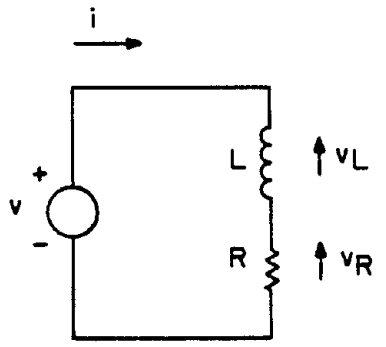


Figure 3.48. A Simple Series RL Circuit.

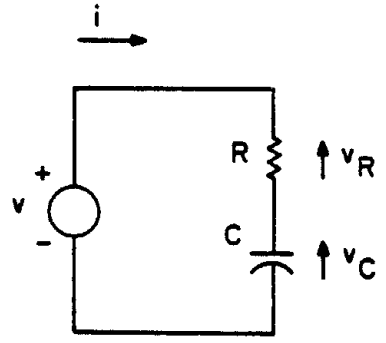


Figure 3.49. A Simple Series RC Circuit.

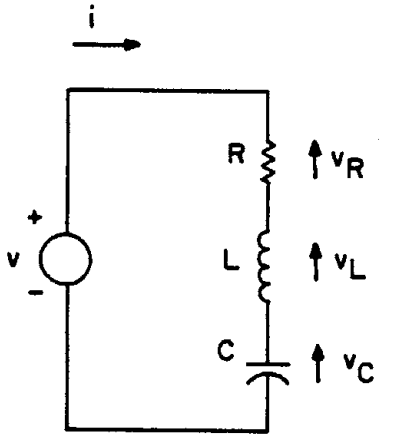


Figure 3.50. A Simple Series RLC Circuit.

$$v = iR + L\frac{di}{dt} + \frac{1}{C}\int_0^t idt + V_0. \qquad (3.93)$$

To arrive at an equation which is easier to handle mathematically, equation 3.93 can be differentiated once:

$$\frac{dv}{dt} = R\frac{di}{dt} + L\frac{d^2i}{dt^2} + \frac{i}{C} + 0. \qquad (3.94)$$

This equation again describes (or models) the circuit for all electrical situations, as no restrictions have been placed on voltage and current.

The preceding has shown that the application of circuit relationships, when voltages and currents represent any form, results in a differential equation. Through classical differential equation methods, such equations can provide a required solution. However, often the coverage of these techniques at this point can confuse the understanding of the vital aspects of electrical fundamental methods.

Transients and Circuit Response. Solutions of these equations for all situations yields the complete response of the circuit. For linear circuits, the solution will have two parts: forced response and natural response. The "forced (or steady-state) response" is attributed directly to the applied source (or "forcing function"). This is the action of voltage and current within the circuit if no changes or disturbances are made. The "natural (or transient) response" is a characteristic of the circuit only, not a result of the sources. Such action occurs when a circuit is disturbed by a change in the applied sources or in one of the circuit elements. After the change, circuit currents and voltages undergo transition from their original state to the point when their action is again steady-state. The time period involved is normally very short, and the occurrence within the transition is called a "transient."

For simplicity, the forcing functions earlier in this chapter were d-c, and in network analysis the study was devoted to resistive circuits and d-c sources. The reason was that in resistive circuits, only the forced response is present.

When inductance and capacitance are circuit elements, both forced and natural circuit responses can be encountered. Yet, when considering steady-state voltages and currents, knowledge of circuit transients is not required (such was the case earlier with steady a-c). Transient information, however, is an extremely important input to the design of mine power systems. Accordingly,

Chapter 10 is devoted to the subject. By far the majority of mine power problems, on the other hand, only require knowledge of the steady-state circuit currents and voltages. As will be shown, the solution of differential equations is not needed, even though inductance and capacitance might be present, as long as only steady-state response is considered.

It has been shown in this section that any resistor, inductor, or capacitor carrying a sinusoidal current has a sinusoidal voltage developed across it. Furthermore, the sum or difference of two sinusoidal waveforms with the same frequency is another sinusoid. From these concepts, it can be shown that "if voltage or current at any part of a linear circuit is sinusoidal (i.e., alternating at a particular frequency), voltages and currents in every part of the circuit are sinusoidal with the same frequency." This theorem is only true for circuits in which there are no transient disturbances (or where their effect has long died away) and the voltages and currents are in steady-state. The following section will cover the analysis of circuits under steady a-c.

3.7 Steady Alternating Current

The form of steady a-c has already been shown and used in the analysis of simple a-c circuits. The material presented in this section, however, necessitates a review of a familiar but easily forgotten subject, "complex algebra."

Complex Numbers. "Real numbers" such as 2, 4, and π are easy to understand in terms of physical things. Any mathematical operation on these numbers always results in another real number, except when the square root of a negative real number is taken. The $\sqrt{-1}$ cannot be satisfied by any real number. Therefore, the square root of any negative number is called an "imaginary number." Mathematicians distinguish imaginary numbers by writing "i" in front of them; to avoid confusion with current, electrical engineers use the symbol, "j," where

$$j = \sqrt{-1}\,.$$

Addition or subtraction of an imaginary number yields another imaginary number. Yet, when an imaginary number is added to a real number, a "complex number" is created. These have the rectangular form, $x + jy$ (for instance, $3 + j4$), where x is the real part and y the imaginary part, or if

$$Z = x + jy$$

then

$$\mathrm{Re}[Z] = x \quad \mathrm{Im}[Z] = y. \tag{3.95}$$

Complex numbers can be represented graphically by a pair of perpendicular axes as shown in Figure 3.51. The horizontal axis is for real quantities, the vertical one for imaginary. Considering $x + jy$, if $y = 0$, the complex number is a pure real number and falls somewhere on the real axis. Similarily, if $x = 0$, the complex number, now being pure imaginary, exists on the vertical axis. Hence, complex numbers encompass all real and all imaginary numbers.

Rectangular Forms. With

$$Z = x + jy$$

$$W = u + jv,$$

the following are common definitions and mathematical operations of complex algebra.

1. Two complex numbers are equal if and only if the real components are equal and the imaginary components are equal:

$$Z = W, \text{ IFF } x = u, \; y = v.$$

2. To sum two complex numbers, the real and imaginary parts are summed separately:

$$Z \pm W = (x \pm u) + j(y \pm v).$$

3. The product of a real and an imaginary number is imaginary:

$$x(jy) = j(xy).$$

4. The product of two imaginary numbers is a negative real number:

$$(jy)(jv) = - yv.$$

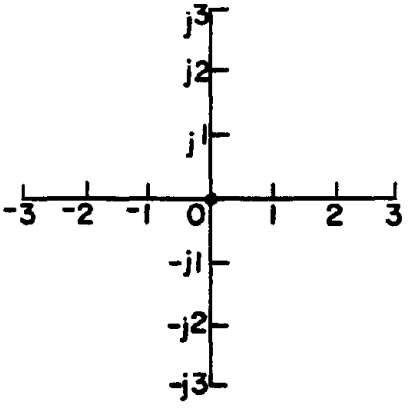


Figure 3.51. Graphical Representation of a Complex Number.

5. The multiplication of two complex numbers follows the rules of algebra (note, an easier way to perform multiplication will be shown):

$$(x+jy)(u+jv) = xu + jxv + juy - yv$$

$$= (xu-yv) + j(xv+uy).$$

6. By definition, the "conjugate" of a complex number is formed by changing the sign of the imaginary part. An asterisk denotes the conjugate:

$$Z = x + jy \qquad Z^* = x - jy.$$

7. For division, the numerator and denominator are multiplied by the conjugate of the denominator (again, an easier method exists):

$$\frac{x+jy}{u-jv} = \frac{x+jy}{u-jv}\ \frac{(u+jv)}{(u+jv)} = \left(\frac{xu-yv}{u^2+v^2}\right) + j\left(\frac{uy+xv}{u^2+v^2}\right).$$

Other Complex Forms. Besides rectangular, there are three other general forms of complex numbers: trigonometric, polar, and exponential. Figure 3.52 illustrates the conversion of rectangular to trigonometric or polar forms where:

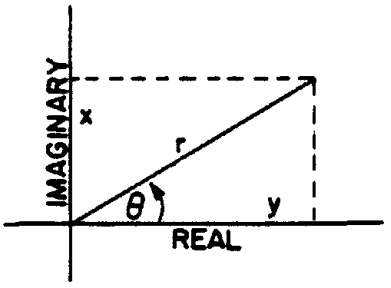


Figure 3.52. Trigonometric or Polar Representation of a Complex Number.

$$Z = x + jy. \tag{3.96}$$

The "absolute value" of Z is represented by "r," and

$$x = r\cos\theta$$

$$y = r\sin\theta$$

where

$$\theta = \tan^{-1}\left(\frac{y}{x}\right)$$

$$r = (x^2+y^2)^{1/2}. \tag{3.97}$$

Hence, the "trigonometrical form" of the complex number is

$$Z = r(\cos\theta + j\sin\theta) \tag{3.98a}$$

with the conjugate,

$$Z^* = r(\cos\theta - j\sin\theta). \tag{3.98b}$$

The "polar form" is widely used in circuit analysis and is simply written as

$$Z = r \angle\theta \tag{3.99a}$$

and the conjugate,

$$Z^* = r \angle -\theta.$$

Euler's theorem states that

$$\cos\theta + j\sin\theta = e^{j\theta}. \tag{3.100}$$

This expression allows a complex number to be written as an exponent, the "exponential form,"

$$Z = r(\cos\theta + j\sin\theta) = re^{j\theta} \tag{3.100a}$$

and

$$Z^* = re^{-j\theta}. \tag{3.100b}$$

All four complex forms are therefore identical or

$$Z = x + jy = r(\cos\theta + j\sin\theta) = r \angle\theta = re^{j\theta}.$$

A particular form can enable more easy mathematical manipulation of complex numbers. For addition or subtraction, the rectangular expression is the best, but multiplication and division are much more convenient when the number is in polar or exponential form. For instance, in polar,

$$Z_1 Z_2 = r_1 \angle\theta \; r_2 \angle\phi = r_1 r_2 \angle\theta+\phi$$

$$\frac{Z_1}{Z_2} = \frac{r_1 \angle\theta}{r_2 \angle\phi} = \frac{r_1}{r_2} \angle\theta-\phi$$

and exponential,

$$Z_1 Z_2 = (r_1 e^{j\theta})(r_2 e^{j\phi}) = r_1 r_2 e^{j(\theta+\phi)}$$

$$\frac{Z_1}{Z_2} = \frac{r_1 e^{j\theta}}{r_2 e^{j\phi}} = \frac{r_1}{r_2} e^{j(\theta-\phi)}.$$

It will be shown shortly that circuits containing resistance, inductance, and capacitance can be represented by complex numbers, and the solution of such under steady a-c for voltage, current, and power will employ complex algebra. This will be done with almost as much ease as the d-c circuit analysis presented earlier.

Effective Alternating Current. The power available in the outlets of this country's homes is a very familiar quantity; it is sinusoidal, having a frequency of 60 Hz and a "voltage" of 115V. However, what does this 115 V actually stand for?

The voltage waveform, being a sinusoid, is not constant with time. Therefore, the "voltage" is certainly not instantaneous. If a measuring device was connected to an outlet so the waveform could be visually observed, it would be found that "voltage" is also not the maximum value, V_m, as this waveform crest is $115\sqrt{2}$ or 162.6V. The word cannot fit the concept of average value because the average of a sine wave is identically zero. As another resort, the average over one positive or one negative half-cycle of the waveform could be calculated, but the result shows such a measure as $0.637V_m$ or 103.5 V. To answer the question, the reason for measuring the "voltage" must be considered. In any system, current and voltage are defined in terms of what they will do. Consequently, the "voltage" is the effective value of the sinusoidal waveform; it is a measure of the effectiveness of the voltage source in delivering power to a resistive load. The effective value is called "root-mean-square" or rms.

To gain a valuable insight into root-mean-square measurements, return to the concept of instantaneous power, where

$$p = vi.$$

If the power was being developed across a resistance, R, it was shown that

$$p = i^2 R$$

and

$$p = \frac{v^2}{R}.$$

For a-c, these equations have little practical value as they represent the value of power for a particular instant as in a-c, this is ever changing. Power is the rate of doing work; therefore, a reasonable measure is the average rate or "average power." For average power, P, consumed by the resistance, R,

$$P = \text{ave}(p) = \text{ave}(i^2R) = (\text{ave } i^2)R$$

and

$$P = \text{ave}\left(\frac{v^2}{R}\right) = \frac{(\text{ave } v^2)}{R} .$$

The search is for an effective way to measure or quantify a-c voltage and current. The units of voltage and current in d-c are easy to comprehend; the magnitudes are constant with time. Their ability to deliver power is constant. Therefore, it is appropriate to equate a-c and d-c rates of work, P_{dc} and P_{ac}, respectively:

$$P_{dc} = I^2R = P_{ac} = (\text{ave } i^2)R$$

or

$$I^2 = (\text{ave } i^2)$$

or

$$I = \sqrt{(\text{ave } i^2)} = \text{rms current.} \qquad (3.101a)$$

Employing the same procedure,

$$V = \sqrt{(\text{ave } v^2)} = \text{rms voltage.} \qquad (3.101b)$$

Effective current and voltage are therefore the square root of the mean-square values or root-mean-square; they are sometimes written I_{rms} and V_{rms}. It can be shown from the voltage and current waveforms (i.e., substituting $I_m\cos(\omega t+\theta)$ into equation 3.101a and similarly for voltage) that:

$$I_{rms} = \frac{I_m}{\sqrt{2}} \text{ or } I_m = \sqrt{2}\, I_{rms} \qquad (3.102a)$$

and

$$V_{rms} = \frac{V_m}{\sqrt{2}} \text{ or } V_m = \sqrt{2}\, V_{rms} \qquad (3.102b)$$

Root-mean-square currents and voltages are used so often that, when referring to an alternating-current magnitude, they are directly implied. Further, they are almost always used in calculations. For these reasons, the subscripts of V_{rms} and I_{rms} are dropped, and just V and I written to indicate rms voltages and currents. All common a-c voltmeters and ammeters are also calibrated to read rms values. (Measurement devices are presented in Chapter 4, Section 9.)

The preceding thought of average power applies only to resistance. Average power in the steady state to either a theoretically pure inductance or pure capacitance is identically zero. This can be proved by integrating instantaneous power to these elements to obtain an average. The results show that the energy received during one-half cycle is stored then transferred back to the source through the balance of the cycle. The stored energy in the capacitance is greatest at the maximum of the voltage wave, while it is maximum in the inductance at the current-wave crest.

Phasors. As might have been gleaned from the preceding information, a steady-state sinusoidal current or voltage at a given frequency is characterized by only two parameters: amplitude and phase-angle. Such is shown in Figure 3.53a where two voltage waveforms are separated by a phase angle. Graphically, an a-c quantity may also be represented by a "phasor;" illustrated in Figure 3.53b, the phasor shows magnitude and direction (time). In this illustration, a continually-rotating line (the phasor) is assumed to have:

1. a length representative of V_m,
2. rotation about point "0," and
3. an angle increasing with time according to $\theta_t = \omega t + \theta$.

The figure shows the line as if a snapshot has been taken, freezing action. The alternating quantity, $V_m \cos(\omega t + \theta)$, can be observed as the projection of the phasor on the horizontal axis (by convention). In other words, as the phasor rotates in Figure 3.53b, a plot of its projection on the horizontal axis with time

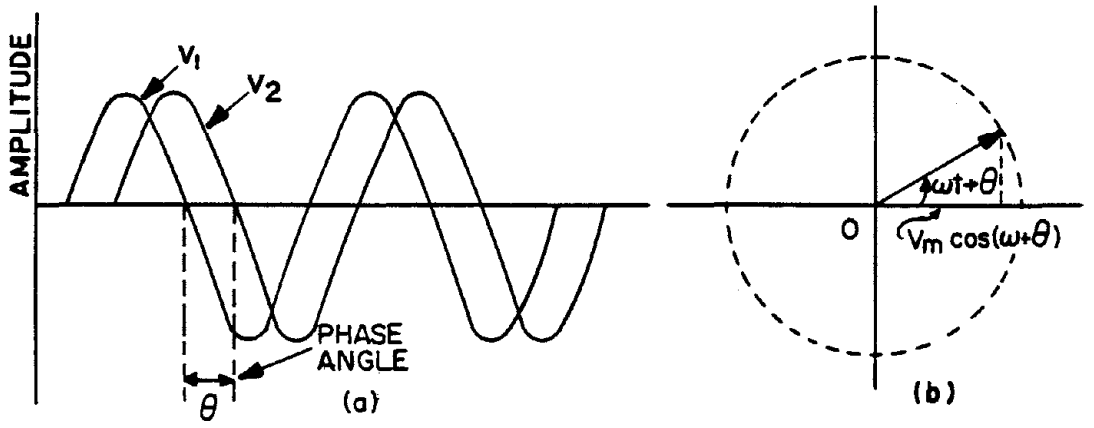


Figure 3.53. A Sinusoid Versus Time and as a Phasor.

reproduces a waveform like that in Figure 3.53a. Since phasor length, as shown here, represents crest voltage but does not necessarily need to be equal to it, common practice is to draw phasors in terms of effective (rms) values. Although voltage has been employed as an example, phasors can represent sinusoidal current among other things.

Voltage and current phasors are both illustrated as rotating lines in Figure 3.54a, where

$$v = V_m \cos(\omega t+\phi)$$

$$i = I_m \cos\ \omega t.$$

To show current with voltage, two phasors can be drawn, one advanced by the phase angle, ϕ. Both lines rotate indefinitely about the axes, and one line will always lead the other by the same relative position. Therefore, the axes are superfluous and need not be drawn. Since it is necessary to orient the phasors at a specific point in time, a convenient instant could be when the current phasor angle is zero as in Figure 3.54b. Here, the current phasor is termed a "reference phasor," and all other phasors are drawn relative to it. Either voltage or current can be selected as reference.

A phasor may be expressed in several ways. To illustrate the most-used expressions, consider Figure 3.55a, which shows one phasor displaced from the horizontal by an angle, $\omega t+\theta$. Recalling complex algebra, the horizontal axis can be assigned real, the vertical imaginary numbers.

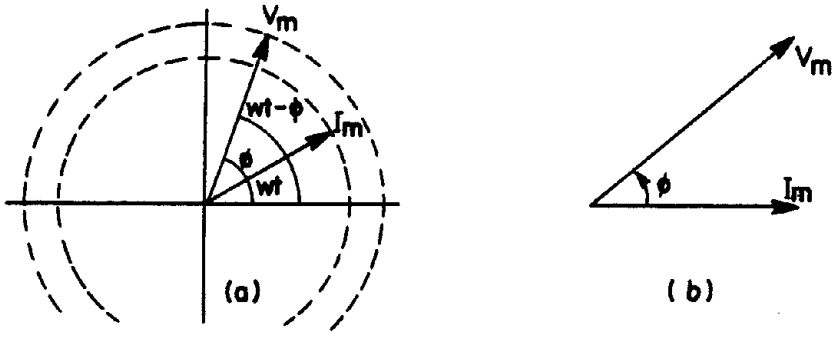


Figure 3.54. Phasor Representation of both Current and Voltage.

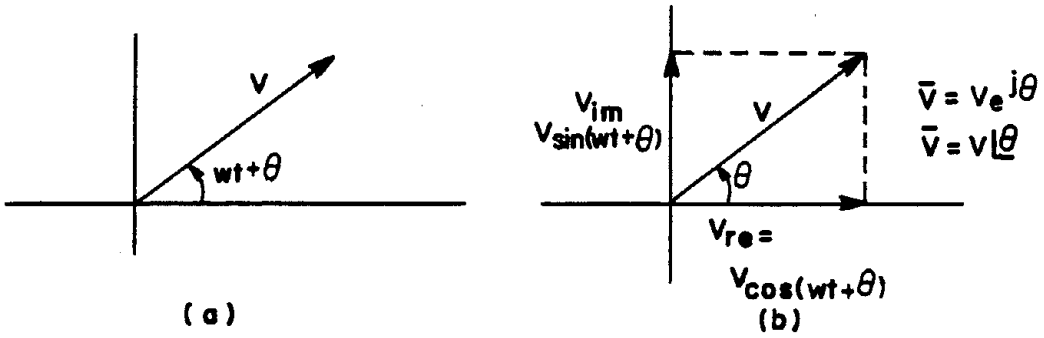


Figure 3.55. Other Expressions for Phasors.

The phasor, $\bar{V}$, is then the sum of the real and imaginary components, $\bar{V}_{re}$ and $\bar{V}_{im}$ or,

$$\bar{V} = \bar{V}_{re} + \bar{V}_{im} . \qquad (3.103)$$

Figure 3.55b clearly illustrates the "rectilinear form" or nature of equation 3.103. The real and imaginery components of the phasor are:

$$\bar{V}_{re} = V\cos(\omega t+\theta) \qquad (3.104a)$$

$$\bar{V}_{im} = jV\sin(\omega t+\theta) \qquad (3.104b)$$

thus

$$\bar{V} = V\cos(\omega t+\theta) + jV\sin(\omega t+\theta) \qquad (3.104c)$$

or,

$$\bar{V} = V(\cos(\omega t+\theta) + j\sin(\omega t+\theta)). \qquad (3.104d)$$

$\bar{V}$ is used to signify that the voltage is a phasor and, again, the imaginary operator, j, signifies that $\bar{V}_{im}$ exists on the imaginary axis. Accordingly, the phasor may be considered as the vector sum of two phasors at right angles to each other. Applying Euler's theorem (equation 3.100) to equation 3.104d,

$$\bar{V} = Ve^{j(\omega t+\theta)} \qquad (3.105a)$$

or

$$\bar{V} = Ve^{j\omega t}e^{j\theta}. \qquad (3.105b)$$

The factor, $e^{j\omega t}$, is superfluous as it contains no unique information about the phasor; therefore, it can be suppressed:

$$\bar{V} = V_e{}^{j\theta}, \qquad (3.106)$$

which is called the "exponential form" of the phasor. Equation 3.105c thus can be expressed in "polar form,"

$$\bar{V} = V \angle\theta. \qquad (3.107)$$

These phasor forms are very handy in solving a-c circuit problems. Interestingly, the terms, "phasor" and "vector," are often interchanged.

Phasors and Complex Quantities. Upon introducing the action of time-varying sinusoids, certain voltage-current phase-angle relationships were discovered existing for pure resistive, inductive, and capacitive circuit elements. In general, if a steady-state sinusoidal current has the "time-domain" form:

$$i = I_m \cos(\omega t+\theta) \qquad (3.108a)$$

and voltage:

$$v = V_m \cos(\omega t+\phi) \qquad (3.108b)$$

current is said to be lagging voltage by the phase-angle, $\phi-\theta$, or conversely, leading voltage by the phase angle, $\theta-\phi$. Using the exponential and polar phasors, this current and voltage can also be stated

$$\bar{I} = Ie^{j(\omega t+\theta)}, \ \bar{I} = Ie^{j\theta}, \text{ or } \bar{I} = I \angle\theta \qquad (3.109a)$$

and

$$V = Ve^{j(\omega t+\phi)}, \ \bar{V} = Ve^{j\phi}, \text{ or } \bar{V} = V \angle\phi \qquad (3.109b)$$

where I and V are the rms values of current and voltage, respectively. To preface steady-state circuit analysis, pure circuit elements must again be considered, this time to analyze the voltage-current relationships using complex quantities. Equations 3.108a and 3.108b are assumed as the general current through and voltage across each element.

If sinusoidal current is applied to a resistance, R, the voltage across it is

$$v = Ri.$$

Applying the general time-domain expressions,

$$V_m \cos(\omega t+\phi) = RI_m \cos(\omega t+\theta)$$

or in exponential form

$$Ve^{j(\omega t+\phi)} = RIe^{j(\omega t+\theta)}.$$

Suppressing $e^{j\omega t}$,

$$Ve^{j\phi} = RIe^{j\theta}$$

or in polar form

$$V \angle \phi = RI \angle \theta$$

or in phasor form ($V \angle \phi$ and $I \angle \theta$ are the phasor polar representations),

$$\bar{V} = R\bar{I}. \tag{3.110}$$

This is the same relationship that exists for time-varying waveforms and direct-current. It is apparent that angles θ and ϕ are equal and that voltage and current are in phase (see Figure 3.56a).

Suppose the same general forms of current and voltage were applied to a pure inductance where, as before,

$$v = L\frac{di}{dt}$$

then, using the general exponentials,

$$Ve^{j(\omega t+\phi)} = L\frac{d}{dt}(Ie^{j(\omega t+\theta)}).$$

Differentiating ($e^{j\theta}$ is a constant with time),

$$Ve^{j(\omega t+\phi)} = j\omega LIe^{j(\omega t+\theta)}$$

and suppressing $e^{j\phi t}$,

$$Ve^{j\phi} = j\omega LIe^{j\theta}.$$

Thus, in phasor form,

$$\bar{V} = j\omega L\bar{I}. \tag{3.111}$$

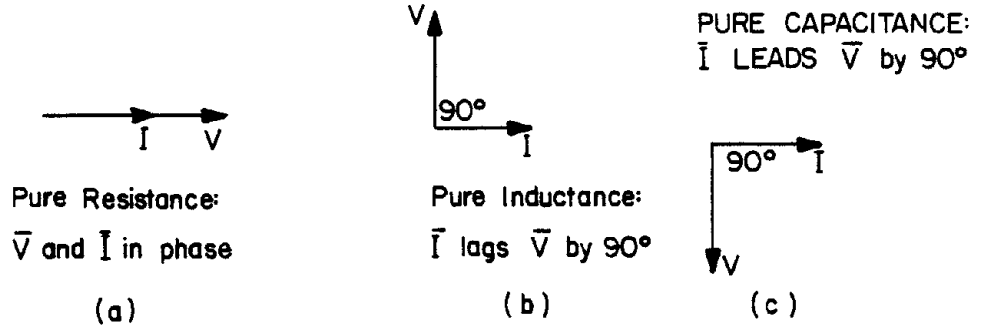


Figure 3.56. Voltage-Current Phasor Relationships for Circuit Elements.

The imaginary operator, j, denotes a +90° displacement of voltage from current; such as illustrated in Figure 3.56b. In general, if the current phasor has an angle, θ, the voltage phasor angle, ϕ, is $\theta + 90°$ for a pure inductance.

For a pure capacitance,

$$i = C\frac{dv}{dt}.$$

Employing the same process to find equation 3.111,

$$\bar{I} = j\omega C\bar{V} \qquad (3.112a)$$

or

$$\bar{V} = \left(\frac{1}{j\omega C}\right)\bar{I} = \left(\frac{-j}{\omega C}\right)\bar{I}. \qquad (3.112b)$$

In this case, -j indicates -90° displacement of the voltage phasor from current, as shown in Figure 3.56c.

Now that the phasor relationships of the fundamental elements have been covered, the stage is set for the next section, "Impedance Transforms."

Impedance Transforms. The current-voltage relationships for the three fundamental elements have been found using phasors, as

$$\bar{V} = R\bar{I} \qquad \bar{V} = j\omega L\bar{I} \qquad \bar{V} = \frac{\bar{I}}{j\omega C}.$$

These can be rewritten as voltage phasor to current phasor ratios:

$$\frac{\bar{V}}{\bar{I}} = R \quad \frac{\bar{V}}{\bar{I}} = j\omega L \quad \frac{\bar{V}}{\bar{I}} = \frac{1}{j\omega C}.$$

A very important quantity, "impedance," signified by "$\bar{Z}$," is defined as the ratio of the phasor voltage to the phasor current for a circuit or

$$\bar{Z} = \frac{\bar{V}}{\bar{I}} . \tag{3.113}$$

This expression is often termed, "Ohm's law for a-c circuits." Impedance is a complex quantity with dimensions of ohm's, but it is not a phasor. Therefore, the impedance of the pure passive circuit elements, resistance, inductance, and capacitance, are respectively,

$$\bar{Z}_R = R \quad \bar{Z}_L = j\omega L \quad \bar{Z}_C = \frac{1}{j\omega C}. \tag{3.114}$$

These can be applied directly for circuit analysis when a circuit is in steady state. In other words, element impedances are employed to convert or transform a time-domain circuit model into a form where the circuit can be analyzed using only complex algebra. Hence, by the process, the expressions of equation 3.114 are called "impedance transforms," and the transformed mathematical model is then in the "impedance (or $j\omega$) domain." No differential equations are therefore used to solve a steady a-c circuit.

All previous fundamental theorems, laws, and circuit-analysis techniques also apply to steady a-c circuit analysis using impedances. Thus, an a-c circuit representation in the impedance domain is analogous to a d-c circuit model. On the other hand, the concept of impedance has no meaning in the time domain with time-varying voltages and currents.

To demonstrate these thoughts, consider the simple RL circuit in Figure 3.57a, now with a complex voltage source (i.e., a steady-state sinusoid defined as a phasor). For this, the

current through the resistance and inductance is the phasor, $\bar{I}$, therefore,

$$\bar{V}_R = \bar{I}R$$

$$\bar{V}_L = \bar{I}j\omega L.$$

By Kirchhoff's voltage law,

$$\bar{V} = \bar{V}_R + \bar{V}_L$$

or

$$\bar{V} = \bar{I}R = \bar{I}j\omega L = \bar{I}(R + j\omega L).$$

The impedance (equivalent) of the entire circuit is then

$$\bar{Z} = \frac{\bar{V}}{\bar{I}} = R + j\omega L. \qquad (3.115)$$

Because impedance is a complex quantity, it also has a polar form:

$$\bar{Z} = Z \angle \theta \qquad (3.116)$$

where

$Z = (R^2 + (\omega L)^2)^{1/2}$, termed the magnitude of the impedance (Ω),

$\theta = \tan^{-1}(\frac{\omega L}{R})$.

A phasor diagram for the circuit current and voltages is given in Figure 3.57b. (Note: as current is common to both elements, it could be used as the reference phasor.) Here, voltage across the resistor, V_R, is in phase with current, while that across the inductor, V_L, leads current by 90°. The total circuit voltage, $\bar{V}$, can be resolved noting that

$$\bar{V} = \bar{V}_R + \bar{V}_L = V \angle \theta$$

where

$V = (V_R^2 + V_L^2)^{1/2}$, the magnitude of the source voltage (V),

$\theta = \tan^{-1}(\frac{V_L}{V_R})$.

This last angle is identical to that found for the impedance. It should be indicated that the current and voltage relationships for the inductor are as was previously found when time-domain voltages and currents were considered.

Now consider Figure 3.58a, a simple RC series circuit in which:

$$\bar{V}_R = \bar{I}R$$

$$\bar{V}_C = \bar{I}(\frac{1}{j\omega C}) = -j\frac{\bar{I}}{\omega C}$$

and

$$\bar{V} = \bar{I}R - \frac{j\bar{I}}{\omega C} = \bar{I}(R - \frac{j}{\omega C}).$$

The impedance becomes

$$\bar{Z} = \frac{\bar{V}}{\bar{I}} = R - \frac{j}{\omega C} = R + \frac{1}{j\omega C} \qquad (3.117)$$

Figure 3.58b, the circuit phasor diagram, shows the current-voltage phase-angle relationships, with the voltage across the capacitor now lagging that across the resistor.

Carrying the process on for an RLC series circuit (Figure 3.59a), the voltage across each element is:

$$\bar{V}_R = \bar{I}R$$

$$\bar{V}_L = \bar{I}j\omega L$$

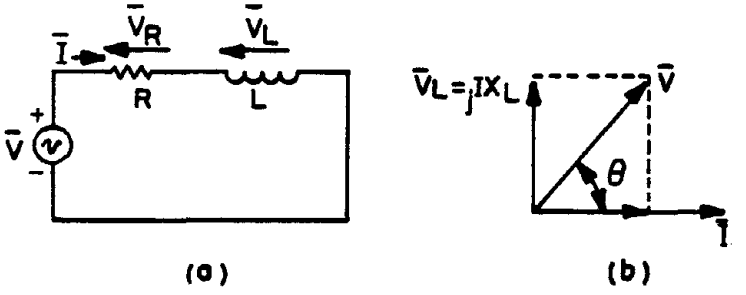


Figure 3.57. Steady Sinusoid Analysis of a Simple RL Series Circuit.

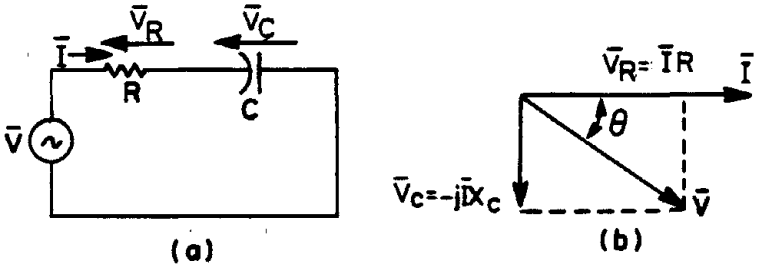


Figure 3.58. Steady Sinusoid Analysis of a Simple RC Series Circuit.

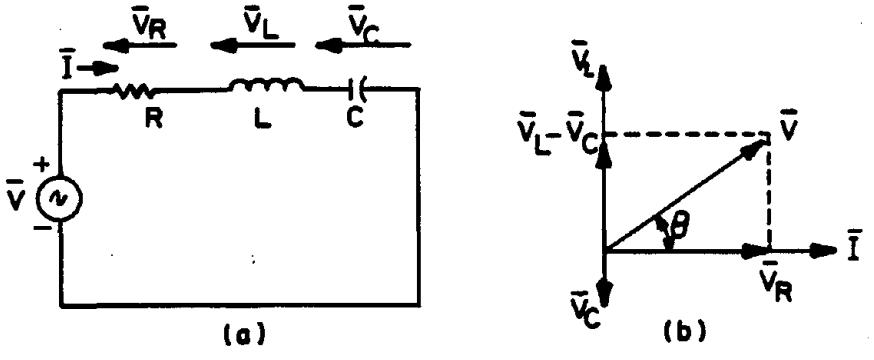


Figure 3.59. Steady Sinusoid Analysis of a Simple RLC Series Circuit.

$$\bar{V}_C = \bar{I}\left(\frac{1}{j\omega C}\right),$$

and across the entire circuit,

$$\bar{V} = \bar{V}_R + \bar{V}_L + \bar{V}_C$$

or

$$\bar{V} = \bar{I}R + \bar{I}j\omega L + \bar{I}\frac{1}{j\omega C} \qquad (3.118)$$

with the circuit impedance,

$$\bar{Z} = R + j\omega L + \frac{1}{j\omega C}$$

or

$$\bar{Z} = R + j\left(\omega L - \frac{1}{\omega C}\right). \qquad (3.119)$$

The foregoing gives the essence of impedance transforms. Each impedance (equations 3.115, 3.117, and 3.119, indeed the "equivalent" circuit impedances) has been found to have a form:

$$\bar{Z} = R + jX = Z \angle \theta$$

where

R = the resistance component (Ω)

X = the reactance component (Ω)

$Z = (R^2 + X^2)^{1/2}$, the magnitude of impedance (Ω)

$\theta = \tan^{-1}(X/R)$

in which, depending on the pure circuit elements,

$X = \omega L$ = inductive reactance (Ω)

$X = \frac{1}{\omega C}$ = capacitive reactance (Ω)

$$X = \omega L - \frac{1}{\omega C} = \text{reactance for series LC elements } (\Omega).$$

From the above equation, it can be seen that resistance is constant while reactance is variable with frequency.

To clarify the transform process, regress to the time-domain expression found for a general series RLC circuit:

$$v = iR + L\frac{di}{dt} + \frac{1}{C}\int_0^t idt + V_0. \qquad (3.93)$$

It has been demonstrated in the impedance domain for steady a-c that:

$$\bar{V} = \bar{I}R + \bar{I}j\omega L + \bar{I}\frac{1}{j\omega C}. \qquad (3.118)$$

Accordingly, time-domain differential equations can be changed to the impedance domain when the circuit is under steady a-c by:

1. replacing v with $\bar{V}$ (in rms),
2. replacing i with $\bar{I}$ (in rms),
3. replacing $\frac{d}{dt}$ with $j\omega$,
4. replacing $\int...dt$ with $\frac{1}{j\omega}$, and
5. letting $V_0 = 0$.

However, assigning the impedances directly using equation 3.114 is a much more efficient approach to a-c circuit analysis, and more will be stated regarding this soon.

Admittance. "Admittance," given the symbol, "$\bar{Y}$," is defined as the reciprocal of impedance, $\bar{Z}$, and

$$\bar{Y} = \frac{\bar{I}}{\bar{V}}. \qquad (3.120)$$

The units are now Siemens, S, replacing the previous designation, "mhos." Admittance is therefore a complex quantity, the real part being conductance, G, and the imaginary component susceptance, B, or

$$\bar{Y} = G + jB. \qquad (3.121a)$$

It should be noted that conductance is not the reciprocal of resistance unless reactance is zero, likewise for susceptance, reactance, and resistance. In general form, from equating $\overline{Y}$ and $\overline{Z}$,

$$G = \frac{R}{R^2 + X^2} \text{ and } B = \frac{-X}{R^2 + X^2}. \qquad (3.121b)$$

Admittance affords basically the same convenience in steady a-c circuit analysis that conductance provides for parallel d-c circuits.

Analysis. As previously stated, all circuit-analysis techniques that were covered for d-c circuits still apply to steady a-c circuits in the impedance domain. These include network reduction, Kirchhoff's laws, loop and node analysis, network theorems, plus delta-wye transforms. Simply, impedances replace resistances in the concept, and steady a-c sources replace d-c. Even with d-c, the impedance domain can be used; in other words, d-c sources can be thought of as steady-state sinusoids with $\omega = 0$. Therefore, with d-c reactance has no effect.

A summary of circuit relationships follow, this time with impedance. Obviously, some of these have just been demonstrated.

1. Impedances in series. A single equivalent impedance, Z, is:

$$Z = Z_1 + Z_2 + Z_3 + \ldots\ldots\ldots + Z_n \qquad (3.122)$$

2. Impedances in parallel. A single equivalent here is:

$$\frac{1}{Z} = \frac{1}{Z_1} + \frac{1}{Z_2} + \frac{1}{Z_3} + \ldots\ldots\ldots + \frac{1}{Z_n} \qquad (3.123)$$

3. Admittances in parallel.

$$Y = Y_1 + Y_2 + Y_3 + \ldots\ldots\ldots + Y_n \qquad (3.124)$$

4. Voltage distribution of series impedances.

$$\overline{V}_1 = \frac{Z_1}{Z}\overline{V},\ \overline{V}_2 = \frac{Z_2}{Z}\overline{V}, \ldots\ldots\ldots \qquad (3.125)$$

where $\overline{V}$ is the input voltage, $\overline{V}_1$ is across $\overline{Z}_1$, and so on.

5. Current distribution through parallel admittances.

$$\bar{I}_1 = \frac{Y_1}{Y}\bar{I},\ \bar{I}_2 = \frac{\bar{Y}_2}{Y}\bar{I}, \ldots\ldots\ldots \quad (3.126)$$

where $\bar{I}$ is the total circuit current, $\bar{I}_1$ is through Y_1, and so on. Or parallel impedances.

$$\bar{I}_1 = \frac{Z}{Z_1}\bar{I},\ \bar{I}_2 = \frac{Z}{Z_2}\bar{I}, \ldots\ldots\ldots \quad (3.127)$$

The overlines are removed on the above impedances and admittances for convenience, but it should be remembered that all are complex numbers. In essence, a-c circuits in the steady state, therefore, can be solved almost as easily as d-c circuits employing only resistance. The major addition now is that the solution uses complex algebra.

3.8 Power

The measures of instantaneous power, p, and average power, P, have already been introduced. Instantaneous power does not have application in steady a-c circuit analysis, so the concept of average power has been developed to gauge the rate at which electricity does work. This section continues the foundations for mine-power fundamentals which Chapter 4 will expand into full comprehension. There, it will be three-phase power; here, the purpose is to introduce single-phase power.

Average Power and Power Factor. To find the average power consumed by a circuit, the resistance of each element can be considered, and all the individual power consumptions computed. Reactance, either capacitive or inductive, does not affect average power. After all the average powers have been determined, their sum yields the total average power delivered to the circuit. Obviously, if the circuit elements are numerous, this process is involved, but the approach is sometimes necessary. If only average power for the total circuit is needed, it is more desirable to perform only one calculation by computing average power in terms of the circuit's terminal current and voltage.

Yet, when complex or imaginary components exist in the circuit, can they be ignored as was just implied? Because voltage and current waveforms might not be in phase, the product of sinusoidal voltage and current no longer equals average power when a phase-angle is involved. To examine what occurs if a circuit has reactance, out-of-phase instantaneous voltage and current can be used to calculate average power.

Assume that the following current and voltage are monitored at the terminals of a circuit:

$$i = I_m \cos \omega t$$

$$v = V_m \cos (\omega t + \theta).$$

Current is taken as reference, and the phase angle, by which voltage leads current, is θ. The instantaneous power consumed is then

$$p = vi = V_m I_m \cos(\omega t + \theta)\cos \omega t.$$

From the trigonometric identity for the product of two cosines,

$$p = \frac{V_m I_m}{2} (\cos\theta + \cos(2\omega t + \theta))$$

or

$$p = \frac{V_m I_m}{2}\cos\theta + \frac{V_m I_m}{2}\cos(2\omega t + \theta). \qquad (3.128)$$

The first term of equation 3.128 is constant, while the second is a sinusoid. Thus, taking the average to find average power results in

$$P = \text{ave}(p) = \frac{V_m I_m}{2} \cos\theta. \qquad (3.129)$$

Realizing the $V_m = \sqrt{2}\,V$ and $I_m = \sqrt{2}\,I$, average power becomes

$$P = VI \cos \theta \qquad (3.130)$$

in which V and I are rms voltage and current at the circuit terminals and θ is their phase-angle. If the voltage and current had been d-c values, the average power would just be the product of voltage and current. When voltage and current are sinusoidal, however, equation 3.130 relates the average power entering any circuit is the product of the effective voltage, effective current, and the cosine of the phase angle.

The function, cos θ, is called "power factor," abbreviated "pf." For a purely resistive load, the phase angle is zero and the power factor is unity. Unity power factor may also exist

when inductance and capacitance are present, if the effects of reactive elements cancel. If the circuit is totally reactive (either inductive or capacitive), the phase-angle is a positive or negative 90°, pf is zero, and average power must be zero.

Complex and Apparent Power. When reactance is in a circuit, a component of circuit current is used to transfer stored energy. The energy is periodically stored in and discharged from the reactance. The stored energy adds to circuit current but not to average power (average power to reactive elements is zero). In such cases, power factor is not unity. Thus, as no work is performed by the added current, power factor can be considered a measure of circuit efficiency to perform work, and average power is often called "active power" or "real power," defined by equation 3.130.

Power calculations are simplified if power is defined by the complex quantity shown in Figure 3.60 and mathematically expressed as:

$$\overline{S} = P + jQ \qquad (3.131)$$

in which

$\overline{S}$ = complex power

P = real power, as before

Q = "reactive power" or "imaginary power."

Imaginary power accounts for the energy supplied to the reactive elements. If

$$P = VI \cos\theta,$$

then the magnitude of complex power, S, termed "apparent power," is

$$S = VI \qquad (3.132)$$

and imaginary power is

$$Q = VI \sin\theta. \qquad (3.133)$$

Voltage and current are again rms and θ is the phase-angle. Therefore,

$$\bar{S} = P + jQ = VI\cos\theta + jVI\sin\theta$$

or

$$\bar{S} = VI(\cos\theta + j\sin\theta) = VIe^{j\theta} = VI\,\underline{|\theta}\,. \qquad (3.134)$$

Complex power is then simply the product of terminal rms voltage and current magnitude acting at a phase angle. Applying d-c concepts, the product, VI, is the power apparently absorbed by the circuit, hence the term. Apparent power, real power, and imaginary power are dimensionally the same, but to avoid confusion with real power (units of watts, W), apparent power has units of "volt-amperes," VA, and reactive power uses "volt-amperes-reactive," var.

When sinusoidal voltage and current are general, such as

$$\bar{V} = V\,\underline{|\theta}$$

$$\bar{I} = I\,\underline{|\phi}\,,$$

instead of using equations 3.131 and 3.134, the following is a more convenient expression to compute complex power:

$$\bar{S} = \bar{V}\,\bar{I}^* \qquad (3.135)$$

where

$\bar{V}$ = complex voltage (V)

$\bar{I}^*$ = the conjugate of complex current (A).

Accordingly,

$$\bar{S} = \bar{V}\,\bar{I}^* = V\,\underline{|\theta}\;\; I\,\underline{|-\phi} = VI\,\underline{|\theta-\phi}$$

or

$$\bar{S} = Ve^{j\theta}Ie^{j-\phi} = VIe^{j(\theta-\phi)}$$

where,

$\theta-\phi$ = the phase angle between voltage and current.

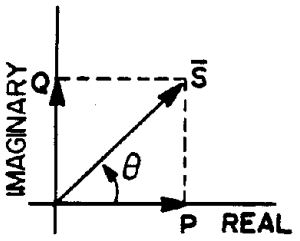


Figure 3.60. Power Represented as Real and Imaginary Components.

Any circuit in steady-state can be reduced to the general impedance

$$Z = R + jX$$

or

$$Z = |Z| \angle\theta = |Z|e^{j\theta} = \frac{V}{I} e^{j\theta} \qquad (3.136)$$

where,

$$\theta = \tan^{-1}\left(\frac{X}{R}\right).$$

By relating the complex power consumed by a circuit to this impedance, another useful expression can be found:

$$\bar{S} = VI\ e^{j\theta} = I^2\left(\frac{V}{I} e^{j\theta}\right) = I^2 Z$$

hence

$$\bar{S} = I^2(R + jX) = I^2R + jI^2X.$$

Because $\bar{S} = P + jQ$,

$$P = I^2R \quad Q = I^2X \qquad (3.137a)$$

or

$$P = V_R^2/R \quad Q = V_X^2/X. \tag{3.137b}$$

The current, I, in equation 3.137a is real rms not complex; the rms voltages in equation 3.137b are those existing across the individual elements (not across the total circuit).

It may already be obvious that the circuit impedance angle is identical to the power-factor angle. In addition,

1. if a circuit contains resistance and capacitance (a capacitive load, $Z = R - jX$), current leads voltage, the phase angle is negative, and Q is negative;
2. if the circuit is an inductive load ($Z = R + jX$), current lags voltage, the phase angle and Q are positive.

With either case, the power factor ranges from zero to unity (purely reactive to purely resistive). To assist reference to the load's nature, a capacitive load is said to have a "leading pf," and an inductive load a "lagging pf." These concepts are illustrated in Figure 3.61.

The complex power delivered to several loads is the sum of the complex power consumed by each individual load, no matter how they are interconnected. This relationship can be shown using the simple circuit in Figure 3.62. Total complex power to the system is

$$\bar{S} = \bar{V}\,\bar{I}^* = P + jQ$$

but

$$\bar{I} = \bar{I}_1 + \bar{I}_2$$

thus

$$\bar{S} = \bar{V}(\bar{I}_1^* + \bar{I}_2^*)$$

$$\bar{S} = \bar{V}\,\bar{I}_1^* + \bar{V}\,\bar{I}_2^* = \bar{S}_1 + \bar{S}_2$$

or

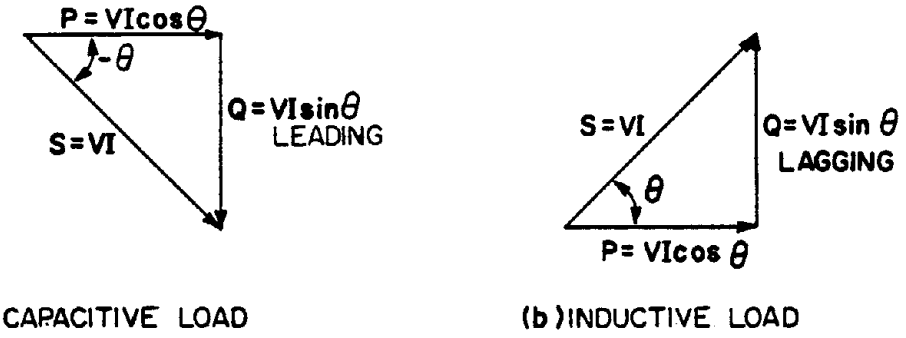


Figure 3.61. Illustration of Leading and Lagging Power Factors.

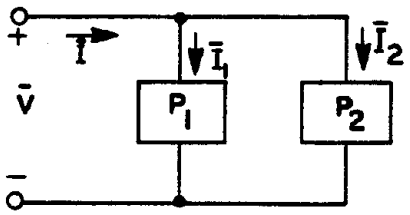


Figure 3.62. Circuit Demonstrating Sum of Complex Powers.

$$\bar{S} = P_1 + jQ_1 + P_2 + jQ_2.$$

The practical significance of this is extensive. For example, if a circuit has a lagging power factor, a capacitance (with a leading power factor) can be selected then placed in parallel so as to negate or reduce the total circuit imaginary power (with the capacitance). The net result is to reduce total circuit current, while the load consumes the same real power (thus, performs the same work). Such is the essence of "power factor improvements."

There are many other practical examples that can be cited about the formulas just covered. These must wait, however, until more fundamental concepts are available. Notwithstanding, these examples are a significant part of the chapters that follow.

3.9 Resonance

Series RLC Circuits. In Section 3.7, the impedance for a simple RLC series circuit as shown in Figure 3.63 was found to be:

$$Z = R + j\omega L + \frac{1}{j\omega C} = R + j(\omega L - \frac{1}{\omega C}). \qquad (3.119)$$

A special circuit phenomenon can be demonstrated with this equation; there exists one specific frequency, ω_o, where total circuit reactance is zero and the circuit impedance is purely resistive or

$$\omega_o L - \frac{1}{\omega_o C} = 0 \text{ or } \omega_o L = \frac{1}{\omega_o C} \qquad (3.138a)$$

and

$$Z_o = R. \qquad (3.138b)$$

At ω_o, the circuit is said to be in "resonance," and

$$\omega_o^2 = \frac{1}{LC} \text{ or } \omega_o = \frac{1}{(LC)^{1/2}}.$$

Since $\omega = 2\pi f$, the "resonance frequency," f_o is given by

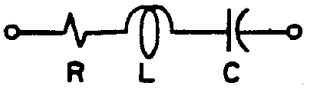


Figure 3.63. A Simple Series RLC Circuit for Resonance.

$$f_o = \frac{1}{2\pi (LC)^{1/2}}. \qquad (3.139)$$

For a series RLC circuit in resonance, therefore,

1. the applied voltage, $\bar{V}$, and the resulting current, $\bar{I}$, are in phase;
2. the power factor of the circuit is unity;
3. the impedance, Z, is minimum, and
4. the current, $\bar{I}$, is maximum.

At all other frequencies, significantly higher or lower than f_o, the series RLC circuit appears as a high-impedance. With frequencies below resonance, capacitive reactance is greater than inductive reactance so the angle of impedance is negative (total reactance is negative). Above resonance, the situation reverses with the impedance angle being positive. The foregoing statements are apparent in Figure 3.64, a plot of circuit impedance versus frequency.

Energy is perhaps the most fundamental concept of resonance. The energy stored in a resonance circuit is essentially constant, yet the level within the circuit may be many times the energy being supplied from an external source during any period. The source does not supply any reactive power, only active. The reactive power is transferring energy back and forth between the resonant-circuit inductance and capacitance. This situation provides the theoretical background for some mine power system severe overvoltages and, therefore, the concept will be further explored in Chapter 10.

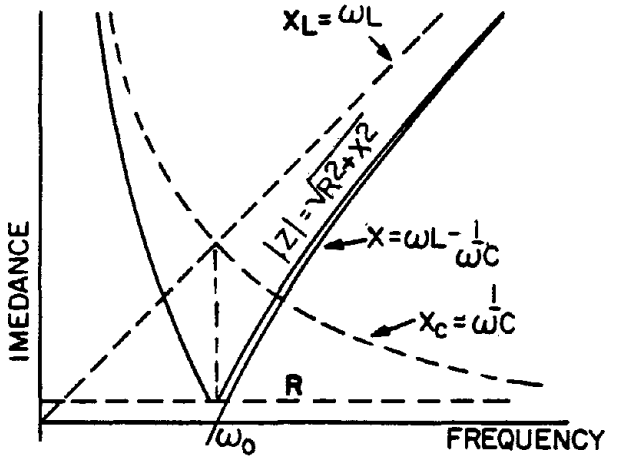


Figure 3.64. A Plot of Impedance Magnitude Versus Frequency for a Series RLC Illustrating Resonance.

Some important facts about circuits in resonance follow. The result of the energy transferral can be very high-voltages existing across the inductance and capacitance within the resonant circuit, several times the terminal voltage. The amount of energy stored, compared with that which is dissipated by the resistance, is related to the sharpness of the "response curve," such as shown in Figure 3.64. The circuit's "quality factor" is the measure of the ratio and is defined

$$Q_o = 2\pi \frac{\text{maximum energy stored}}{\text{total energy lost per period}}, \tag{3.140}$$

where the period is one complete cycle of the resonant frequency. The proportionality constant, 2π, is employed so that the most useful expressions for Q_o can be obtained. It can be shown by finding the energy stored in either reactive component of the circuit to that dissipated in the resistance that

$$Q_o = \frac{\text{reactance}}{\text{resistance}} = \frac{\omega_o L}{R} = \frac{1}{\omega_o CR}. \tag{3.141}$$

Quality factor normally has more application in the communications aspects of electrical engineering than in the power aspects. For instance, the "width" of the response curve is also related to Q_o and has great relevance to the "tuned" circuits used in radio and television.

Parallel Resonance. The resonance of the simple parallel RLC circuit, shown in Figure 3.65a, is very similar to that just discussed. This circuit is obviously ideal, but the performance is of general interest. Its admittance can be written as

$$Y = G + j\omega C + \frac{1}{j\omega L} = G + j(\omega C - \frac{1}{\omega L}). \tag{3.142}$$

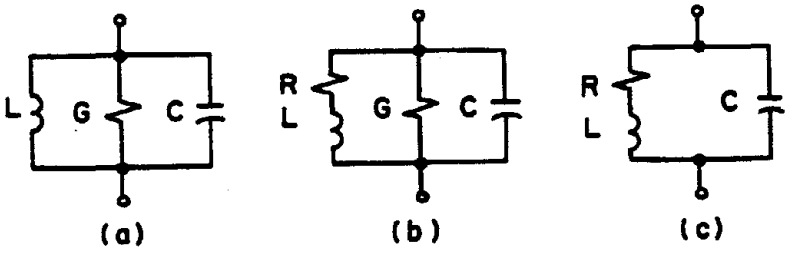


Figure 3.65. Circuits that Exhibit Parallel Resonance.

The circuit is in resonance when susceptance B, is zero. Hence, the circuit exhibits low admittance and high impedance at resonance, when the series RLC circuit had low impedance (high admittance):

$$\omega_o C - \frac{1}{\omega_o L} = 0 \text{ or } \omega_o C = \frac{1}{\omega_o L} \tag{3.143a}$$

and

$$Y_o = G. \tag{3.143b}$$

On the other hand, the resonant frequency is again:

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

The statements previously given for series circuits also apply, except current replaces voltage and voltage replaces current.

Such is the concept of "duality." Anything stated about a series-resonant circuit applies to its "dual," the parallel-resonant circuit, if each of the words in the following list are replaced by an opposite word:

voltage	current
impedance	admittance
resistance	conductance
reactance	susceptance
inductance	capacitance
series	parallel.

Therefore, Q_o of this parallel-resonant circuit is the dual of equation 3.140 or

$$Q_o = \frac{\text{susceptance}}{\text{conductance}} = \frac{\omega_o C}{G} = \frac{R}{\omega_o L}. \tag{3.144}$$

The concept also relates to many fundamentals covered in preceding sections. For example, two circuits are called duals if the loop equations for one have the same forms as the node equations for the other.

Because Figure 3.63a is ideal (the inductance must have associated resistance), Figure 3.63b and 3.63c are presented to show

practical circuits which exhibit parallel resonance. These will be explored in Chapter 10.

3.10 Transformers

Magnetic Coupling. Early in this chapter, the concept of mutual inductance was introduced. To review, Faraday found that a changing current in one circuit would induce a voltage in a nearby circuit. If the adjacent circuits are simply conductors and are labeled 1 and 2, as in Figure 3.66, the statement means that:

1. i_1 in circuit 1 produces v_2 in circuit 2,
2. v_2 in turn causes i_2 to flow (only indeed if circuit 2 is part of a complete loop), then
3. i_2 induces v_1 in circuit 1.

These interrelated phenomena can be thought of as "magnetic coupling" between the two circuits, and it has been shown that:

$$v_1 = L_{12}\frac{di_2}{dt} \text{ and } v_2 = L_{21}\frac{di_1}{dt}$$

where

$$L_{12} = L_{21} = M = \text{mutual-inductance, H.}$$

Because of the equality, "M" is used to represent mutual-inductance. These equations are only true for straight wires, and magnetic coupling again only exists if voltage and current are time varying.

The circuits considered before this section, loops or meshes composed of passive and active elements, were "conductively coupled" by common branches or nodes. Through magnetic coupling, the following paragraphs will develop the fundamentals behind perhaps the most important component of a-c mine power systems, the transformer.

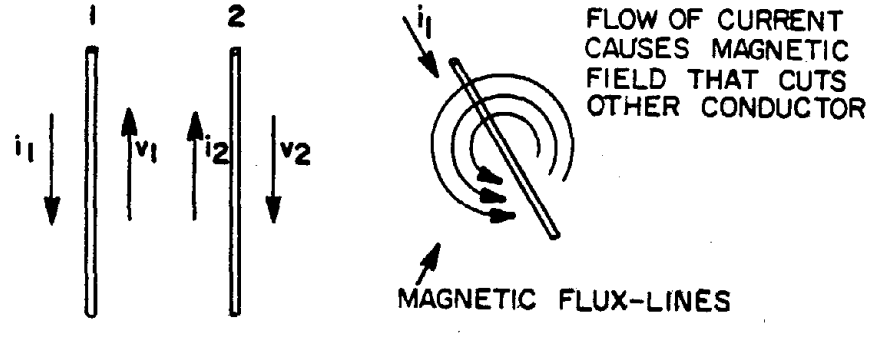


Figure 3.66. Magnetic Coupling Between Two Conductors.

Transformers are prime examples of magnetic coupling as they are often designed to optimize it while their operation is based inherently on mutual inductance. They are employed to increase the magnitude of voltage for more economical power transmission or decrease the level to provide a more suitable voltage for electrical-equipment operation. The changes can be made with either (in essence) total isolation or direct conduction between circuits.

Instead of straight conductors, assume two coils are situated side-by-side and their magnetic action is passing through any environment (see Figure 3.67). The current in coil 1 then is partly a result of self-inductance in coil 1 and mutual-inductance from coil 2 (vice versa for coil 2). Expressed mathematically:

$$v_1 = \left(L_1 \frac{di_1}{dt} \pm M\frac{di_2}{dt} \pm \ldots\right) \qquad (3.145a)$$

$$v_2 = \left(\pm M\frac{di_1}{dt} + L_2 \frac{di_2}{dt} \pm \ldots\right) \qquad (3.145b)$$

in which

L_1, L_2 = the self-inductances of coil 1 and coil 2, respectively (H)

M = mutual inductance (H).

The additional terms, implied in equations 3.145, exist only if more than two coils (or circuits, or windings) are interacting and are presented to make the expressions more general. The plus and minus terms of the equations deserve special attention.

Sign convention has been well-defined for inductors, and coil 1 or coil 2, taken individually, are inductors. A current flowing

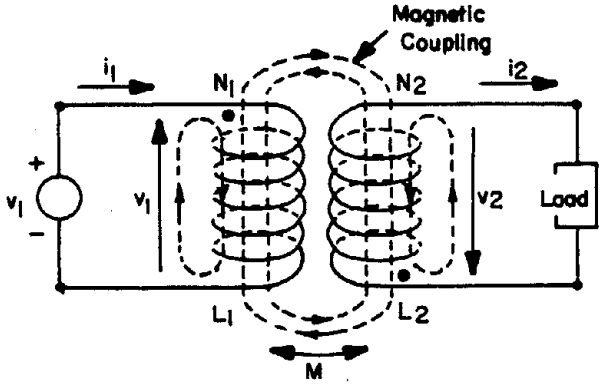


Figure 3.67. Magnetic Coupling Between Two Coils.

into the coil produces an opposing voltage, hence a positive sign or "polarity." Potential created by mutual inductance, M, however, cannot be treated in the same manner. The voltage may be of either positive or negative polarity depending on the "winding sense," the direction the coils are wound with respect to one another. Consider the two coils wound on a common core in Figure 3.68a. They are wound in the same direction and have the same sense. If a current is flowing into the top of the upper coil, the voltage produced by this current adds to that produced by the same current direction in the lower coil. Yet, in Figure 3.68b, the sense of the lower coil is reversed, and the same current as before in the top coil now creates a voltage that opposes that produced in the lower coil. Therefore, the polarity of mutual-inductance voltages can be found by physical sketches, but such is impractical in circuit diagrams. To simplify representation, magnetic-coupled coils are often marked with "dots." A dot is placed at the terminals of each coil which are instantaneously at the same polarity by mutual-inductance alone. Thus, in Figure 3.69a, i_1 enters the dotted terminal of L_1, v_2 is sensed positively at the dotted terminal of L_2, and

$$v_1 = L_1 \frac{di_1}{dt} + M \frac{di_2}{dt} \tag{3.146a}$$

$$v_2 = M \frac{di_1}{dt} + L_2 \frac{di_2}{dt}. \tag{3.146b}$$

In analyzing circuits, it may be more desireable to reference v_2 as positive at the undotted terminal of L_2 as in Figure 3.69b, then

$$v_1 = L_1 \frac{di_1}{dt} - M \frac{di_2}{dt} \tag{3.146c}$$

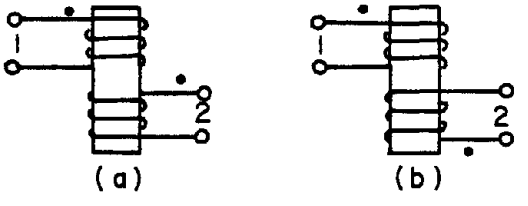


Figure 3.68. Demonstration of Coil Winding Sense.

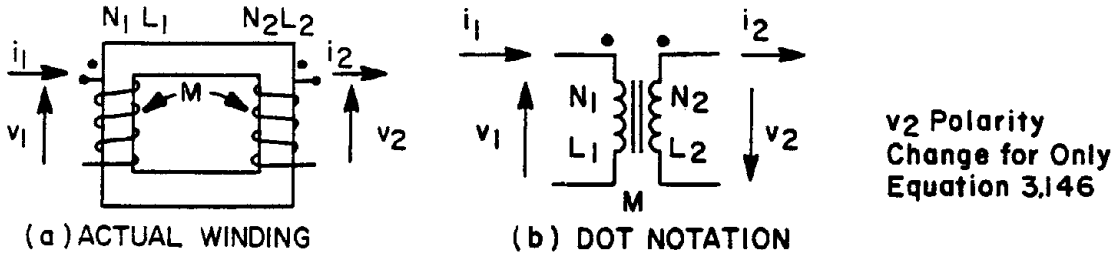


Figure 3.69. Dot Convention for Mutual-inductance Sign.

and

$$v_2 = -M \frac{di_1}{dt} + L_2 \frac{di_2}{dt}. \qquad (3.146d)$$

It is important that in either instance the mutual voltage is produced independently from that of self-induction.

The equations just presented are valid for any voltage or current waveform. If the currents are sinusoidal with radian frequency, ω, the transforms can be employed so, for equations 3.146c and 3.146d

$$V_1 = j\omega L_1 I_1 = j\omega M I_2 \qquad (3.147a)$$

$$V_2 = -j\omega M I_1 + j\omega L_2 I_2. \qquad (3.147b)$$

Realizing that mutual inductance plays an important role, these relationships can be utilized to analyze circuits containing magnetically-coupled elements. It should be stated that equations 3.146 and 3.147 relate only to the magnetically-coupled elements; equations with these devices in a complete circuit will follow.

The Ideal Transformer. The level of mutual inductance, M, depends upon the spacing and orientation of the coils and the permeability of the medium between. In other words, M is a function of flux linking between the coils, and more will be said about this phenomenon later in the section. In Figure 3.69a, by comparing the power entering L_1 of the circuit with that stored or available in L_2, it can be proven from flux-linking concepts that

$$M \leq (L_1 L_2)^{1/2} . \qquad (3.148)$$

Consequently, M has an upper limit which is the geometrical mean of the two inductances involved. The amount to which M approaches its maximum is described by the "coefficient of coupling." This is by definition

$$k = \frac{M}{(L_1 L_2)^{1/2}} \qquad (3.149)$$

where k can range from zero to unity. Coils having a low coefficient of coupling are said to be "loosely-coupled." Here, the coils could be far apart or have an orientation so they have little magnetic flux interacting between them. Loose-coupled circuits may have a k that ranges between 0.01 and 0.10. For "tightly-coupled" circuits, such as "air-core" coils, k can be around 0.5. Power transformers, which have iron cores and are wound and oriented to provide maximum common magnetic flux, can have a coefficient of coupling very nearly 1.00 (usual range is 0.90 to 0.98).

A "transformer" is a device having two or more tightly-coupled coils (windings) wound on a common iron core. Resistance and other power losses are small. The winding, receiving power, is called a "primary," those delivering power are termed "secondaries" (for example L_1 and L_2 coils of the foregoing). An "ideal transformer" is an approximation of these devices where k = 1 and losses within the device are zero. Hence, an ideal transformer can deliver all the power it receives. Many useful relationships for real transformers can be obtained by assuming the ideal-transformer case.

The self-inductance of a coil has been shown to be proportional to the square of turns, N, forming the coil if all the flux created by the current in the coil links all the turns (see Section 3.4, Inductance). If a sinusoidal current, I, flows in a coil of N turns, then the voltage produced across an N-turn coil must be N times that caused in a one-turn coil. Further, for a sinusoidal voltage, V, which is constant across an N-turn coil, the current allowed through must be 1/N times that caused in a one-turn coil. Both these statements can be proven by magnetic-field concepts, assuming that all magnetic flux produced in a coil links all turns. If follows for an ideal transformer with two windings that:

$$\frac{L_1}{L_2} = \frac{N_1^2}{N_2^2} \qquad (3.150)$$

$$\frac{V_2}{V_1} = \frac{N_2}{N_1} \tag{3.151}$$

$$\frac{I_1}{I_2} = \frac{N_2}{N_1} \tag{3.152}$$

where

N_1 = the number of turns in the primary winding

N_2 = the number of turns in the secondary winding

L_1, I_1, V_1 = the primary winding inductance, rms current, and rms voltage, respectively

L_2, I_2, V_2 = the secondary winding inductance, rms current, and rms voltage, respectively.

For this two winding arrangement, the voltage and current can be complex sinusoids. The "turns ratio," a, of the transformer is defined as the ratio of the number of turns in the secondary winding to the number in the primary winding:

$$a = \frac{N_2}{N_1}. \tag{3.153a}$$

Hence for an ideal transformer,

$$a = \left(\frac{L_1}{L_2}\right)^{1/2} = \frac{V_2}{V_1} = \frac{I_1}{I_2}. \tag{3.153b}$$

In other words, the sinusoidal voltages across the primary and secondary windings are in direct proportion to the number of turns of the windings, with currents related inversely to the turns. In addition, the last equation shows that the complex power at the primary and secondary windings are indeed equal:

$$V_1 I_1 = V_2 I_2.$$

The magnitude of this power in voltamperes is normally specified as the maximum allowable capacity of power transformers.

To demonstrate steady a-c circuit analysis with magnetic-coupled circuits and thereby arrive at another useful transformer relationship, consider Figure 3.70 where a sinusoidal voltage source, V_s, with an internal impedance, Z_g, (the combination is the Thévenin's equivalent for a source) is connected to the primary of an ideal transformer. The secondary delivers power to a load impedance, Z_L. The vertical lines between the transformer windings indicate the core is made of iron laminations. The turns ratio above the transformer symbol, 1:a, relates a convention of N_1 to N_2. Let's determine the ideal transformer input impedance with the load connected (i.e., what load the source sees through the transformer).

Since a voltage source is specified, loop equations appear as the best approach to solving the problem. Two loops, I_1 and I_2 (both express complex currents), are available in the circuit; the loops are magnetically coupled through the transformer. Employing Kirchhoff's voltage law for loop 1,

$$V_s = I_1 Z_g + I_1 j\omega L_1 - I_2 j\omega M$$

and for loop 2,

$$0 = -I_1 j\omega M + I_2 Z_L + I_2 j\omega L.$$

M is again the mutual inductance. Notice that current enters the dot of the primary and leaves the dot on the secondary, making the sign of M negative. Rewriting these into standard loop-equation form:

$$V_s = I_1(Z_g + j\omega L_1) - I_2 j\omega M$$

$$0 = -I_1 j\omega M + I_2(Z_L + j\omega L_2).$$

Solving for I_1,

$$V_s = I_1(Z_g + j\omega L_1) + \left(\frac{\omega^2 M^2}{Z_L + j\omega L_2}\right).$$

Therefore, the impedance seen by the source, Z_{in}, is the ratio of the source voltage to terminal current or,

$$Z_{in} = \frac{V_s}{I_1} = Z_g + j\omega L_1 + \frac{\omega^2 M^2}{Z_L + j\omega L_2}$$

but

$$M^2 = L_1 L_2$$

and so

$$Z_{in} = Z_g + j\omega L_1 + \frac{\omega^2 L_1 L_2}{Z_L + j\omega L_2} .$$

For an ideal transformer, there must be total coupling between primary and secondary windings; thus, the self inductances, L_1 and L_2, have no effect in the circuit, and their value can be considered infinite. Notwithstanding, the ratio is still finite as specified by the turns ratio:

$$L_2 = a^2 L_1 .$$

For this reason, primary and secondary inductances are conventionally not specified on ideal transformers. Entering this thought into the input impedance expression,

$$Z_{in} = Z_g + j\omega L_1 + \frac{\omega^2 a^2 L_1^2}{Z_L + j\omega a^2 L_1}$$

or rearranging

$$Z_{in} = Z_g + \frac{j\omega L_1 Z_L}{Z_L + j\omega a^2 L_1} .$$

Now allowing L_1 tend to infinity, the input impedance for the voltage source becomes

$$Z_{in} = Z_g + \frac{Z_L}{a^2} . \qquad (3.154)$$

Equation 3.154 is significant as it shows that the source sees the load impedance, Z_L, through the transformer as Z_L/a^2. This means that an ideal transformer has the capability of changing an impedance magnitude. Therefore, to assist circuit analysis, the circuit in Figure 3.70a could be redrawn to its equivalent shown in Figure 3.70b; the impedance connected to the secondary is "transformed" to the primary. The reverse process, primary to secondary, obviously also holds, but the impedance is multiplied by a^2. The impedance angle remains constant in either situation.

Real Transformers. In actual transformers, a source must furnish the power dissipated by the secondary load plus the power to operate the transformer. The additional required power over the ideal situation is created from "losses" within the transformer circuit. The amount of power the transformer can handle (its "capacity") is dependent upon these losses as they are dissipated as heat in the core and the windings. Transformer capacity is limited by temperature, usually specified as an "allowable temperature rise" above ambient conditions, because excessively high-temperatures are destructive to insulation.

The major iron-core transformer losses are winding resistance (copper loss), leakage reactance, eddy-current loss, and hysteresis loss. This section will expand upon the ideal transformer concept to produce a transformer equivalent circuit which will be a good approximation for real- or practical-transformer performance under any condition.

Copper Loss. As the conductors used for the transformer windings have resistance, current flowing in the primary and

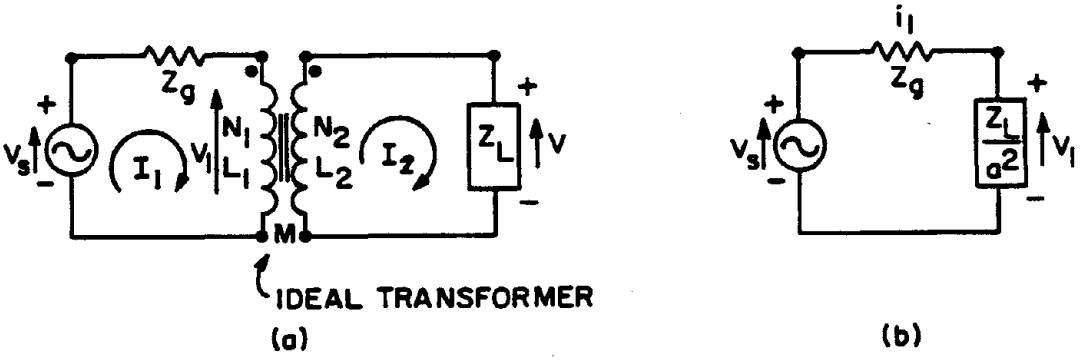


Figure 3.70. Demonstration of Impedance Transfer in Transformers.

secondary produces an I^2R power loss that creates heat. The loss is minimized by larger cross-sectional conductors but, if the resistance cannot be neglected, primary resistance, R_1, and secondary resistance, R_2, can be easily included with the ideal transformer as shown in Figure 3.71.

Leakage Reactance. For the ideal transformer, all the flux produced by the primary must link with the secondary winding. In the real world, however, a small percentage of the total flux produced fails to link all the secondary turns and is called "leakage flux." Leakage flux can be reduced by placing the primary and secondary windings very close together, perhaps interleaving them. Further reduction comes from tightly winding the coils on the core and providing a short magnetic path between (creating a low "reluctance" path between the coils). Nevertheless, even with the best transformer designs, leakage is significant and cannot be neglected.

Inductance is the ratio of flux linkages to the current producing the flux or

$$L = \frac{Nd\phi}{di} \tag{3.155}$$

where

$d\phi$ = magnetic flux, (Wb)

$Nd\phi$ = flux linkage of the circuit, (Wb)

di = current producting the flux, (A).

For transformers with iron (or ferromagnetic) cores, current and flux do not have a linear relationship, and differentials must be used. Consider the time-varying primary current, i_1, in Figure 3.72a, where the changing current produces the magnetic flux, ϕ, and

$$L_1 = \frac{N_1 d\phi_1}{di_1}. \tag{3.156a}$$

The part of ϕ_1 that links the secondary is ϕ_{12} and that which only links the primary or is lost (in terms of magnetic coupling) is ϕ_{L1}, where

$$\phi_1 = \phi_{12} + \phi_{L1} \tag{3.156b}$$

and

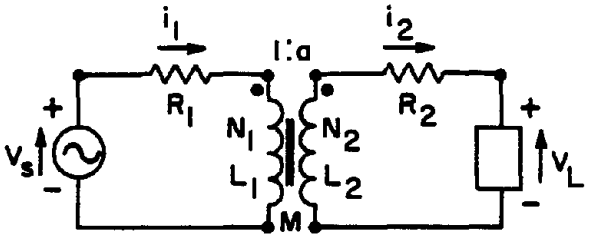


Figure 3.71. Ideal Transformer with Winding Resistance Included.

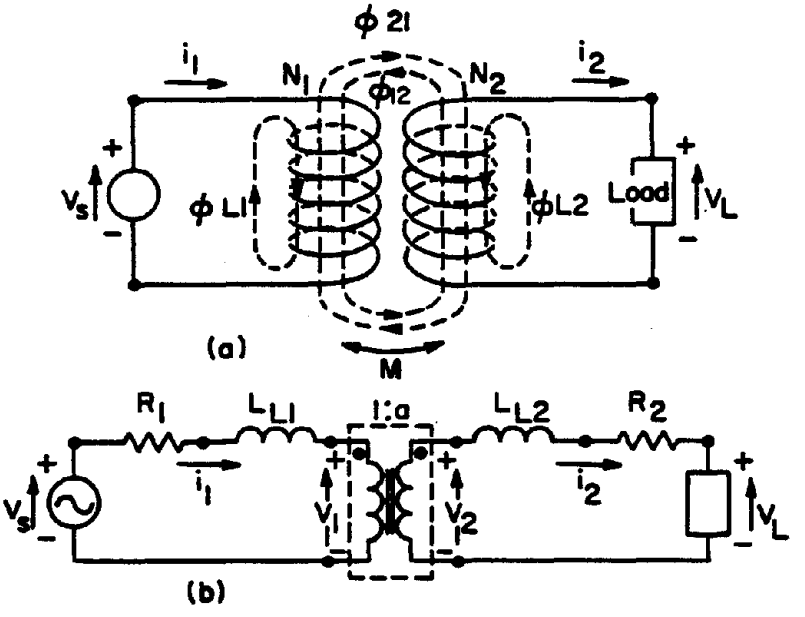


Figure 3.72. Accounting for Transformer Leakage Flux.

$$L_1 = \frac{N_1 d\phi_{12}}{di_1} + \frac{N_1 d\phi_{L1}}{di_1}. \qquad (3.156c)$$

Similarly, although not shown in the figure,

$$L_2 = \frac{N_2 d\phi_2}{di_2} \qquad (3.157a)$$

$$\phi_2 = \phi_{21} + \phi_{L2} \qquad (3.157b)$$

$$L_2 = \frac{N_2 d\phi_{21}}{di_2} + \frac{N_2 d\phi_{L2}}{di_2}. \qquad (3.157c)$$

Interestingly, the coefficient of coupling is also related to flux by

$$k = \frac{\phi_{12}}{\phi_1} = \frac{\phi_{21}}{\phi_2}. \qquad (3.158)$$

The first term in equations 3.156c and 3.157c is the transformer mutual-inductance, and the second terms are the primary and secondary "leakage inductances," L_{L1} and L_{L2}, respectively, or

$$M = \frac{N_1 d\phi_{12}}{di_1} = \frac{N_2 d\phi_{21}}{di_2} \qquad (3.159a)$$

$$L_{L1} = \frac{N_1 d\phi_{LI}}{di_1} \qquad (3.159b)$$

$$L_{L2} = \frac{N_2 d\phi_{L2}}{di_2}. \qquad (3.159c)$$

These equations hold for effective sinusoidal current and, in steady a-c analysis, the leakage inductances become "leakage reactances." Hence, flux leakage can be represented as an inductance or reactance, and Figure 3.72b shows the additional elements which should bring the transformer model closer to practical.

Core Losses and Exciting Current. Even with the addition of winding resistance and leakage reactance, equation 3.153b (for an ideal transformer) still applies and can be rewritten as

$$I_1 = aI_2.$$

Examination of this expression suggests that whenever I_2 is zero, I_1 must be zero. Yet, if an actual transformer primary is connected to an a-c source and the secondary is left unconnected (see Figure 3.73), the primary current still exists, albeit very small. Even though the secondary is open and I_2 is zero, V_2

appears across the secondary winding as a sinusoid. This implies that a changing flux in the transformer's core must be produced by a current in the primary as no other sources of changing flux are available. The small current that produces the changing flux, called "magnetizing current," can be accounted for by adding an inductor, L_e, in parallel with the ideal transformer's primary winding.

Eddy-current loss is a direct result of the changing flux. The flux induces small currents, "eddy-current," in the transformer core material; these have an almost infinite number of closed paths and encircle practically all the flux. Since the iron core has electrical resistance, the result is heat in the core and attendant power loss. The current flows at right angles to the magnetic field as illustrated in the core cross-section of Figure 3.74a. The resistance along the eddy-current path is approximately proportional to the path length. Obviously, if the path length is decreased, the power dissipated in the eddy-current loop will drop. Figure 3.74b shows the core split lengthwise with

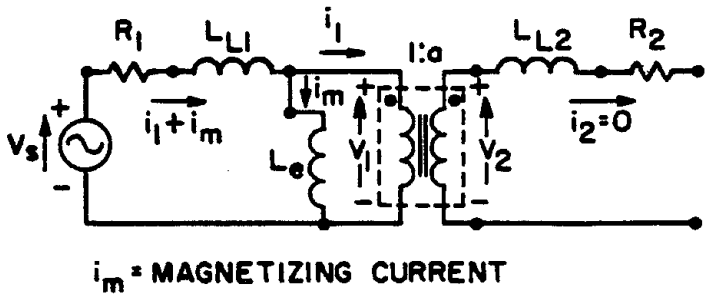


Figure 3.73. Transformer Magnetizing Current.

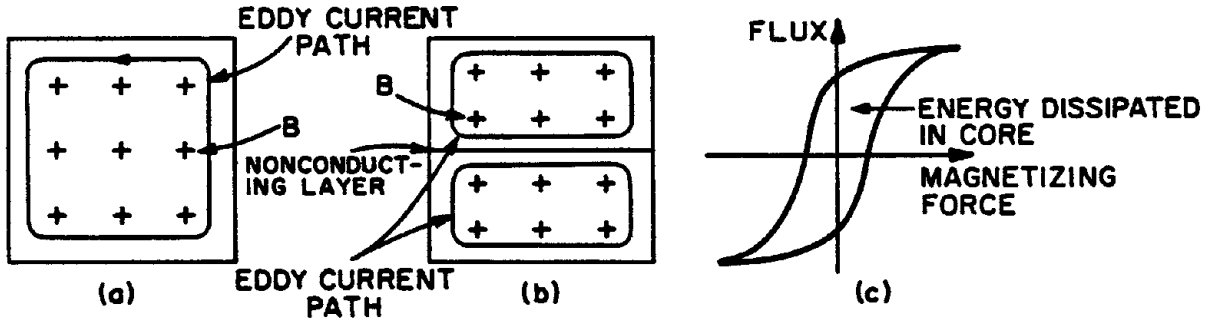


Figure 3.74. Eddy-Current and Magnetic Hysteresis Creating Power Loss in the Core.

a non-conducting layer between the two halves; the result is a desirable decrease in power loss (about two-thirds of original). In practice, transformers are "laminated," made of several thin sheets of steel. Each sheet can be covered with a varnish to act as an insulant but, in most cases, the oxide layer on each steel sheet is sufficient to produce the necessary non-conducting layers. This can substantially reduce eddy-currents but cannot completely eliminate them.

As shown in Figure 3.74c, energy is dissipated in an iron core each time a "hysteresis loop" is traversed. The energy is proportional to the area enclosed in the hysteresis loop and is called the "hysteresis loss" of the transformer core. In simple terms, the effect is related to the fact that the core retains some magnetism, and a "coercive" force is required to overcome this "residual magnetism" each time the a-c current reverses. The loss is due to "retentivity" or molecular friction.

Both eddy-current and, particularly, hysteresis losses are proportional with frequency, and their loss becomes a major consideration in high-frequency applications. However, these core losses can be satisfactorily approximated for one frequency and one voltage (for the primary). Good examples are 60-Hz power transformers where neither frequency nor voltage (actually, magnetic saturation of the core) changes drastically in normal operation. Accordingly, to account for these losses, a resistance, R_e, is again placed in parallel with the ideal transformer's primary. The sum of the currents through R_e and L_e is called "exciting current," I_e, and the total current drawn by the source when the transformer is supplying power to a load is $I_1 + I_e$.

It should be noted that with sinusoidal input voltage to the primary, exciting current is not a sinusoid. Because of the greatly varying permeability of the transformer core, the exciting current has many "harmonic" frequencies. For most purposes, however, it may be assumed as a sinusoid with the same rms value.

The equivalent circuit shown in Figure 3.75 now contains all the necessary components to become a useful model of a practical transformer. In summary, the important parameters are:

1. R_1, primary conductor resistance;
2. R_2, secondary conductor resistance;
3. L_{L1}, primary leakage inductance;
4. L_{L2}, secondary leakage inductance;
5. R_e, a resistance accounting for eddy-current and hysteresis losses;
6. L_e, an inductance accounting for magnetizing current; and
7. an ideal transformer with turns ratio, $a = N_2/N_1$.

Notice that mutual-inductance, M, does not appear in the model as it is represented by the turns ratio of the ideal transformer.

Power-Transformer Construction. The two most widely used transformer construction types are the "core" and the "shell." In shell construction, both primary and secondary windings are placed on an inner leg of the core with the windings constructed in layers, an insulating barrier between. The main result is a very low-leakage flux. For core construction, the primary and secondary windings are located on separate legs. This type provides maximum isolation between the coils. Both constructions are sketched in Figure 3.76.

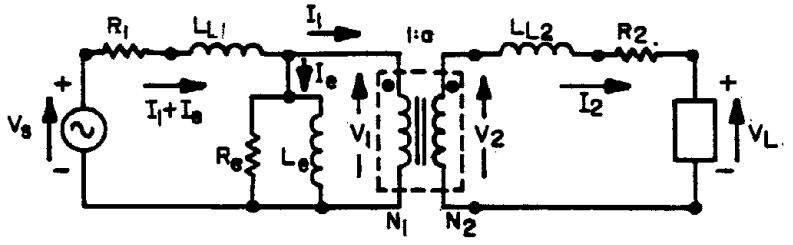


Figure 3.75. Equivalent Circuit of a Practical Transformer.

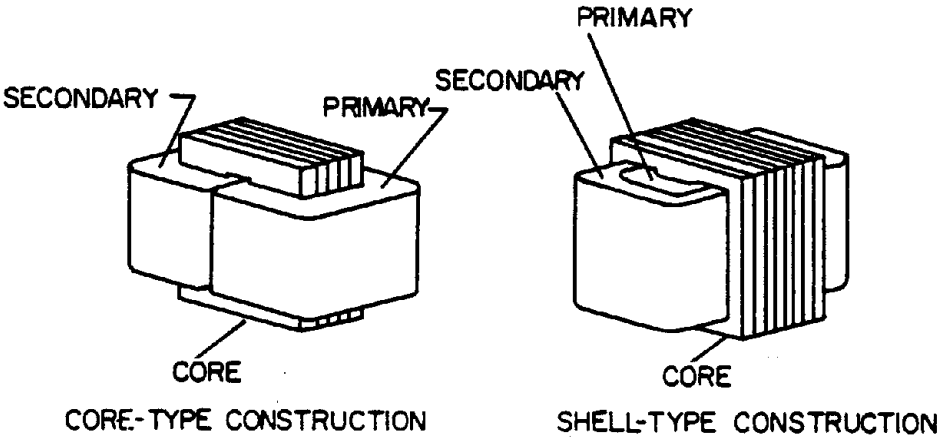


Figure 3.76. Common Power Transformer Construction Techniques.

Transformer Models. As voltage regulation, efficiency, and heating are of prime importance in mine power systems, detailed power-transformer analysis requires the complete equivalent circuit in Figure 3.75. However, realizing that exciting current, I_e, is normally very small compared to load current, I_1, a further approximation can be made by placing R_e and L_e at the transformer input terminals as provided in Figure 3.77. The modification now allows transferring the secondary winding resistance and leakage inductance to the primary circuit (Figure 3.78) and combining these with the primary elements. For many purposes, exciting current is so small that R_e and L_e can be removed from the Model. Figure 3.79 provides this last simplification, where the winding resistance and leakage reactance are said to be referred to the primary and

$$R = R_1 + \frac{R_2}{a^2} \text{ and } L_L = L_{L1} + \frac{L_{L2}}{a^2}. \qquad (3.160)$$

The primary is sometimes called the "high-side" if its winding has a greater voltage rating (or more turns) than the secondary, then the secondary is termed the "low-side." The terminology reverses if the secondary has the higher voltage. In steady a-c analysis, the inductance becomes a reactance X_L, and

$$R = R_1 + \frac{R_2}{a^2} \text{ and } X_L = \omega(L_{L1} + \frac{L_{L2}}{a^2}) \qquad (3.161a)$$

with the primary impedance simply

$$Z = R + jX_L. \qquad (3.161b)$$

If desired, the primary impedance could be moved to the secondary of the ideal transformer (thus, referred to the secondary) by multiplying both terms by a^2.

Transformer-Parameter Determination. Two tests can provide the necessary elements for the transformer model of Figure 3.78 (exciting current components at the primary terminals, secondary parameters referred to the primary).

The first test, the "open-circuit or excitation," is used to find the exciting-current components. The secondary of the transformer is unconnected. Rated voltage at rated frequency is applied to the primary winding. A wattmeter (see Chapter 4, Section 9) is employed to measure the power, P_e, delivered by the source, and an ammeter is used to measure rms exciting-current,

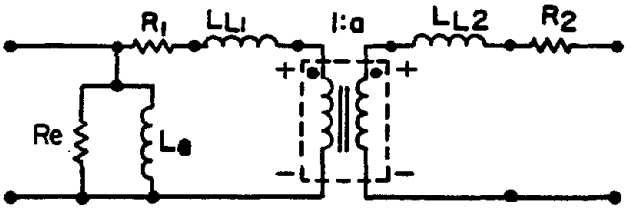


Figure 3.77. Movement of the Exciting Components to the Input.

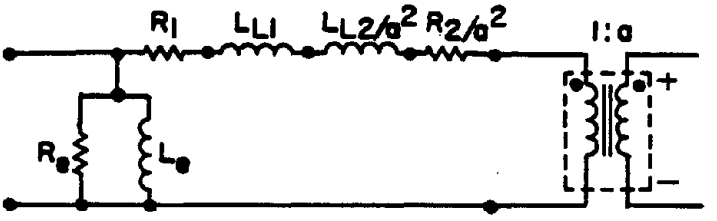


Figure 3.78. Transferring Secondary Components to the Primary.

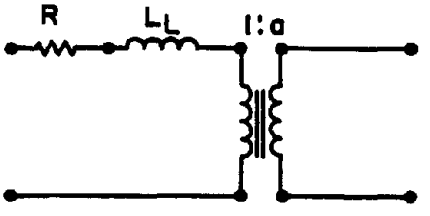


Figure 3.79. Final Simplification of a Practical Circuit Model.

I_e (Figure 3.80a). The power corresponds to the core loss; in other words, P_e is dissipated by R_e. R_e can be found by

$$R_e = \frac{V^2}{P_e} \tag{3.162}$$

where

V = the rms applied voltage (V)

P_e = the measured average power (W)

R_e = the core-loss resistance (Ω).

From the rms value of I_e, assuming exciting current to be a sinusoid, the input admittance of R_e and L_e in parallel can be calculated from:

$$Y_e = \frac{I_e}{V} . \tag{3.163a}$$

Realizing that

$$Y_e = \frac{1}{R_e} + \frac{1}{j\omega L_e}, \tag{3.163b}$$

the component accounting for magnetizing current, L_e, can be obtained from:

$$\frac{1}{\omega L_e} = \left(\frac{I_e^2}{V^2} - \frac{1}{L_e^2}\right)^{1/2} \tag{3.163c}$$

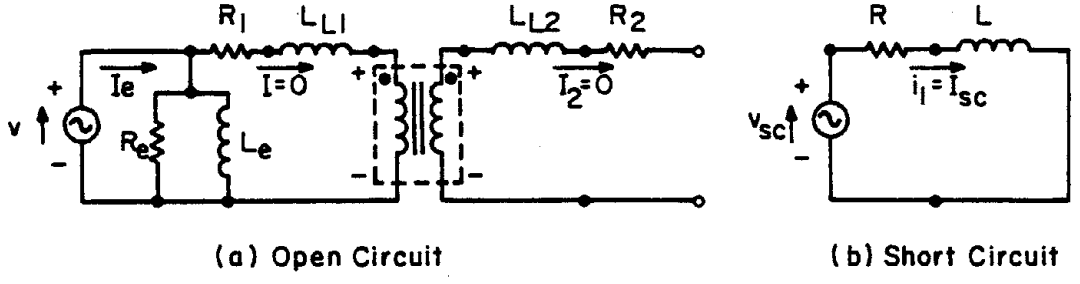


Figure 3.80. Transformer Parameter Test Series.

in which

I_e = the measured rms value of exciting current (A)

$\omega = 2\pi f$ = the applied frequency of the source (must be the rated frequency of the transformer for exact results)

L_e = magnetizing inductance (H).

Therefore, R_e and L_e can be determined from test one.

The second test is projected at winding resistance and leakage reactance (primary and secondary values combined) and is termed a "short-circuit or impedance" test. The secondary terminals are short circuited, and a source is connected to the primary. Voltage at rated frequency is applied to the transformer but at reduced amplitude so only to produce rated current in the primary winding (and thus rated current in the secondary). Current, I_{sc}, and input average power, P_{sc}, are again measured.

The applied voltage for the test is typically much smaller than rated voltage. Yet, the short-circuit (actually, rated) current is much greater than the exciting current so I_e and the associated components can be neglected. As given by Figure 3.80b, the equivalent circuit under these conditions can be simplified to a simple series RL combination. The ideal transformer is not needed because the zero load impedance (short circuit) when transferred to the primary is still zero. Winding resistance and leakage inductance can thus be found from:

$$R = \frac{P_{sc}}{I^2_{sc}} \tag{3.164}$$

and

$$\omega L_L = \left(\frac{V^2_{sc}}{I^2_{sc}} - R^2\right)^{1/2} \tag{3.165}$$

where

P_{sc} = the measured average power (W)

I_{sc} = the measured rms short-circuit current (A)

V_{sc} = the applied rms short-circuit potential (V)

$\omega = 2\pi f$ = the rated frequency

R = primary and secondary winding resistance (Ω)

L_L = primary and secondary leakage inductance (H).

It is important to note again that these values are only valid for the frequency under which the tests are made. Further, it is neither possible nor necessary to break the resultant components into the primary and secondary elements.

Transformer Efficiency and Regulation. Because of winding copper losses and core loss, the output power of a transformer is always less than its input power. The term "efficiency" is used to measure the ability of a transformer to transfer energy from the primary circuit to the secondary circuit and is defined as the average power ratio:

$$n = \frac{P_{out}}{P_{in}} \tag{3.166a}$$

or

$$n = \frac{P_{in} - \text{losses}}{P_{in}} = \frac{P_{out}}{P_{out} + \text{losses}}. \tag{3.166b}$$

Even though the ratio is always less than one, power transformers are designed to be highly efficient devices (n = 0.95 to 0.98). Efficiency does decrease when the device is operated above or below its voltampere capacity.

"Voltage regulation" is a characteristic of power systems and describes the voltage fluctuation that results from varying load or current conditions. Voltage regulation is often applied to transformer secondary voltage variations and is defined as

$$\text{V.R.} = \frac{V_{L(\text{no load})} - V_{L(\text{full load})}}{V_{L(\text{full load})}}(100\%) \tag{3.167}$$

in which

$V_{L(\text{full load})}$ = transformer output voltage at full rated secondary current and rated primary voltage (V)

$V_{L}(\text{no load})$ = transformer output voltage with no secondary load but rated primary voltage applied (V).

It is perhaps clear that voltage regulation is a function of transformer losses, impedance, and efficiency. The concept is extremely important in mine power systems as it often limits how far a mine can be safely expanded from one power source.

Autotransformers. A vital aspect of the preceding two-winding transformers is they provide electrical isolation between the primary and secondary windings. This is desireable for many safety (as well as other) reasons. Although isolation is lost, transformer action can also be obtained with a single-winding; the device is termed an "autotransformer."

To observe autotransformer operation, advantages and disadvantages, an ideal two-winding transformer as in Figure 3.81a can be connected as an autotransformer, Figure 3.81b (the latter, however, is usually constructed with a continuous winding with a "tap" connected, or brought out of, the winding at a specific point). The two-winding transformer has the following specifications:

N_1, V_1, I_1 = primary turns, rated rms voltage, and rated rms current

N_2, V_2, I_2 = secondary turns, rated rms voltage, and rated rms current.

and the maximum apparent power that can be delivered to a secondary load is

$$S_{out} = V_2 I_2.$$

The autotransformer connections are given in Figure 3.82a, but, to help visualize the electrical effect, the circuit is redrawn in Figure 3.82b with both windings placed on the same side of the core symbol. For either figure, the output voltage, V_2', is now:

$$V_2' = V_1 + V_2.$$

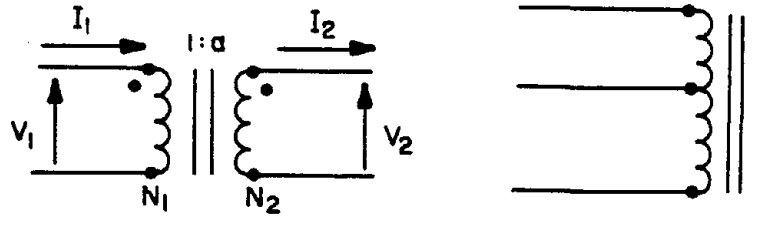


Figure 3.81. Two-winding and Autotransformer Comparison.

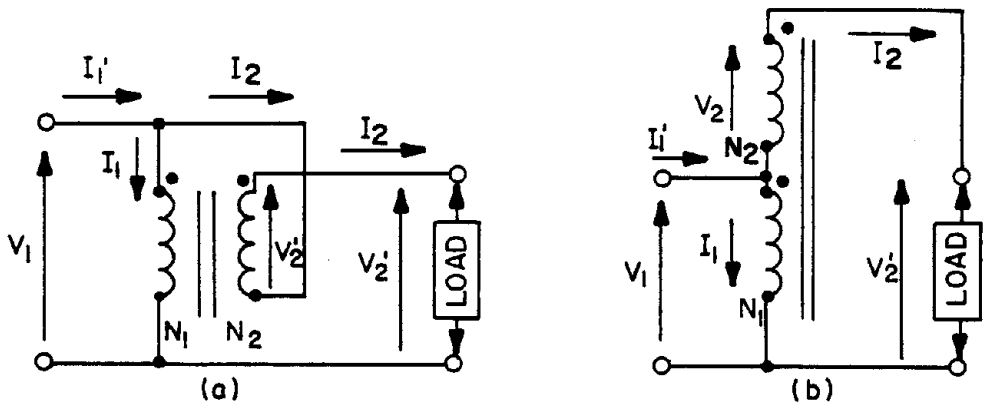


Figure 3.82. Two-winding Transformer as an Autotransformer.

Transformer rated output current, I_2, is still related to rated primary current, I_1, by

$$I_1 = aI_2,$$

but input current to the autotransformer is now

$$I_1' = I_1 + I_2.$$

The maximum power that can be transferred to a load at rated output current, I_2, is now

$$S_{out} = V_2'I_2 + V_1I_2 + V_2I_2.$$

The expression means that the transformer is now able to deliver an increase of V_1I_2 voltamperes over the two-winding connection, yet the transformer windings are still within rated currents and voltages. The fact behind the increase is that some input current is transformed by the transformer while the rest is conducted directly to the load. This is the autotransformer's main advantage over two-winding arrangements. Because primary current is now only a portion of load current, copper losses in autotransformers are especially small, and voltage regulation under varying load conditions is usually good. However, as isolation is lost, some states have outlawed their use in mine power systems for

safety reasons (unless isolation is provided by an additional separate transformer).

Multivoltage Transformers. Transformers considered thus far have had only one secondary, but many have two or more secondary windings. An example of two secondary windings is available in Figure 3.83a, and the reason is to serve loads with different voltage requirements from one source. Magnetic interaction increases substantially over the two-winding variety as mutual inductance exists between all winding combinations. However, taking this into account, the preceding theory can be expanded to model an equivalent circuit.

Winding taps on the primary (Figure 3.83b), secondary (Figure 3.83c), or both are another method of having one transformer serve several voltage applications. When used on the input winding, a higher tap can be selected to account for voltage drops in the circuit delivering power to the transformer, thus maintaining a desired output voltage. This is a common practice on mine-distribution and load-center transformers. A special, but very widely used, application for secondary taps is a utility distribution transformer supplying 240-V and 120-V a-c service. Here, the winding is "center-tapped" with equal turns on either side. The voltage magnitude from either line to the tap is 120 V but, across the total winding, 240 V is available.

Current and Potential Transformers. The prime use of transformers in mine power systems should be apparent now: to supply power at different voltage levels to system portions and equipment. Transformers are also used extensively:

1. to power control circuits (mainly to provide power for circuit breakers and associated circuitry),
2. to power protection devices (usually relays to trip circuit breakers), and

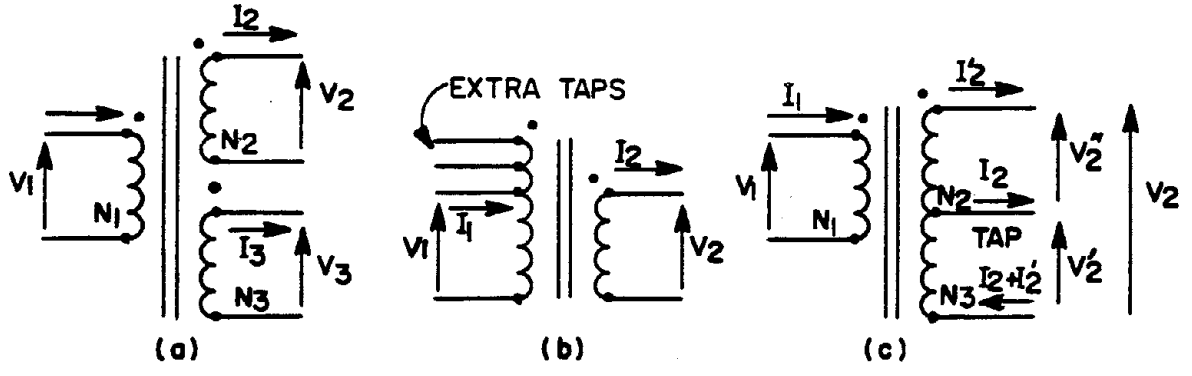


Figure 3.83. Examples of Transformers for Multivoltage Applications.

3. for instrumentation.

Transformers employed for these applications are often given specific names: "potential transformers," abbreviated as PT, and "current transformers," CT. Potential transformers are merely high-quality two-winding transformers with or without taps; the name is modified because they are used to sense voltage.

The current supplied to relays, instruments, and similar equipment is normally provided by current transformers. Some current transformers are like the two-winding devices which have just received so much attention. Illustrated in Figure 3.84a, these have a primary with just a few turns of high-current-capacity conductor and a secondary with numerous turns. The turns ratio (N_2/N_1) is adjusted so the secondary commonly supplies 5 A when full-load current flows in the primary. The primary is placed in series with the circuit that is to be measured and, therefore, CT's can be considered as sensing current.

Two-winding CT's for high-voltage or high-current circuits, such as are usually found in mine power systems, are cost prohibitive, and "bushing-type" or "donut" current transformers are more often used. Sketched in Figure 3.84b, the conductor to be measured passes through a large-diameter ring-shaped laminated iron core and acts as the transformer primary. The secondary winding consists of several turns about the core and supplies current as before. The leakage reactance of this CT type is obviously high and, coupled with other parameters, results in a low accuracy for current measurements. The symbol for either current transformer is available in Figure 3.84c.

A schematic illustrating hypothetical placements of a PT and a CT is provided in Figure 3.85. Also given is a summary of the foregoing purposes and uses. As potential and current transformers are vital protective-circuitry components in mine power systems, they receive further coverage in Chapters 4 and 8.

This chapter section has had more content than any section before it. Beyond the fact that transformers are complex electrical devices, they are mandatory in mine power systems. Chapter 4 will continue the development of transformer fundamentals beyond this single-phase information. The next section, however, will introduce another device vital to many mining operations; the devices are usually connected to power transformer secondaries.

3.11 Semiconductor Devices

General. Through the advancement of technology, the early mining use of motor-generator (M-G) sets and Ignitron rectifiers for power conversion has all but been replaced (except for M-G sets and synchronous rotary converters in specific surface mining equipment) to semiconductor devices.

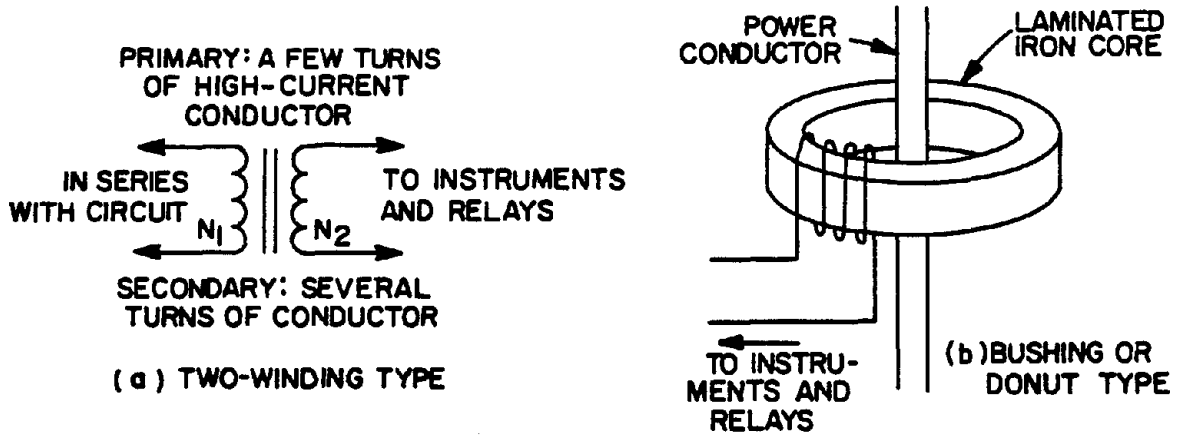


Figure 3.84. Two Types of Current Transformers.

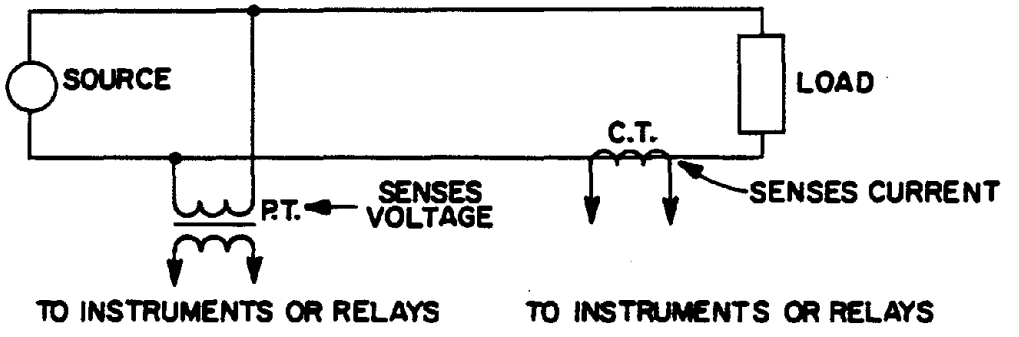


Figure 3.85. Examples of C.T. and P.T. Placement in a Circuit.

Equipment exclusively employing semiconductors to perform their intended functions are often termed "solid-state" or "static." The need for a-c to d-c conversion has been covered in Chapter 2, and semiconductors hold a vital role in present day mine power systems. Their employment has recently expanded from just rectification (the conversion of power to d-c) to now include motor and equipment control, protective relaying, plus lighting power supplies, only to name a few, not to mention the extensive use in communications.

The inclusion of this semiconductor-device fundamental report section is thus imperative. Although vacuum, gas-filled, or metallic (mainly, copper oxide and selenium) devices can perform the same or similar functions, these will not be covered mainly because of minor application to present mining complexes, and the discussion is pointed at semiconductor junction devices. Deviating from the foregoing format to this chapter, many portions of this section are informative rather than theoretical (numerous books have been produced on the subject so it is considered only necessary to cover introductory material).

Semiconductors. "Semiconductors" are nonmetallic elements named for their relatively poor conductivity. Silicon is the most popular semiconductor in electrical or electronic applications with germanium as second. Their usefulness in electrical circuits is that, when impurities or imperfections exist in the crystal lattice, semiconductors can pass current in two different modes. The process of carefully adding impurities to a pure or "intrinsic" semiconductor crystal, while it is being grown, is called "doping." The impurities are other elements that fit into the crystal lattice because of their size and are selected to provide either an excess or a deficiency of electrons.

For example, when a few parts-per-million of arsenic or antimony atoms are used to replaced germanium or silicon, respectively, in the crystal structure, an overabundance of "free" electrons is created. The result is a net negative effect, and the crystal is termed a "n-type" semiconductor. If a potential is placed across the impure crystal, conduction is primarily by an apparent drift of these free electrons.

On the other hand, if indium or gallium is used to dope germanium or silicon, there exists a deficiency of electrons. An excess positive charge is created in the doped crystal, thus it is called a "p-type" semiconductor. Now, if a potential is applied, the atoms conduct current by an apparent movement of electron sites or "holes." These holes are places in the crystal lattice where an electron can be temporarily held. With the abundance of holes, free electrons generated within the crystal quickly recombine with available atoms.

The free electrons in the n-material and the holes in p-material are known as "majority carriers." Because of thermal (and other) energy, free electrons are also available in the p-type, and holes exist in n-type semiconductors. These are called "minority carriers." Nevertheless, even with the excess charge, either semiconductor type is electrically neutral.

Diodes. The operation of most semiconductor devices is dependent upon a "p-n junction," the boundary formed when a piece of p-type is joined with a piece of n-type material. In the actual production, a single semiconductor crystal (or monocrystalline material) is grown so part is doped to create a p-type region with the balance doped for n-type. A solid-state "diode" or "rectifier" has one p-n junction; it is a device that readily passes current in one direction but does not permit appreciable current in the opposite direction. The symbol for a diode or rectifier is given in Figure 3.86a.

Figure 3.86b, a representation of a p-n junction, can be used to explain diode electrical operation. When the two semiconductor materials are joined, a charge redistribution occurs. Both the p- and n-type regions contain a high concentration of majority carriers. Electrons in the n-material "diffuse" across

the junction to the p-material; similarly, holes migrate from the p- into the n-material. The net result of this "diffusion" is a "depletion region" with negatively charged (acceptor) ions on the p-side and positively charged (donor) ions on the n-side of the junction. The electric field on the depletion region, thus established, opposes further majority-carrier diffusion, but the field creates a minority-carrier flow across the junction in the opposite direction.

Current caused by majority-carrier diffusion is called "injection" current, I_I, and from minority carriers, "saturation" current, I_S. If no external voltage is applied to the p-n device (see Figure 3.87a), the junction is in equilibrium as the net hole and electron flow across the junction is zero. In other words, injection current equals saturation current. However, if an external voltage is applied with a polarity such that the p-region is positive with respect to the n-region (Figure 3.87b), the depletion-region electric field is decreased, and a large number of majority carriers are able to cross the junction and diffuse towards the device terminals. Hence, injection current is

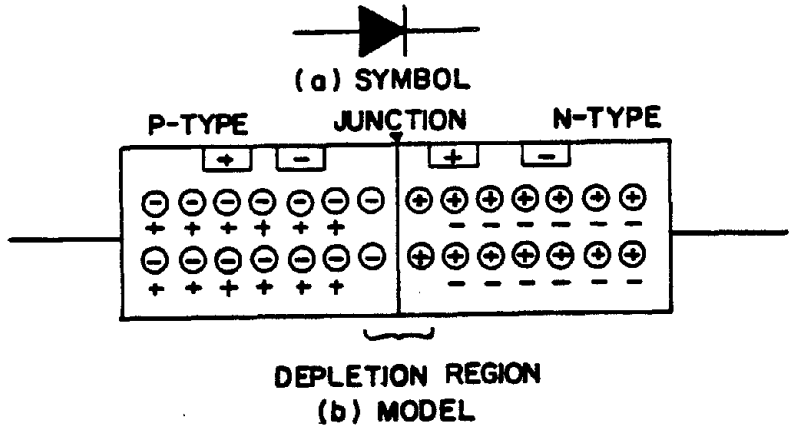


Figure 3.86. Symbol and Operation of a P-N Junction Device.

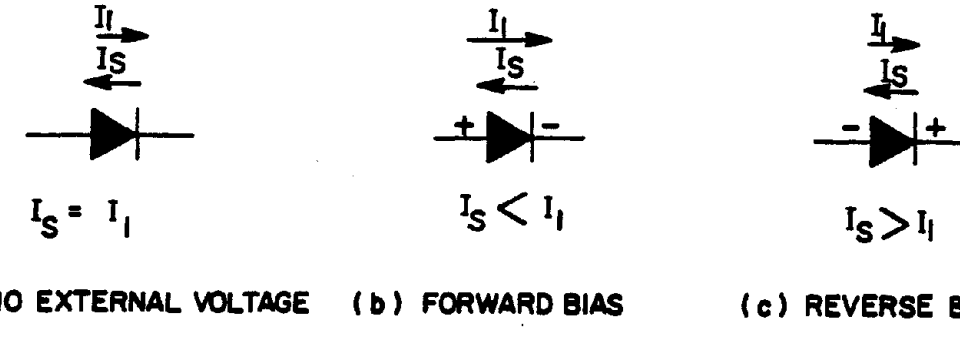


Figure 3.87. Bias Conditions and Current Flow for a Diode.

substantially increased and, because saturation current remains constant, the result is current flow in the external circuit. In this case, the external voltage polarity is called "forward bias," and the current is "forward current." Conversely, "reverse bias," an applied voltage of reverse polarity (Figure 3.87c), opposes majority-carrier diffusion by enforcing the depletion-region electric field, and current is greatly reduced. As saturation current is still constant, the external "reverse current" is primarily a result of minority-carrier diffusion and is therefore very small.

Because there are many more majority carriers than minority carriers, the injection current, under forward bias, is orders of magnitude greater than the constant saturation current. As external circuit current is the algebraic sum of injection and saturation currents, forward current is significantly greater than reverse current. Furthermore, to enhance this one-direction current phenomena, junctions are manufactured so one side of the junction is more heavily doped than the other. Forward current is then mainly a result of majority carriers from the more heavily doped region.

The arrow in the diode symbol is in the same direction as forward current. As a carry-over from vacuum-tube terminology, the arrow is also called an "anode" (the p-region), with the opposite terminal, the "cathode" (the n-region).

Diode Equations. Minority-carrier population is dependent upon temperature and the difference in energy levels between the p- and n-regions. For a constant energy difference, the concentration plus the saturation and reverse currents vary exponentially with temperature. Therefore, temperature is the limiting factor in diode operation; maximum rated current of a given device is determined by the heat dissipation properties of its mounting system.

The formula relating external and saturation current with the energy difference and temperature is

$$I = -I_S\left(e^{\frac{qV}{kT}} - 1\right) \qquad (3.168a)$$

where

I_S = the saturation current (A)

q = the charge of one electron (16×10^{-20} C)

V = the voltage across the junction (less than the external voltage, but approximately equal to it) (V)

qV = the energy difference between the p- and n-materials

k = the Boltzmann constant (1.38×10^{-23} J/°K)

T = the junction temperature (°K).

At room temperature (300°K),

$$I = -I_S(e^{39V} - 1) \qquad (3.168b)$$

or at other temperatures,

$$I = -I_S(e^{39V\frac{T_1}{T_2}} - 1) \qquad (3.168c)$$

where

T_1 = 300°K

T_2 = the other temperature (°K).

The negative sign on saturation current comes from the fact that it is in the opposite direction to forward current. The equations relate that if voltage is 0.1 V or more negative, external current is about equal to saturation current. Therefore, by placing a reverse bias across the device and measuring the resulting reverse current, forward current can be predicted.

The foregoing equations result in the theoretical curve, termed a "characteristic curve," given in Figure 3.88. This curve diverges from that for an actual diode in one main aspect, the "breakdown" of the p-n junction noted at point c. Here, the external voltage meets the limit capabilities of the junction, and a greater reverse voltage will create an "avalanche" current which can destroy the device. Accordingly, p-n junctions normally require a "maximum reverse voltage" or "peak inverse voltage" (piv) rating. "Zener diodes" are of special interest as they operate in this avalanche-current area to "regulate" an applied d-c voltage.

As long as the p-n junction is operated within its reverse-voltage and forward-current limits, the device can be represented by a very low-resistance for forward-bias conditions and a high-resistance during reverse bias. Ideally, and for the majority of applications, a diode can be assumed to have zero and infinite resistance under the same respective conditions.

Rectifier Circuits. A "rectifier" can be considered as a diode specifically designed or applied to convert power to d-c. In mining, the principal application is to use the unilateral properties of the rectifier for direct a-c power conversion. With single-phase a-c, there are three basic rectifier circuits to

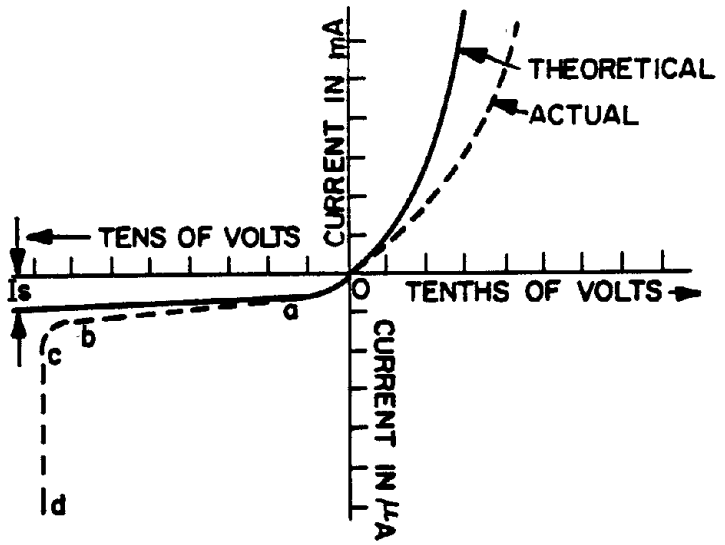


Figure 3.88. Diode or Rectifier Characteristic Curve.

perform this function: "half-wave," "full-wave," and "bridge."

Figure 3.89a illustrates the circuit of a simple half-wave rectifier. A transformer magnetically couples the source to the rectifier, but the same result that will be described occurs with a direct, unisolated source connection. With a sinusoidal-voltage input (Figure 3.89b), the rectifier acts as a switch. When forward biased (positive anode with respect to the cathode), the load, R, is electrically connected to the source but, during reverse-biasing, it is disconnected. In other words, low and high resistance to current exists irrespective of the bias condition. The action creates a "pulsating d-c" waveform across the load as shown in Figure 3.89c. This variation of voltage is also termed "ripple."

As only the positive portions of the input sinusoid appear in the pulsating d-c output, the conversion efficiency of the half-wave rectifier leaves much to be desired. The "single-way" full-wave rectifier is a method of rectifying both the positive and negative portions of a sinusoidal voltage input and can be considered as two half-wave rectifiers. Shown in Figure 3.90a, the circuit utilizes a center-tapped transformer secondary; referenced to ground, V_2 and V_2' waveforms (Figure 3.90b), are then 180° out of phase. Therefore, one rectifier is conducting current (forward-biased) while the other is not (reversed-biased). The consequence is pulsating d-c power to the load during both the negative and positive portions of the a-c input (see Figure 3.90c). The conversion efficiency is greatly improved over half-wave circuits.

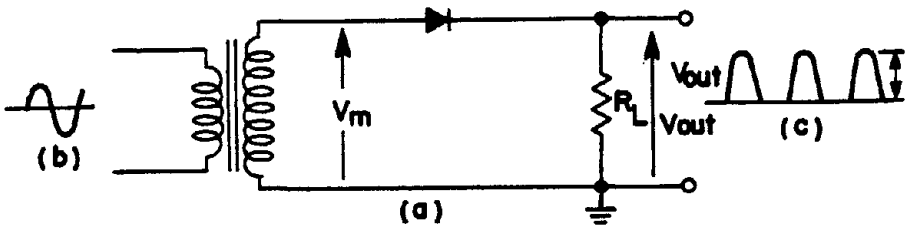


Figure 3.89. Half-wave Rectifier Circuit and Waveforms.

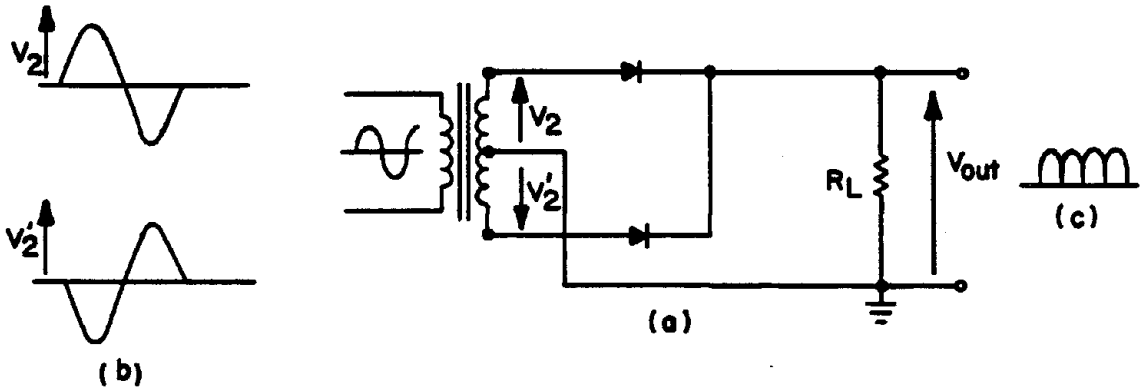


Figure 3.90. Single-Way Full-Wave Rectifier and Waveforms.

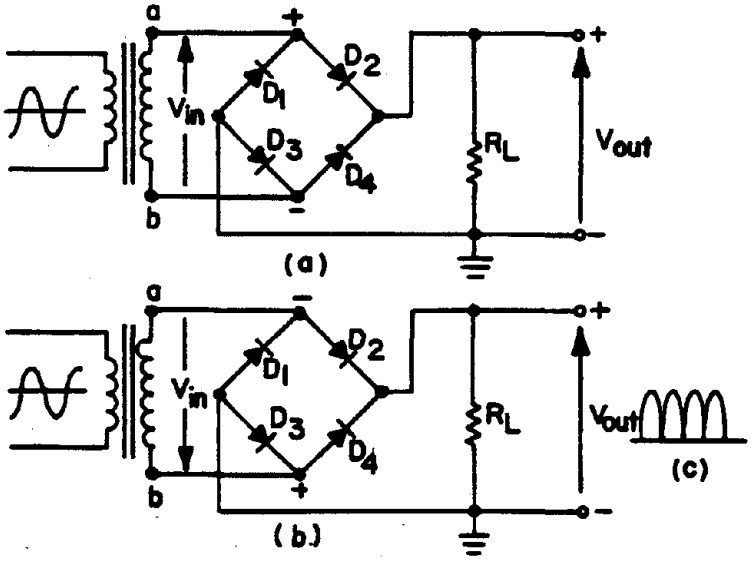


Figure 3.91. Bridge Rectifier Circuit and Waveforms.

Full-wave rectification can also be obtained with the bridge rectifier. As shown in Figure 3.91a, the circuit employs a single-secondary transformer and four rectifiers. During either the positive or negative portions of the input waveforms, two rectifiers are effectively in series with the load resistance. For instance, when the top secondary transformer rectifiers. D_2 and D_3 are forward-biased, but D_1 and D_4 are reverse-biased. Current therefore flows from the top secondary terminal through D_2, R_L, and D_3 back to the transformer. The rectifier-biasing condition reverses with the transformer secondary polarity (Figure 3.91b, bottom), but the current through the load has the same direction. Hence, the same full-wave pulsating d-c waveform in Figure 3.91c appears across the load with only one-half the secondary turns needed for the single-way full-wave rectifier.

Although the output of these three basic rectifier circuits is effective d-c and current flow is in one direction only, the voltage fluctuation or ripple is often too great to be useful. Accordingly, "filtering" is required to change the pulsating voltage to a more ripple-free potential; inductors in series with the load, capacitors "shunting" (in parallel with) the load, or both are employed to smooth the voltage output. An example of this filtering is available in Figure 3.92. In Chapters 4 and 11, when the subject of rectification is again examined, it will be shown that such filtering is not needed for mining d-c power equipment.

Cooling. Earlier, it was stated that the operation of a p-n junction is highly dependent upon temperature. It follows, therefore, that there exists a maximum temperature beyond which the device will be destroyed if operated. Such a point is called the "maximum junction operating temperature" and, for silicon semiconductors, this temperature is usually around 175°C to 110°C. As evident, the maximum does vary from device-to-device and manufacturer-to-manufacturer.

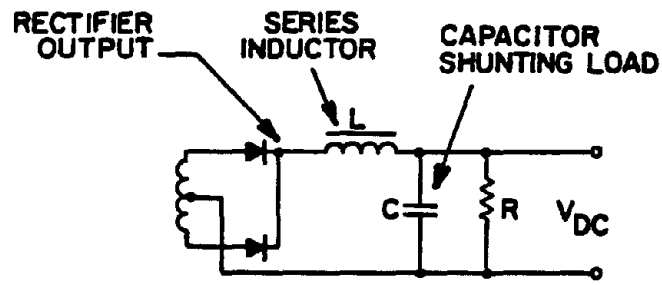


Figure 3.92. Example of Filtering a Rectifier Output.

The temperature at which the junction operates is dependent upon the power dissipated in the junction, the ambient temperature, and the ability of the device to transfer heat to the surrounding environment. Devices designed and operated for small currents usually do not need cooling assistance. However, in p-n junctions dissipating one or more watts, adequate external cooling is required. Here, the simplest method is securely mounting the semiconductor case on a "heat sink," commonly metal with a large surface area. Thermally conductive washers, silicon compounds, and correct bolting pressure allow good heat transfer from the device to the heat sink, then air convection transfers heat to the surrounding atmosphere. In high-power applications, sometimes forced-air cooling of the heat sink is employed to further increase heat dissipation.

Figure 3.93a illustrates a rectifier using a heat sink for this purpose. The diagram in Figure 3.93b represents the relationships of the solid-state device, its heat sink, and the surrounding environment. (It should be noted that this relationship exists for all solid-state devices). The following equation relates these parameters:

$$T_j = \theta_{ja} P_d + T_a \tag{3.169}$$

where

T_j = junction temperature (°C)

T_a = ambient temperature (°C)

P_d = power dissipated by the junction (W)

θ_{ja} = ambient to junction "thermal resistance" (°C/W).

The last item, thermal resistance, is actually composed of three parts as is shown in Figure 3.93b,

$$\theta_{ja} = \theta_{jc} + \theta_{cs} + \theta_{sa} \tag{3.170}$$

in which

θ_{jc} = junction-to-case thermal resistance (°C/W)

θ_{cs} = case-to-heat-sink thermal resistance (°C/W)

θ_{sa} = heat-sink-to-ambient thermal resistance (°C/W).

The junction-to-case and the heat-sink-to-ambient thermal resistances are almost always available from manufacturers. The thermal resistance between the device case and the heat sink can be neglected if mounting is done properly (as was just described).

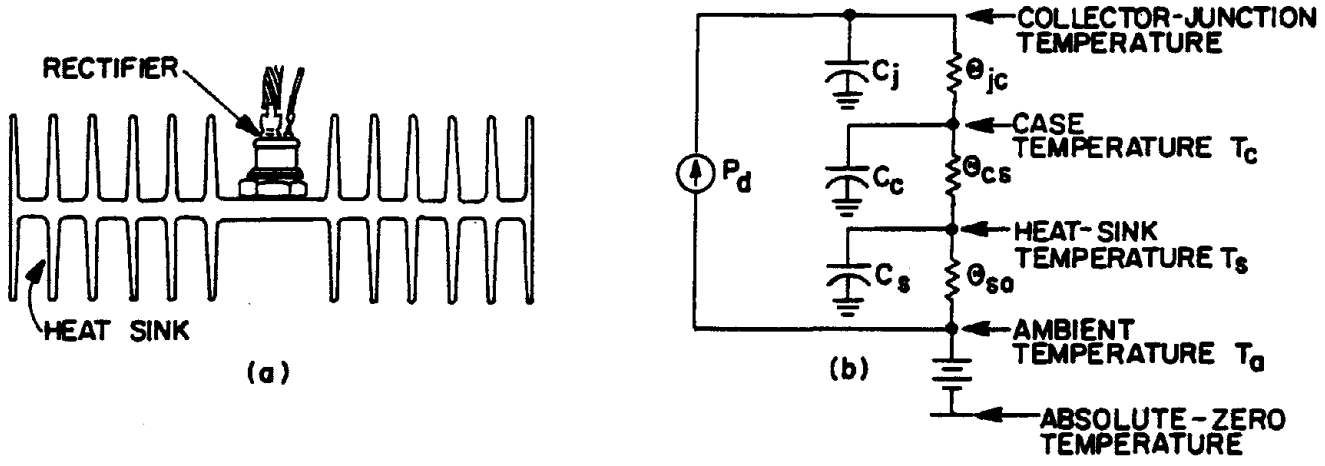


Figure 3.93. Heat-sink Cooling and the Thermal Relationships.

Junction power can be found by the relationship

$$P_d = I_{max} V_f$$

where

I_{max} = maximum forward current (A)

V_f = junction forward voltage drop (V).

The junction-forward voltages normally range from 0.5 to 0.75 V for silicon and 0.2 to 0.3 V for germanium, but typical values for specific devices are also available from manufacturers. With the total thermal resistance, θ_{ja}, known, the operating junction temperature can thus be calculated and compared with the maximum allowed.

Overloads. The thermal relationship of Figure 3.93b shows three capacitances, C_j, C_c, and C_s, which are the thermal capacitances of the p-n junction, the device case, and the heat sink, respectively. An analogy to electrical, thermal capacitance resists changes in temperature. For the p-n junction. C_j is usually very small, hence its time constant is also small. This means that the semiconductor cannot be "overloaded" (excessive power dissipation) for more than just a few milliseconds; otherwise, the device will be destroyed. Accordingly, high-speed overload protection must be applied to semiconductor devices; for

rectifiers, it takes two forms (see Chapter 11):

1. that against excessive overloads and short circuits in load currents, and
2. that against failure in the rectifier itself (say for, overtemperature or excessive voltage).

Transistors. The principal tool of the electronics industry is the "amplifier," a device that can increase the power level of an input waveform or "signal." An amplifier is actually an energy converter where energy from a power supply is converted by the amplifier to signal energy. Many types are in use, and some do not employ electricity. It is beyond the scope of this chapter to describe the operation and circuit arrangement of solid-state arrangements (again, several excellent books are available specifically on the subject), thus the following paragraphs only describe the amplification phenomena existing in semiconductor devices.

A junction "transistor" consists of two junctions in close proximity and parallel to each other in the same crystal. When a p-region is sandwiched between two n-regions, the device is termed a "n-p-n" transistor, a model and the symbol of such are given in Figure 3.94a. Similarly, if the thin portion of n-material is bounded by two p-regions, the transistor is termed "p-n-p," and Figure 3.94b illustrates a model and the symbol of this second type. As listed in the figures, each semiconductor region in both devices is given a name: emitter, base, and collector. The operation of a transistor is dependent upon the bias of each junction.

Operation. Consider first the n-p-n arrangement. If voltages are applied as shown in Figure 3.94a, the emitter-base junction is forward-biased, and the collector-base junction is reverse-biased (these are the normal bias conditions). Thus, electrons will flow into the base region, causing a majority-carrier excess there. Because the base region is made thin and the potential existing across the two n-regions is much higher (than the base-to-emitter potential), most electrons from the emitter region diffuse across the base and are accelerated into the collector region. The electrons drift across the collector and cause current flow in the collector circuit. However, a small percentage (typically, 5% or less) do flow out from the base connection because of recombination with holes in the base region. This phenomenon constitutes an amplifying device as the small base current controls the much larger collector current. A p-n-p transistor operates on the same principle, but hole flow instead of electrons causes the amplification. Accordingly, the bias conditions are reversed from that for a n-p-n (the normal is shown in Figure 3.94b).

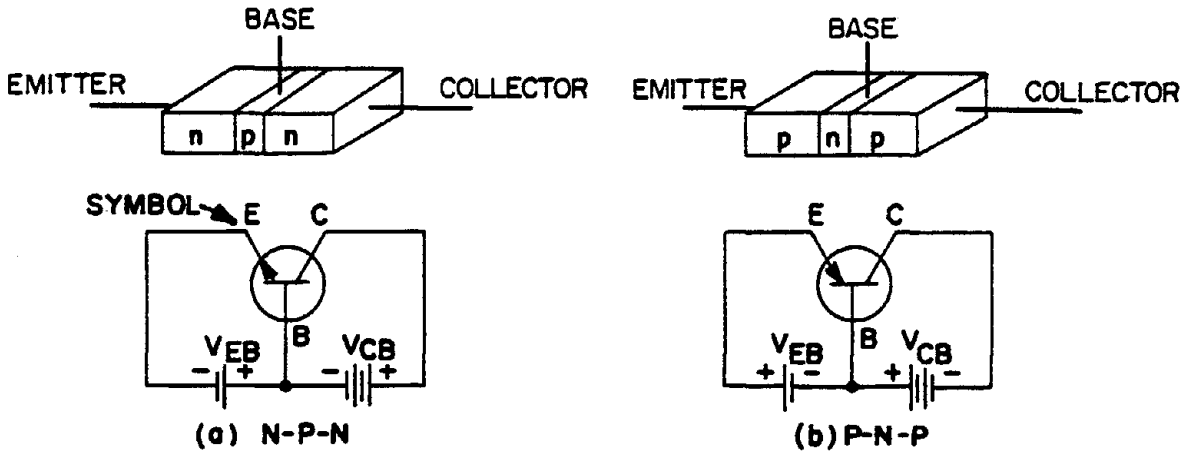


Figure 3.94. N-P-N and P-N-P Junction Transistors.

From the preceding discussion, it seems that either end of the transistor could be called an emitter (either hole or electron flow creates the current amplification), but such is generally not the case. Heat dissipation is much larger in the collector-base junction because of the greater potential difference. Therefore, be they p-n-p or n-p-n, transistors are designed so this collector heat may be diffused.

As might be expected, a saturation current resulting from thermally-generated minority carriers flows across the reverse-biased collector-base junction. In the diode, the current is designated I_S, but it is termed I_{CBO} for a transistor. The increase of I_{CBO} with temperature sets the maximum operating temperature. As with rectifiers, heat sinks are common in high-power transistor applications (to diffuse collector-base junction heat), thus maintaining temperature below critical. The same calculations that were presented in the preceding section apply here also to insure a safe operating temperature.

The fraction of constant emitter current that reaches the collector is called "alpha," α. The collector circuit can be considered the "output" circuit. Hence, it is good to collect as much emitter current as possible, so alpha should be as close to one as possible. When combined with I_{CBO}, collector current, i_C, can be expressed in terms of emitter current, i_E, as

$$i_C = i_E + I_{CBO}. \qquad (3.171)$$

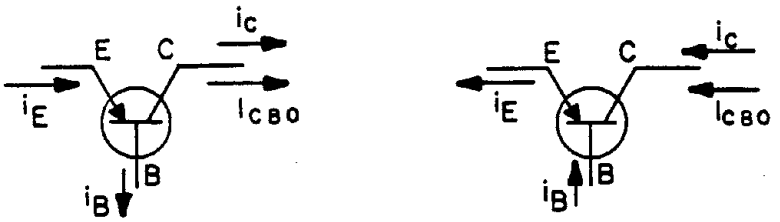


Figure 3.95. Current Relationships for N-P-N and P-N-P Devices.

Figure 3.95 shows the relationships for these currents. In practical applications, I_{CBO} is often so small that it can be neglected.

As base current controls collector current, an important expression can be obtained from Figure 3.95 using Kirchhoff's current law:

$$i_B = i_E - i_C$$

or

$$i_B = i_E - (i_E + I_{CBO})$$

$$i_B = (1 - \alpha)i_E - I_{CBO}. \qquad (3.172a)$$

In terms of collector current, it can be shown that

$$i_C = \left(\frac{\alpha}{1 - \alpha}\right)i_B + \frac{I_{CBO}}{1 - \alpha}. \qquad (3.172b)$$

The term, $\alpha/(1 - \alpha)$, is called "beta," β, the "d-c current amplification factor," and

$$i_C = \beta i_B + (1 + \beta)I_{CBO}. \qquad (3.172c)$$

This last equation shows the significant effect of temperature on transistor operation, i.e., the temperature sensitive I_{CBO} is multiplied by $(1 + \alpha)$. Even though α is less than one, β may range from 20 to 200 for amplifying transistors.

Junction transistors can be operated with any one of the terminals common to the input and output, thus there are three basic circuit arrangements: common-base, common-emitter, and common-collector. The most popular is common-emitter.

Common-base. Illustrated in Figure 3.96, the "common-base" or grounded-base configuration employs the emitter and base terminals as input with the collector and base terminals supplying output. Current "gain," the ratio of output to input, is approximately equal to but slightly less than one. Because of the emitter-base junction being forward-biased, the circuit has low-input impedance (looking into the input terminals), but the output impedance is high in comparison to the input, as the collector-base junction is reverse-biased. With this, voltage and power gain can be realized.

Figure 3.96 actually shows two common-base amplifiers. Two different circuits, signal and bias, are necessary for the operation of either. The bias-voltage sources (often termed the amplifier power supply) fix the d-c level for proper operation of the two junctions. If the signal input and output are not separated electrically from the bias source, shown in Figure 3.96a, the circuit is called a "d-c amplifier." Although very beneficial in many applications (for instance, amplifying d-c voltages for instrumentation), a signal with d-c content or "offset" can interfere with correct transistor biasing. Figure 3.96b illustrates a popular method of removing this problem: the use of capacitors to "isolate" the amplifier. The capacitor exhibits high-impedance to d-c but low-impedance to a-c signals, thus they "block" input and output d-c. Other means, such as transformers, can provide the same function yet, as the circuit now only reacts to a-c signals, it is called an "a-c amplifier."

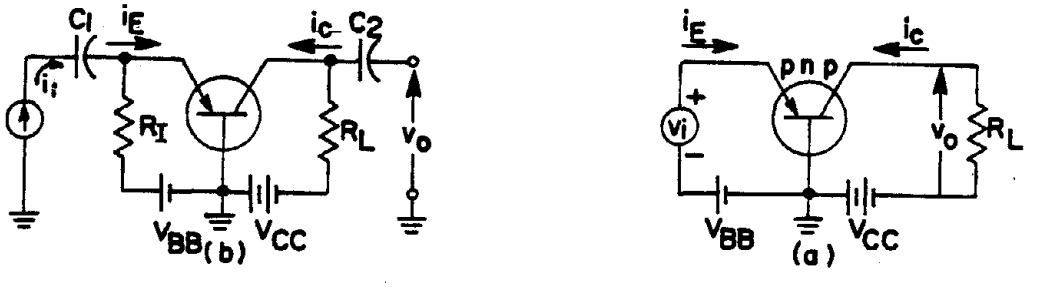


Figure 3.96. Common-Base Amplifiers.

For either case, a small change in input voltages causes significant variation in the injection current across the emitter-base junction. As previously discussed, most majority-carriers diffuse to the collector causing collector current, i_C. If the load resistance, R_L, is small with respect to the transistor-output impedance, i_C is approximately equal to i_E. The collector current creates voltage variations across the load resistance; this constitutes the output voltage, which can be much larger than the input voltage.

Many equivalent circuits have been developed for this amplifier configuration, and the IEEE standard is called the "hybrid-parameter" or "h-parameter" circuit. As with the transformer equivalent circuits covered earlier, these greatly assist analysis of transistor use. However, as common-base amplifier analysis is practically the same as for common-emitter amplifiers, the common-emitter amplifiers are the most used, equivalent circuits and graphical analysis examples are covered in the next subsection.

Common-Emitter Amplifiers. In the common-emitter transistor arrangement, the source signal only supplies current to the base. Because base current is much smaller than either emitter or collector current, current gain, G_i, is high. Neglecting I_{CBO} in equation 3.172c, it is approximately equal to

$$G_i = \frac{i_C}{i_B} = \frac{\beta i_B}{i_B} = \beta,$$

which can be from 10 to several hundred. Attendently, the input impedance is higher than for common-base amplifiers.

Figure 3.97 shows a basic common-emitter amplifier. The control action of base current can be demonstrated by assuming the base-emitter forward-bias is increased. The increase creates a corresponding increase in emitter-base junction current, thus collector current is substantially raised. Because base current is approximately proportional to (but usually much less than) collector current, base current is the control parameter of the amplifier.

The concept of characteristic curves has already been introduced by Figure 3.88 in the section on diodes and rectifiers. Characteristic curves are an extremely useful tool for the design and analysis of transistor circuits. Controlling the number of necessary curves are the four independent transistor parameters. Using Figure 3.97, these are as follows:

1. α and β increase with V_{CE}, the collector-to-emitter voltage
2. i_B is dependent on i_C and V_{CE}

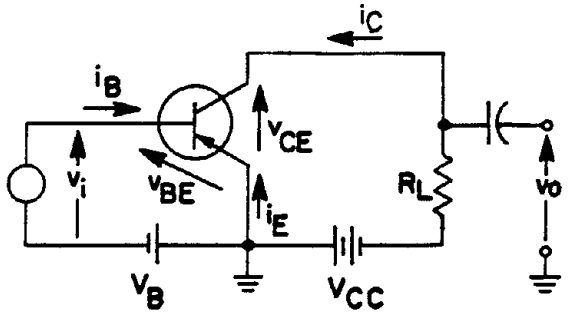


Figure 3.97. A Common-Emitter Amplifier.

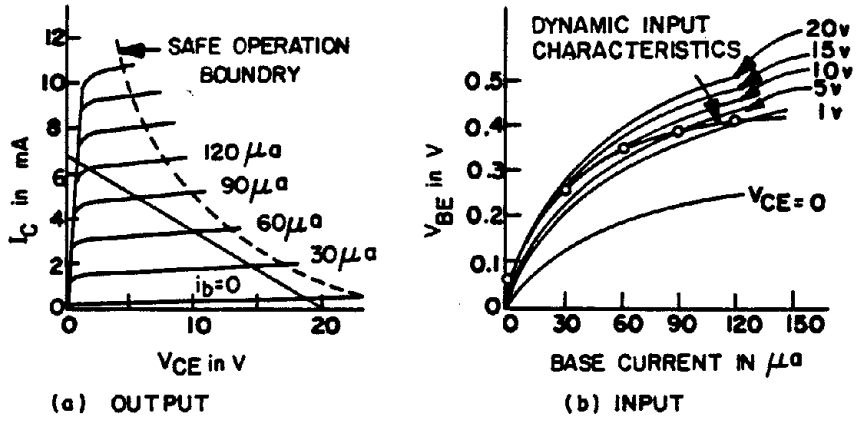


Figure 3.98. Common-Emitter Characteristic Curves.

3. i_B is not a linear function of i_C
4. i_C is approximately zero, when V_{CE} is zero, regardless of i_B.

Consequently, two sets or "families" of curves are needed:

1. collector or output characteristics, i_C versus v_{CE} for varying values of i_B, and
2. common-emitter input characteristics, v_{BE} versus i_B for varying values of V_{CE}.

Figures 3.98a and 3.98b show typical output and input characteristics for a n-p-n transistor connected for common-emitter operation. The non-linear and proportional properties of the four independent transistor parameters are evident in the graphs. Figure 3.99 demonstrates how these curves can be employed for design and analysis purposes. The analysis uses a "load line" to observe

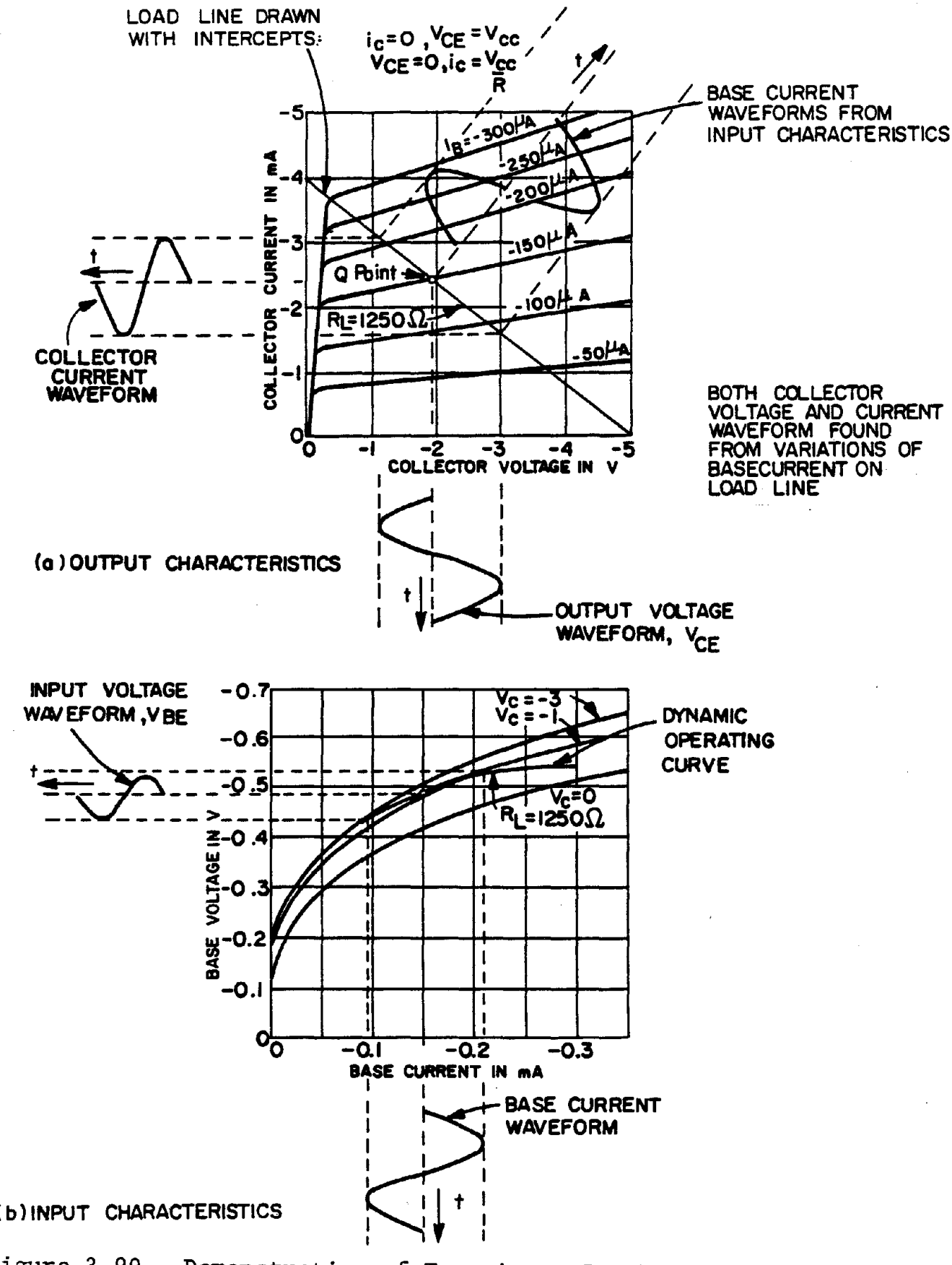


Figure 3.99. Demonstration of Transistor Graphical Analysis.

dynamic variations of voltage and current. In the figure it can be noted that the bias conditions about which the transistor operates is termed the "quiescent point."

The dashed-lines in Figure 3.98 are very important as they delineate a safe-operation boundary. Outside this area, damage to the transistor will probably result; hence, manufacturers specify maximum permissible collector voltage, current, and power dissipation. As noted earlier, allowable power dissipation must be reduced as temperature is increased.

Again employing the four independent parameters, transistor equivalent circuits can be devised. The two most popular are the "T" and the hybrid-parameter (Figure 3.100). The hybrid equivalent is actually a Thévenin's equivalent coupled to a Norton's equivalent circuit by the transfer function, h_f (h_{fe} for common-emitter). Table 3.3 summarizes the mathematics used to find each component for either model as well as for common-base applications. Hybrid-parameters are almost always given by the manufacturers.

Figure 3.97 provides an amplifier circuit with two batteries supplying d-c for transistor bias. A single d-c source is more desireable in practical applications, and four bias techniques are common for common-emitter amplifiers. As shown in Figure 3.101, each uses resistors to supply d-c bias to the base for quiescent-point establishment. Of the circuits illustrated, the "stabilized bias" circuit best affords "thermal stability," maintaining the q-point within a desired or specified range, regardless of normal operation temperature. The "bypass" capacitor, shown across the emitter resistor of that circuit, establishes a constant base bias by bypassing time-varying voltages.

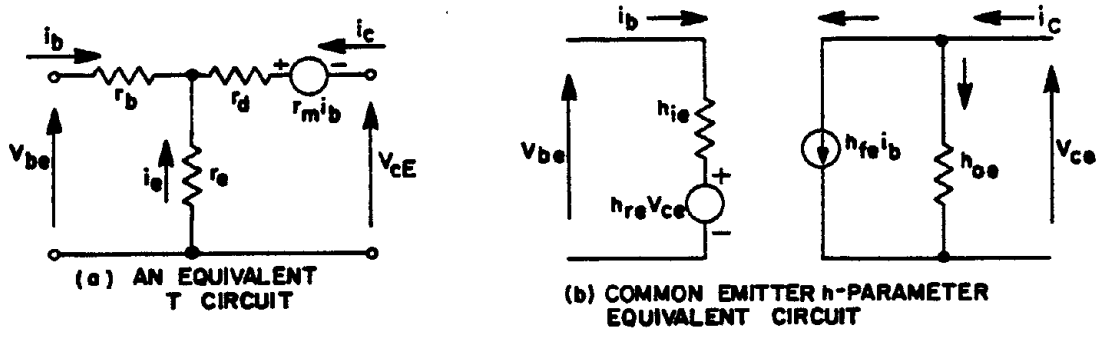


Figure 3.100. Two Equivalent Circuits for Transistors.

Table 3.3. Formulae for the Equivalent Circuits of Figure 3.100.

Hybrid-Parameter Elements (e = common emitter, b = common base) h_i = the input impedance when the output voltage is held constant.

$$h_{ie} = \left.\frac{dv_{BE}}{di_B}\right|_{v_{CE} = \text{constant}} \qquad h_{ib} = \left.\frac{dv_E}{di_E}\right|_{v_c = \text{constant}}$$

h_o = the output admittance when the input current is constant.

$$h_{oe} = \left.\frac{di_c}{dv_{CE}}\right|_{iB = \text{constant}} \qquad h_{ob} = \left.\frac{di_E}{dv_c}\right|_{i_E = \text{constant}}$$

h_r = reverse transfer ratio: the ratio of voltage induced in the input to the output voltage with input current constant.

$$h_{re} = \left.\frac{dv_{BE}}{dv_{CE}}\right|_{i_B = \text{constant}} \qquad h_{rb} = \left.\frac{dv_E}{dv_C}\right|_{i_E = \text{constant}}$$

h_f = forward current amplification factor: the ratio of output current to input current with output voltage constant.

$$h_{fe} = \left.\frac{di_c}{di_B}\right|_{v_{CE} = \text{constant}} = \beta \qquad h_{fb} = \left.\frac{di_c}{di_E}\right|_{v_C = \text{constant}} = -\alpha$$

T Equivalent Circuit.

$$r_b = h_{ie} - (1 + h_{fe})\frac{h_{re}}{h_{oe}} \qquad r_e = \frac{h_{re}}{h_{oe}}$$

$$r_d = \frac{1 - h_{re}}{h_{oe}} \qquad r_m = \alpha' r_c \cong \alpha r_c$$

$$\alpha' = \alpha - (1-\alpha)\frac{r_b}{r_c} \cong \alpha$$

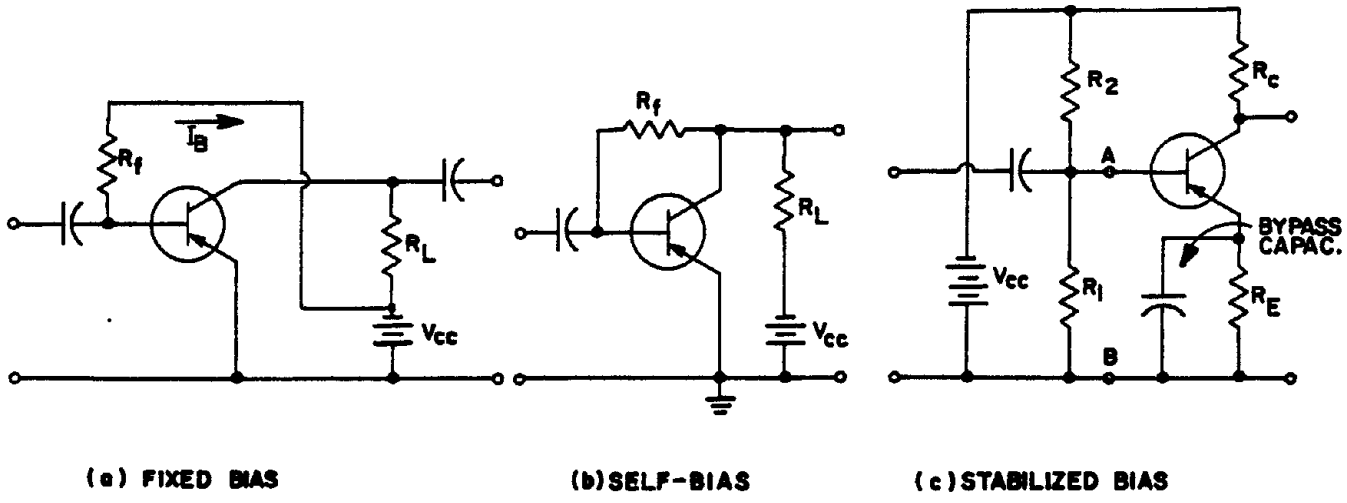


Figure 3.101. Bias Techniques for Common-Emitter Amplifiers.

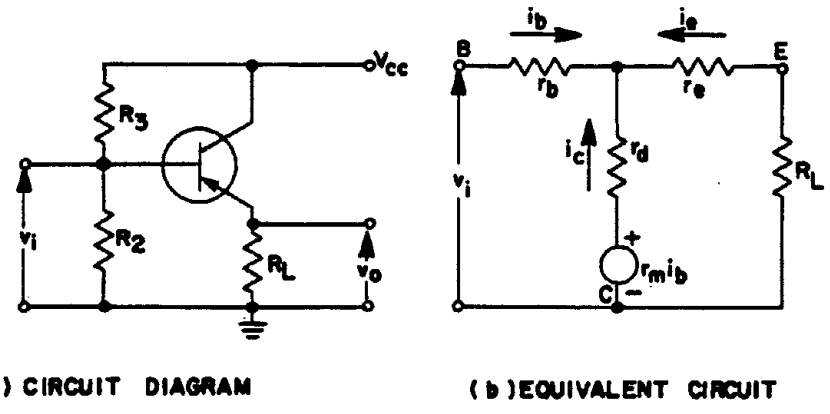


Figure 3.102. Common-Collector Amplifier Arrangement.

Common-Collector Amplifiers. The two preceding amplifier configurations employed the collector circuit for output. In the common-collector arrangement, the output is obtained across a load resistance in the emitter circuit as illustrated in Figure 3.102. Because the source and output voltages are now in series but have opposing polarities, the circuit gives high-input impedance and about unity voltage gain, yet current gain is approximately the same as common-emitter amplifiers. A main advantage to the common-collector is that the output impedance is about equal to the load resistance (lower than the preceding two connections). This allows adjustment to precisely fit the output needs of the circuit; hence, the circuit is used for impedance matching the output of the source signal with the input of another amplifier.

Field-Effect Transistors. Field-effect transistors (FETs) can be classified into two general types: junction FETs and metal-oxide semi-conductor (MOS) transistors. These devices are voltage controlled (junction transistors can be considered as current controlled) and have very high-input impedances, approaching that available from vacuum tubes.

To demonstrate their amplifying action, consider the model of an "n-channel" junction FET cross-section shown in Figure 103a (note, the channel could have either a p- or n-channel). Channel current is controlled by reverse-biasing the gate-to-channel junction. The size of the depletion region about the gate, thus the effective width of the channel, is directly controlled by the level of reverse-bias. Therefore, voltage changes between the gate and the source terminals control the allowable current through the channel from the drain to the source terminals. Figure 3.101b gives the symbols for junction FETs.

An important advantage of FETs over bipolar (two junction) transistors is that the source-to-drain channel is resistive without a diode effect. This allows FETs to be, in essence, operated as electrically-controlled resistors.

In metal-oxide semiconductor transistors (or MOS-FETs), the depletion region used in the junction FET is replaced by a thin layer of silicon oxide, a good insulator, and the semiconductor employed for the gate is replaced by a metal conductor (forming a high-quality capacitor). A model of a MOS-FET is given in Figure 3.104. The operation of these transistors is similar to junction FETs but is much more complex. For the "depletion" type MOS-FET, the channel normally conducts; the gate potential is used to reduce or stop the current. In "enhancement" types, the channel current is normally off, current is allowed to flow by applying the gate potential. The symbols for MOS-FETs are provided in Figures 3.104a and b.

As an application example, Figure 3.105 shows a junction FET used in a typical amplifier circuit. The input signal is applied across the gate to the source, with output taken from drain-to-

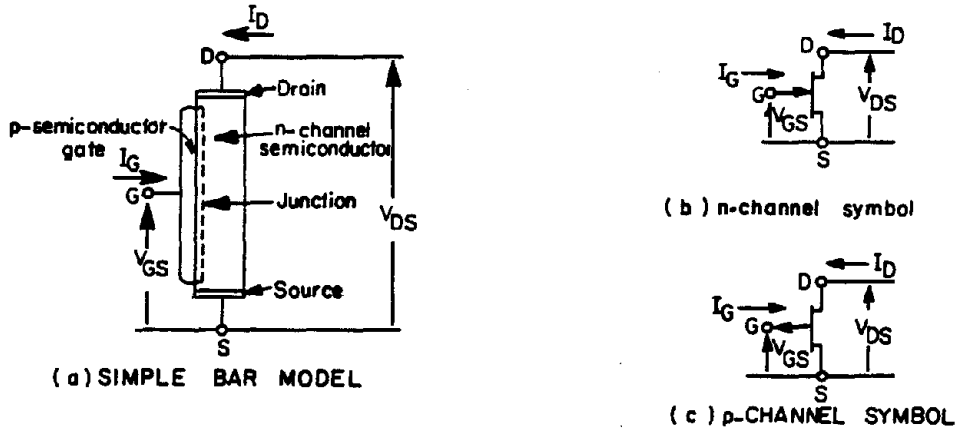


Figure 3.103. Model and Symbols for Junction Field-Effect Transistors.

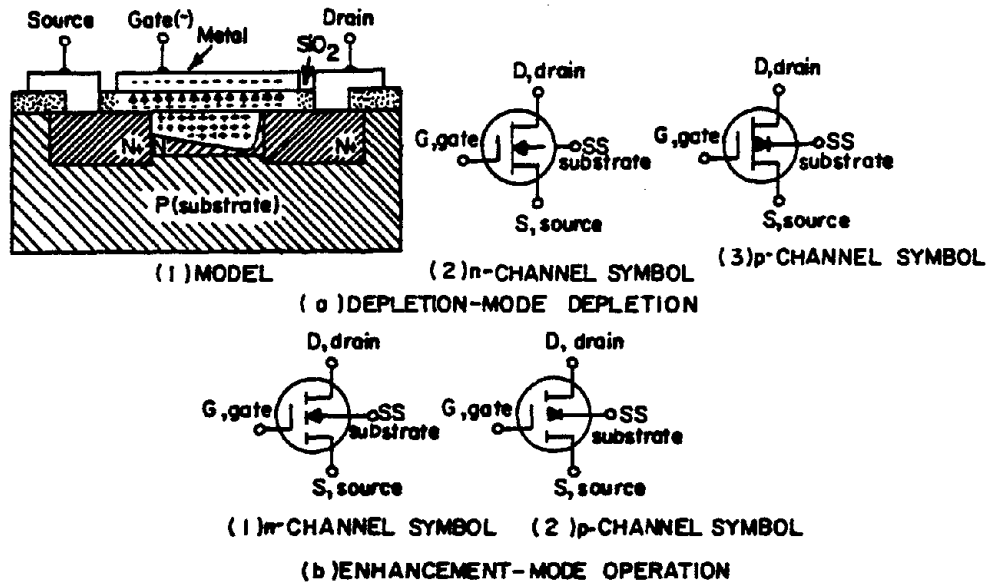


Figure 3.104. Model and Symbols for MOS-FET Devices.

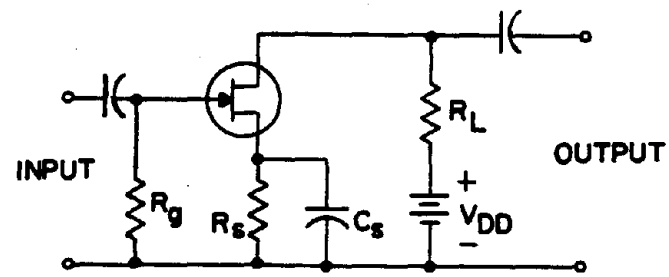


Figure 3.105. A Junction-FET Application Example.

source. R_S is employed to set the proper d-c quiescent-point bias for the gate, and the capacitor in the source circuit bypasses a-c thus maintaining the bias level.

Summary. The preceding information on transistors has been intended as an introduction of a few important devices and for complete information the references must be consulted. Nevertheless, the future employment and referral to transistors in subsequent report sections necessitates the coverage. Frankly, transistors are an extremely important, but often hidden, segment of mine power systems. The next section will cover another device, which has revolutionized the control of electrical machinery.

Silicon-Controlled Rectifiers. In the past few years, the use of solid-state power equipment has accelerated in mining. One primary reason has been the introduction and acceptance of static or solid-state starting of conveyor-belt drive motors. The heart of these starters is the silicon-controlled rectifier or "SCR." SCRs have many other applications; among these, the most commonly found are dimmers for home lighting.

Silicon-controlled rectifiers are three-terminal semiconductor devices, having a four-layer p-n-p-n material combination. Figure 3.106a shows the actual SCR construction (actually, a model), the symbol for a SCR is given in Figure 3.106b, while Figure 3.106c illustrates how the operation of the three-junction combination can be equated to two transistors connected as shown.

The equivalent circuit is represented by one n-p-n and one p-n-p transistor. When the bias on the gate, the n-p-n transistor base, is negative with respect to the cathode, the n-p-n transistor cannot conduct appreciable current; in other words, it is "cut off." As no n-p-n transistor collect current can flow, the p-n-p transistor is also cut off. The impedance between the anode and cathode for this bias condition is high, and the SCR operation condition is called "OFF." However, if the gate bias is made positive so the n-p-n transistor conducts, current will flow into

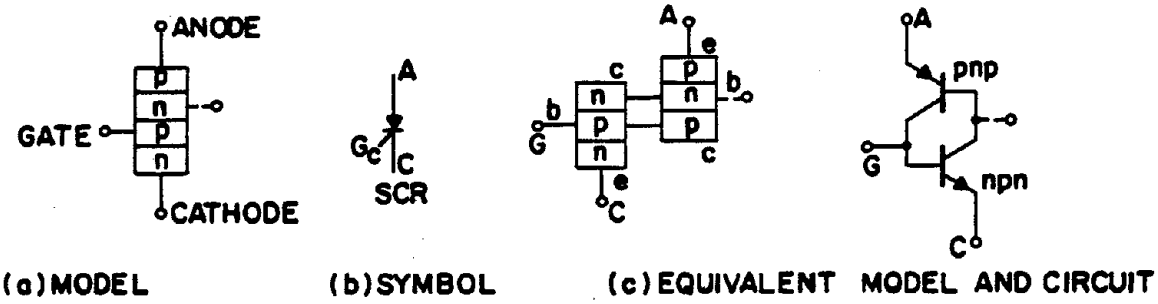


Figure 3.106. Silicon-controlled Rectifier Model and Equivalent.

the n-p-n collector from the p-n-p transistor base. This p-n-p base current in turn causes collector current in the p-n-p transistor. The action between the two transistors has a "positive feedback" effect because an increase in current in one transistor creates an increase in the other. Therefore, once conduction in the SCR is established, the gate no longer has any controlling effect, and the SCR is latched "ON" (i.e., anode-to-cathode impedance becomes very low). Further, the gate cannot turn the SCR conduction OFF. Cessation of current requires a negative gate bias and an essentially zero anode-to-cathode voltage. This allows cut off of the p-n-p transistor. The OFF and ON characteristics are apparent in the typical curve provided in Figure 3.107. The "breakover voltage" noted is that anode-to-cathode potential at which the SCR will turn itself ON.

There are many applications for the SCR or, as they are at times called, the "thyristor." Some of the devices and system components that they replace include:

1. Thyratrons,
2. mercury-arc rectifiers,
3. saturable-core reactors,
4. relays and contactors,
5. rheostats and motor starters,
6. constant-voltage transformers,
7. autotransformers, and
8. mechanical speed changers.

Thyristor applications are a major subject in Chapter 12.

Integrated Circuits. The semiconductor devices discussed so far in this section, if manufactured as single units (e.g., one diode or one transistor), are termed "discrete" components. They must be combined with other electrical and electronic components to perform a required function. Manufacturing processes have been refined so that several transistors, diodes, and resistors can be made in one single circuit or, in other words, on one

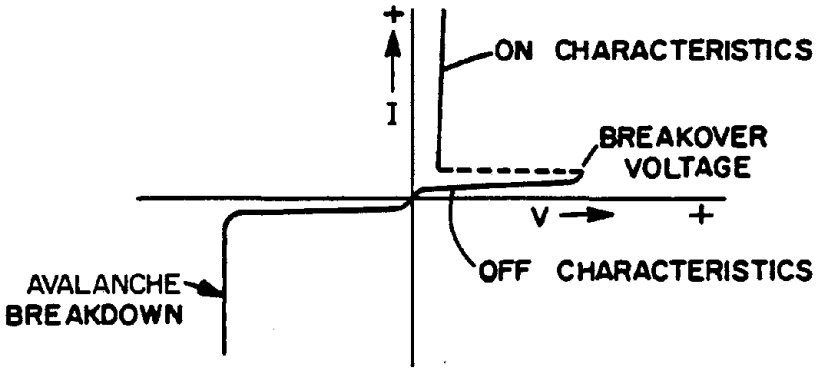


Figure 3.107. General Characteristic Curve for a SCR.

single semiconductor "chip." Such devices are termed "integrated circuits" (IC) with the area in electrical engineering known as "microelectronics." Today, many circuits requiring numerous individual devices, such as complete amplifiers and digital computers, are packaged as a single unit or "micro-circuit." When employing only one semiconductor chip, the IC is called "monolithic," and an example of one such device is shown in Figure 3.108. When the unit is created by the interconnecting of more than one micro-circuit, the device is an "hybrid" IC.

The structure illustrated in Figure 3.108 represents the cross-section of a simple monolithic integrated circuit. The device is fabricated on a chip of p-type semiconductor (termed a "substrate") by forming a number of junctions. The three sections shown are electrically isolated by reversed biased p-n junctions, and the silicon surface is protected by a silicon-oxide layer. On top of this layer is deposited a thin film of metal to interconnect the different regions. The top-view of an actual IC is provided in Figure 3.109. These devices can contain hundreds of transistors but can be small enough to pass through the eye of a needle.

Except for high-power applications, integrated circuits are preferred over discrete-component assemblies. They add reliability to equipment in which they are used while reducing both size and cost. Consequently, IC's are employed where specific circuits required many transistors, diodes, and resistors. In circuit diagrams, commonly only the symbol for the application will be shown; some of these are given in Figure 3.110. Their use is extremely widespread in recently manufactured mining equipment, especially in control and communications applications.

3.12 Summary

The purpose of the foregoing chapter has been to cover many of the basic theoretical aspects behind mine electrical systems. Directed towards d-c and single-phase a-c, the content has spanned fundamental electrical phenomena, the experimental laws and parameters, d-c and a-c circuit analysis, power, transformers, and finally basic semiconductor devices. The comprehension of these laws, parameters, and concepts is necessary to understand subsequent report chapters. This will be very apparent in the next chapter which details power-system concepts and three-phase circuit basics.

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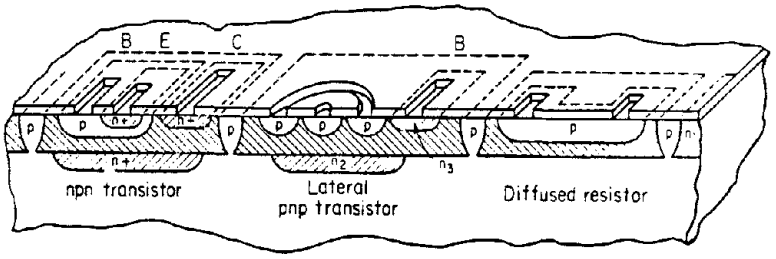


Figure 3.108. Sketch of a Simple Monolithic IC Cross Section.

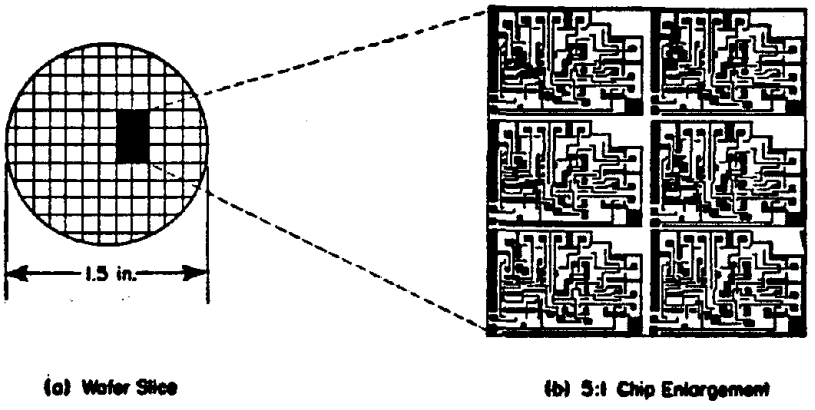


Figure 3.109. Top-view of an Actual Integrated Circuit.

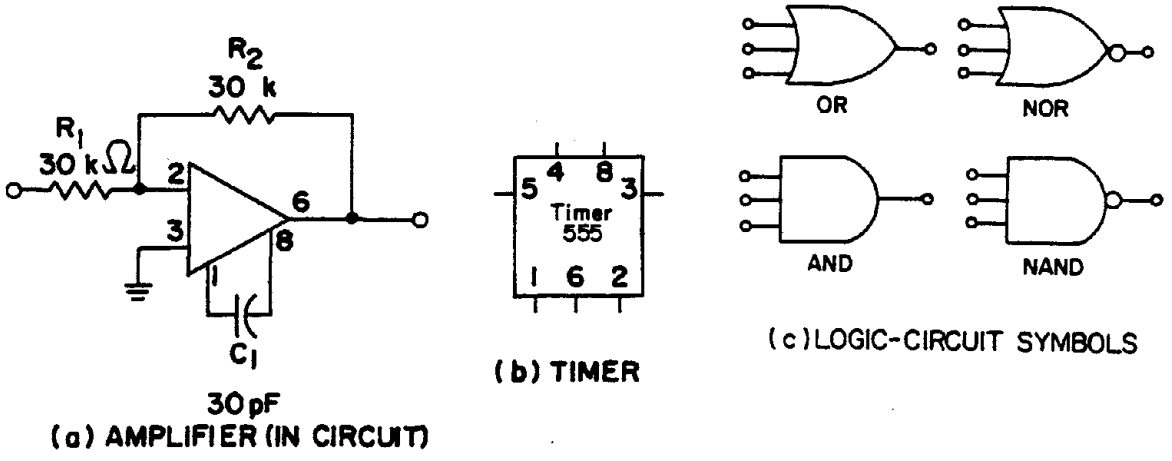


Figure 3.110. Examples of Symbols Employed for Integrated Circuits.

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Chapter 4

POWER SYSTEM CONCEPTS

4.1 General

"Power systems" can be simply described as those which "transmit" power from a source to the loads. For the mine alone as was mentioned in Chapter 2, the source is often the secondary of a substation transformer with the loads being motors on mining machinery and ancillary equipment. The problem, however, is that the transmission of power is commonly performed by "three-phase systems," and the material contained thus far in the report has only detailed d-c and single-phase a-c circuits. Therefore, this chapter builds upon Chapter 3 by introducing many power-system concepts.

The following sections are primarily concerned with three-phase power systems plus the basic tools and special mathematics necessary to study them. Many references have again been employed to assemble the material and are available at the end of the chapter. As most information is considered common electrical engineering knowledge, seldom will a specific reference be cited. Noteworthy, however, is Eaton's Electric Power Transmission Systems (1); this excellent elementary power-system textbook has been especially useful.

4.2 The Basic Power Circuit

Many power systems or system segments can be reduced down to the simple series circuit shown in Figure 4.1. This familiar single-phase a-c circuit consists of a source (or supply) voltage, an impedance, and a load (or "receiver") voltage. Such a representation is often called the "Thévenin's equivalent" of the power system. Finding the series circuit may involve many simplifying assumptions or procedures, some of which are yet to be covered, but the result has numerous applications in analyzing the behavior of electrical power systems.

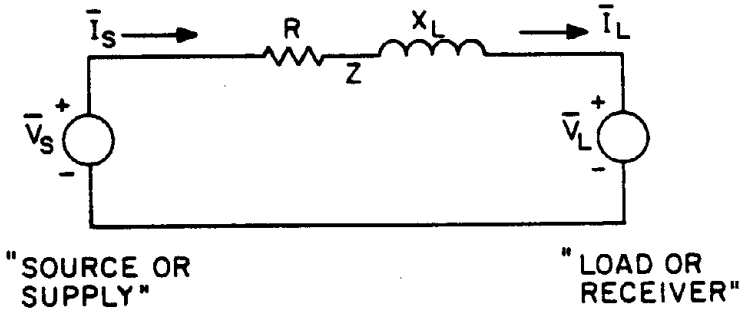


Figure 4.1. The Basic Power Circuit.

One specific analysis example is voltage regulation. Here, the source voltage is kept constant, and variations of the load voltage are observed with a range of load-current conditions (causing a change in voltage drop across the impedance). Applying the thought to an underground coal mine, the source could be the secondary of a load-center transformer, the impedance would be that of the trailing cable, and the load might be the motors of a continuous miner. On a larger scale, a substation output voltage, feeder cable, and load-center primary voltages could constitute a desired Thévenin's equivalent for analysis. Both these situations are illustrated in Figure 4.2. As the chapter unfolds, more applications will become apparent.

Actual analysis of the basic power circuit (Figure 4.1) can use any applicable technique already given in Chapter 3. For instance, employing the impedance domain and Kirchoff's voltage law yields:

$$\bar{V}_s - \bar{I}Z - \bar{V}_L = 0$$

or

$$\bar{V}_s = \bar{V}_L + \bar{I}Z$$

and

$$\bar{V}_L = \bar{V}_s - \bar{I}Z.$$

With such, any variable or constant can be a complex expression. Nevertheless, the equations describe the "performance" of the power system for which the circuit represents (i.e., source voltage for a specific load current and load voltage, and so forth). When three-phase systems are involved, the solution (even the finding of the equivalent circuit) must also utilize the additional methods that follow in this chapter.

4.3 Three-Phase Circuits

A continuous sine wave of an alternating-current is often referred to as a "phase." The term, "single phase," has been applied to a-c systems where power is delivered from a single sinusoidal source. When power is transmitted to a load by applying two or more sinusoidal sources with fixed phase differences, the power system is called "polyphase." The most popular system that delivers large quantities of power (including both single-phase and polyphase) is three-phase.

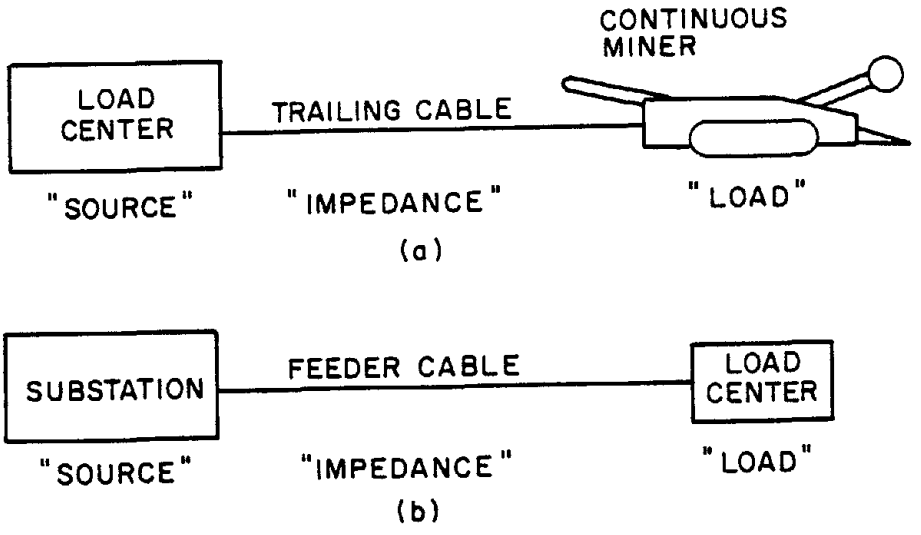


Figure 4.2. Applications of the Basic Power Circuit.

The analysis of three-phase circuits can be extremely complicated. Special techniques have been developed to assist with general problem solutions (see Section 4.4) but even so the work can be cumbersome. However, three-phase power systems are purposely designed to be "balanced" and, if actual differences existing among phases can be neglected, the analysis of three-phase circuits can be almost as simple as single-phase.

4.3-1 Balanced Three-Phase Circuits

Generation. Balanced three-phase power consists of three generated voltages, each of equal magnitude and frequency but separated by 120°. When these voltages are applied to a system of balanced impedances, balanced currents result. In other words, a balanced three-phase power system can be divided into three portions. Any voltage or current in one portion has a counterpart in another portion which is identical but 120° out-of-phase.

To illustrate this voltage generation, consider the elementary three-phase generator illustrated in Figure 4.3a. The armature consists of three single stationary conductors displaced by 120°, and a magnetic field structure rotates counterclockwise within. As the rotating magnetic flux cuts each winding, a voltage is induced. These are out-of-phase with one another as shown in Figure 4.3b. A composite of these instantaneous voltages is provided in Figure 4.3c to exemplify the phase relationships, which also can be clarified with phasors (Figure 4.3d). It can be noted with either representation that the voltage in winding aa' reaches a

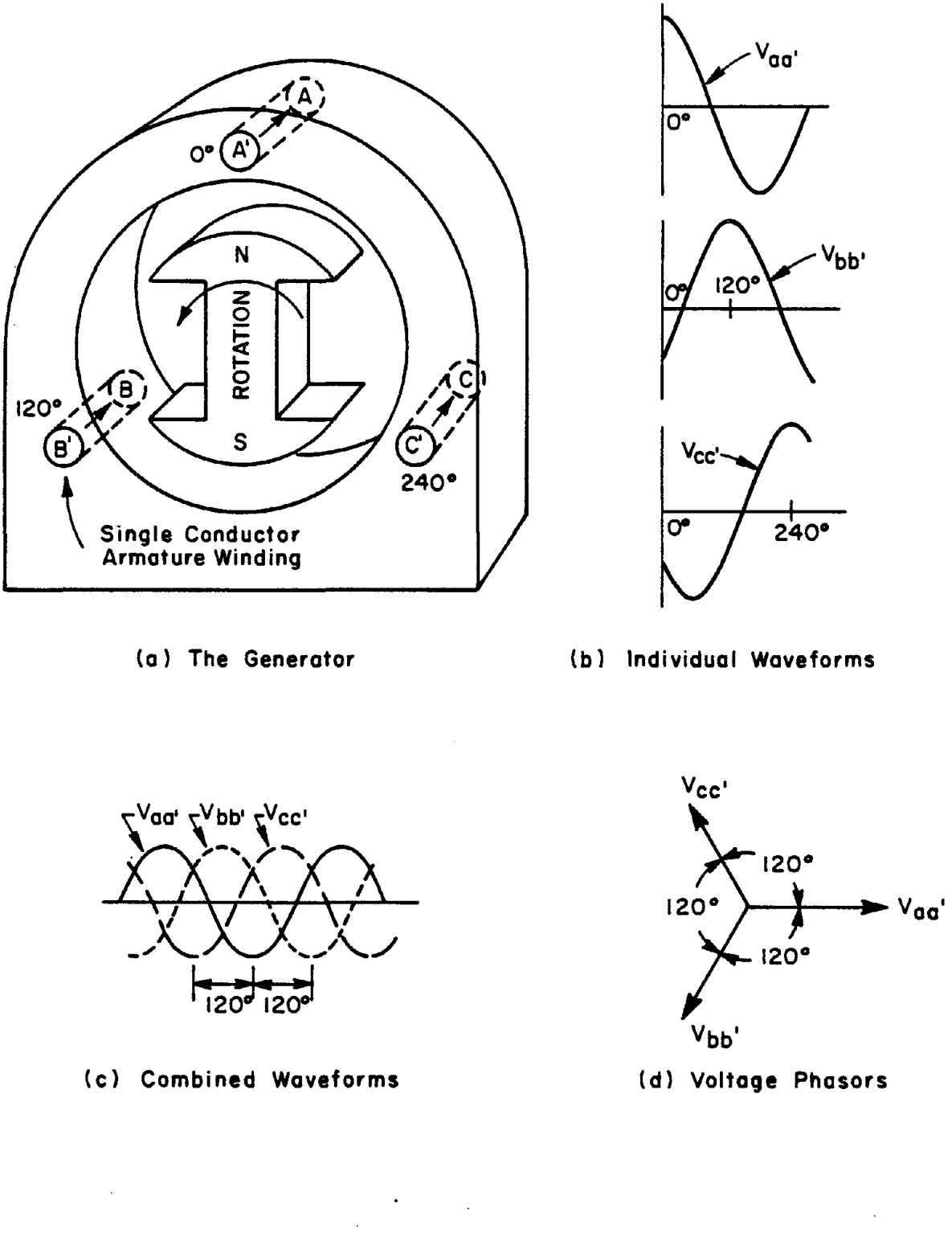


Figure 4.3. Elementary Three-Phase Generation.

maximum first, followed by bb', and then cc'. Such defines the "positive sequence," abcabc....., that is evident from the counterclockwise-rotating phasors of Figure 4.3d. If the phasors were allowed to rotate in the opposite direction (clockwise), the sequence is termed "negative" (cbacba.....).

An outstanding advantage of balanced three-phase systems is that they provide a more uniform flow of energy than single-phase (and even two-phase). The 120° timing results in the individual power waves (in each phase) never reaching zero at the same time and, more importantly, the total instantaneous power from all three phases remains constant. For three-phase motors, this translates to convenient starting, constant torque, and low vibration. It would seem logical that if three-phases provide a substantial increase in operating efficiency, more equally spaced phases would result in an additional improvement. However, three-phase systems are generally more economical than other polyphase systems as the complications of additional phases offset the slight efficiency increase.

A source supplying these three-phase voltages is normally connected either in delta or wye. As shown in Figure 4.4, either configuration can in practice be closely approximated by ideal voltage sources (or, in some cases, ideal voltage sources in series with small internal impedances). Three-phase sources always have three terminals, called "line" terminals, but may have a fourth terminal, the neutral connection. These produce three separate potentials between any two line terminals, which are called "line-to-line" voltages. Also generated are three separate voltages between each line terminal and the neutral, be it a direct connection as in Figure 4.4c or some imaginary neutral joint; these are termed "line-to-neutral" potentials.

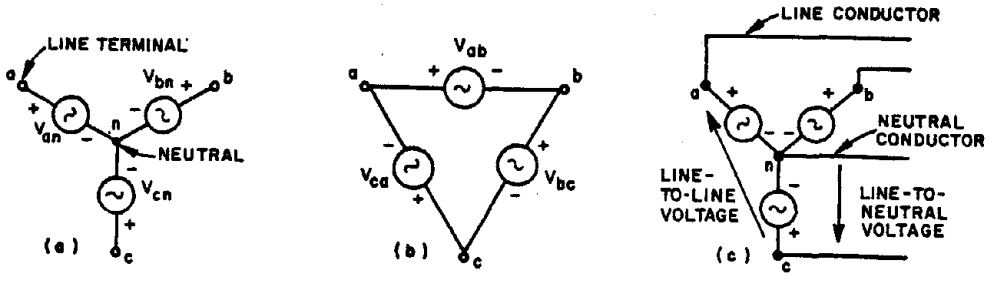


Figure 4.4. Three-Phase Voltage Sources.

Three-Phase System Voltages. Line-to-line voltage can be considered as a condition existing between two phases, while line-to-neutral is a condition for one phase only. Obviously, there must exist interrelationships between these two voltage notations, as well as among voltages of one notation. The wye-connected source of Figure 4.5a can be employed to demonstrate the correspondence.

If the line-to-neutral voltages, $\bar{V}_{an}$, $\bar{V}_{bn}$, and $\bar{V}_{cn}$, are positive sequence and the phasor of $\bar{V}_{an}$ is taken as a reference, then $\bar{V}_{bn}$ and $\bar{V}_{cn}$ are related to $\bar{V}_{an}$ by:

$$\bar{V}_{bn} = \bar{V}_{an}\angle -120° \qquad \bar{V}_{cn} = \bar{V}_{an}\angle -240° \tag{4.2a}$$

or

$$\bar{V}_{an} = \bar{V}_{bn}\angle +120° = \bar{V}_{cn}\angle -120°. \tag{4.2b}$$

Equations 4.2a and b relate that if a specific phasor (representing one phase voltage) is rotated 120°, it is identical to the phasor for another phase. By Kirchhoff's voltage law, the line-to-line voltage is equal to the sum of the two line-to-neutral voltages; for instance, between phases a and b,

$$\bar{V}_{ab} = \bar{V}_{an} + \bar{V}_{nb} \tag{4.3a}$$

but

$$\bar{V}_{nb} = -\bar{V}_{bn}$$

and

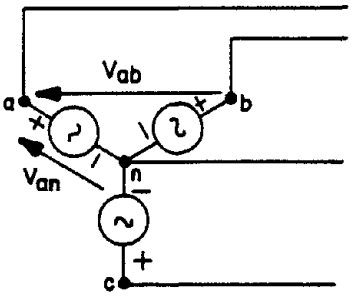
$$\bar{V}_{bn} = \bar{V}_{an}\angle -120°,$$

hence,

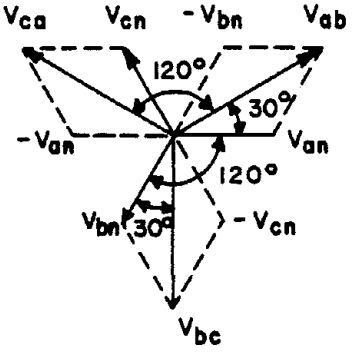
$$\bar{V}_{ab} = \bar{V}_{an} - \bar{V}_{an}\angle -120° \tag{4.3b}$$

or

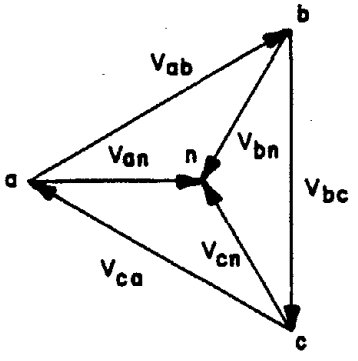
$$\bar{V}_{ab} = \sqrt{3}\,\bar{V}_{an}\angle +30°. \tag{4.3d}$$



(a) A Three-Phase Wye Source



(b) Line-to-Line and Line-to-Neutral Voltage Phasors



(c) Graphical Construction

Figure 4.5. Wye-Connected Source Demonstrating Line-to-Line and Line-to-Neutral Voltages.

Equation 4.3d is truly significant because it states the relationship between line-to-line and line-to-neutral voltages for balanced three-phase systems. In particular, the following can be extracted:

$$|V_{ab}| = |V_{bc}| = |V_{ac}| = \sqrt{3}|V_{an}| = \sqrt{3}|V_{bn}| = \sqrt{3}|V_{cn}| \qquad (4.4a)$$

and

$$|V_{an}| = |V_{bn}| = |V_{cn}| = \frac{1}{\sqrt{3}}|V_{ab}| = \frac{1}{\sqrt{3}}|V_{bc}| = \frac{1}{\sqrt{3}}|V_{ca}|. \qquad (4.4b)$$

It is important to note that, in addition to the foregoing identities, for a balanced three-phase system:

$$\bar{V}_{an} + \bar{V}_{bn} + \bar{V}_{cn} = 0 \qquad (4.5a)$$

and

$$\bar{V}_{ab} + \bar{V}_{bc} + \bar{V}_{ca} = 0. \qquad (4.5b)$$

A phasor diagram illustrating all line-to-line and line-to-neutral voltages of these systems is given in Figure 4.5b. Here, the correspondence by equation 4.3d is apparent.

The same reasoning, that has just been used for voltages, can be applied to currents; this will be handled shortly.

Load Connections. As with sources, balanced three-phase loads can be connected delta or wye. However, the interest in three-phase transmission comes from how delta or wye sources supply power to delta or wye loads. The usual combinations are:

1. four-wire, wye-to-wye;
2. three-wire, wye-to-wye;
3. wye-to-delta;
4. delta-to-delta; and
5. four-wire wye-to-delta.

By analyzing each combination, certain advantages and disadvantages can be seen, and some important points about balanced three-phase systems can be gained. Such is available in the following discussion. To enhance the presentation, the lines connecting sources to loads are assumed to have no impedance (obviously, in the real world, they must have impedance).

Figure 4.6a shows the first arrangement to be considered, the "four-wire wye-to-wye." The source here could be either a generator or secondaries of an ideal three-phase transformer; the load, Z_a, Z_b, Z_c, could be, for example, a motor. These conductors are connected between the source line terminals and the load; the fourth conductor, the "neutral return" (or just simply, the "neutral"), connects the neutral of the source and the common junction of the three load impedances.

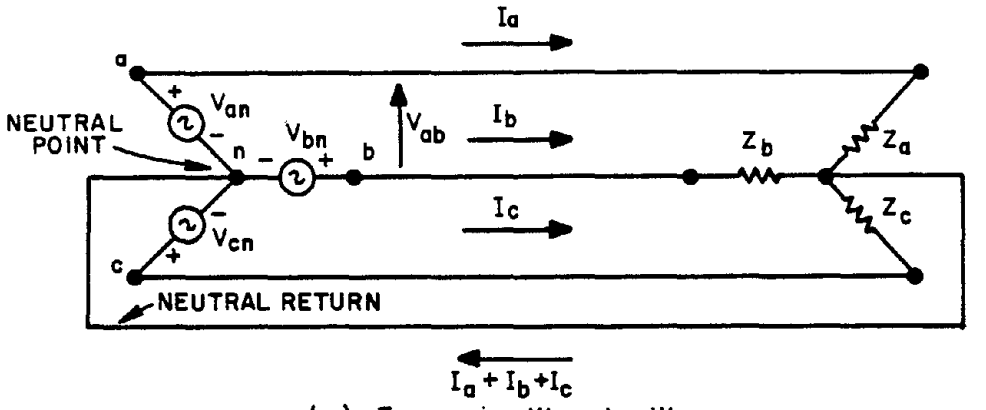
For perfect conditions, the generation is balanced, distribution impedances per phase (again, these are assumed zero here) are equal, and the load impedance in each phase circuit is identical. Hence, the magnitude of the "line" (or "phase") currents, $\bar{I}_a$, $\bar{I}_b$, and $\bar{I}_c$, must also be equal. By Kirchhoff's current law and the 120° displacement of the three line currents, the neutral-return current must be:

$$\bar{I}_a + \bar{I}_b + \bar{I}_c = 0 \qquad (4.6)$$

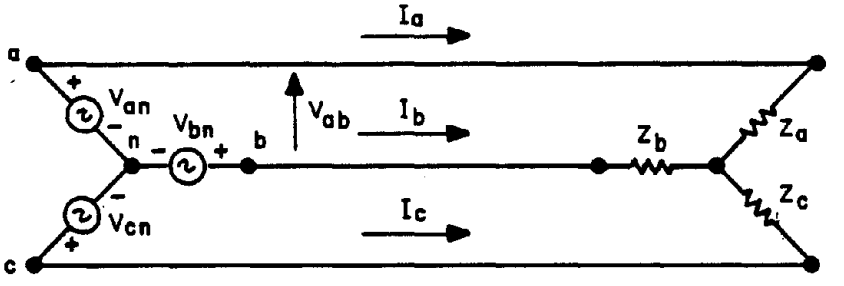
which means the neutral conductor actually carries no current under this ideal situation. Furthermore, there will be no voltage drop across the neutral, no matter what the neutral impedance is. In other words, the potential at the neutral of the source equals that of the load.

If the neutral carries no current under balanced conditions, what purpose does it really serve and can it be removed? Consider Figure 4.6b, a "three-wire wye-to-wye" system, which does not employ the neutral conductor. Although this system is used in some applications, problems can arise. The role of the neutral conductor is to minimize these problems.

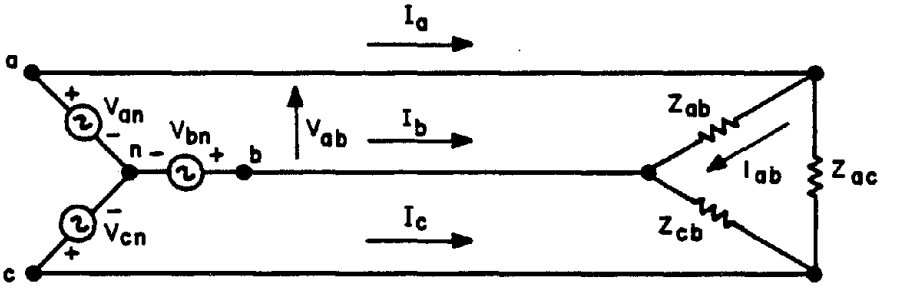
In the real world, no balanced three-phase system can be perfect, and the sources, the distribution impedances and the loads can easily become unbalanced (i.e., unequal from phase to phase). The result is, therefore, unbalanced currents and voltages. For one thing, without the neutral conductor, the neutral of the source will not equal the load neutral. Further, considering just load unbalance, unequal voltages will be produced across the loads, no matter how balanced the source. In mining machines, a motor under this condition is likely to deteriorate, and the result is maintenance problems. Notwithstanding, safety problems



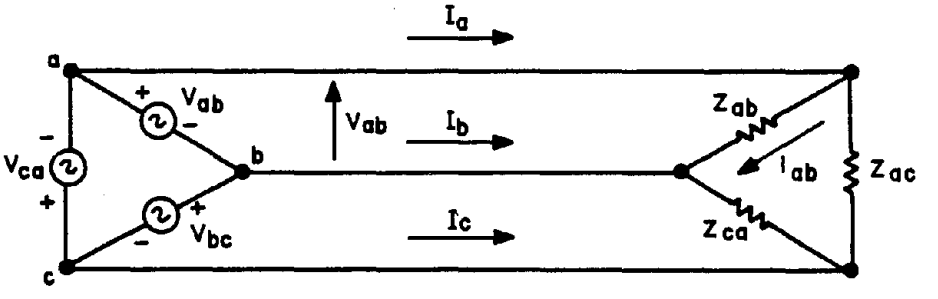
(a) Four-wire Wye-to-Wye



(b) Three-wire Wye-to-Wye



(c) Wye-to-Delta



(d) Delta-to-Delta

Figure 4.6. Balanced Three-Phase Load Connections.

can abound just from the unequal neutral potentials alone; Chapter 6 will investigate many of these problems in detail.

It is apparent that the neutral conductor does serve as a vital role in actual three-phase power systems. Its size and, accordingly, its current-carrying ability do not need to match that of the phase conductors in order to provide the necessary function. In a properly operating power system, normal conditions do cause some neutral current, yet this is usually very small compared to the phase current. On a neutral current basis alone, neutral conductor size requirements are thus small. However, in mining applications, such currents are not the only criterion to conductor size, and system malfunctions must be taken into account (see Section 4.6).

Instead of wye-connected, a three-phase load is more likely to be delta-connected. The "three-wire wye-to-delta" system, shown in Figure 4.6c, is an example. The prime advantage of this arrangement is that, under unbalanced load conditions, the source will deliver power proportionately to each load. Therefore, the Δ-connected loads need not be precisely balanced. Flexibility is increased because phase-to-phase loads may be added or removed without significantly upsetting operation. Such changes with wye-connected loads are difficult to impossible.

The advantage of a delta load suggests a delta-connected source, as in Figure 4.6d. There are two main reasons for not doing this. First, a slight unbalance in the source can create large circulating currents around a delta loop (e.g., source V_{ab} and load Z_{ab}). The extra current can reduce the available current capacity of the source and also increase power losses in the system. Second, it is highly desireable for safety to maintain equipment frames (usually metallic) at the neutral potential of the source. The logical and, sometimes, the more economical point to employ is the neutral of the wye-connected source. Known as a "four-wire wye-to-delta" system, which is illustrated in Figure 4.7, it is presently the most popular three-phase power-connection arrangement in mining. The neutral conductor here is more often termed a "grounding conductor." A neutral point can also be derived from a delta source using a zig-zag or grounding transformer (see Chapter 6). However, the first undesirable feature of delta sources remains.

Line and Phase Currents. Currents in a specific phase conductor or one "leg" of a wye-connected source or load are termed "line currents." As with line-to-neutral voltages, they can be considered as a condition of one phase only. However, currents flowing between two phases are called "phase currents" (or line-to-line currents), a correspondence to line-to-line voltages. An obvious example of phase current is that flowing through one leg of a delta-connected load. For the balanced three-phase system, as might be assumed, the magnitudes of the three-phase current through each leg of the delta are equal.

Figure 4.8a, a schematic of a balanced delta load, shows the three line currents (I_a, I_b, I_c) and three phase currents (I_{ab}, I_{bc}, I_{ca}) and can be utilized to demonstrate the relationship between the two. Considering just phase a and using Kirchhoff's current law,

$$\bar{I}_a = \bar{I}_{ab} - \bar{I}_{ca}. \tag{4.7a}$$

From the same reasoning that related line-to-neutral to line-to-line voltages,

$$\bar{I}_a = \sqrt{3}\,\bar{I}_{ab}\,\underline{|-30^\circ} \tag{4.7b}$$

which means that, in the balanced case, the magnitude of line current is larger than phase current by a factor of $\sqrt{3}$. The phasors are displaced by 30°, and the symmetry of phase and line currents is shown in Figure 4.8b.

Equivalent Delta and Wye Loads. There are many instances where it is desirable to replace a balanced delta-connected load with a wye (and vice versa). The ground work to perform this

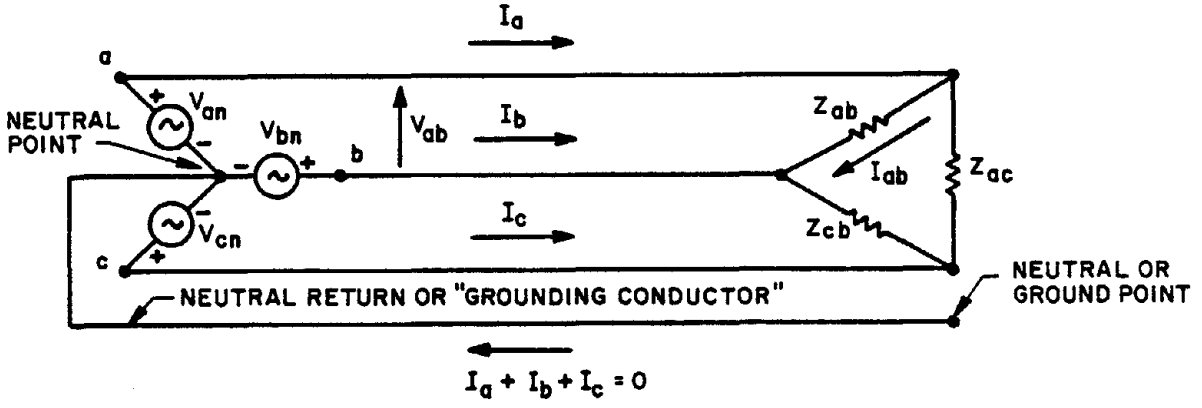


Figure 4.7. A Four-Wire Wye-to-Delta System.

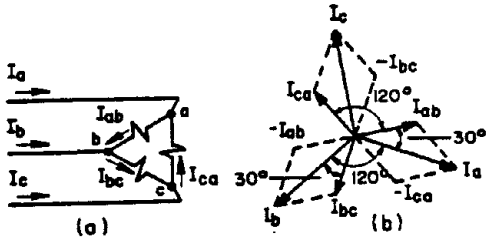


Figure 4.8. A Balanced Delta Load Illustrating Phase and Line Currents.

has already been established in Chapter 3. From equation 3.48,

$$Z_{an} = \frac{Z_{ab}Z_{ca}}{Z_{ab} + Z_{bc} + Z_{ca}} \tag{4.8}$$

and so on for Z_{bn} and Z_{cn} in terms of the delta impedances. Equation 4.8 provides equivalence of delta and wye for all situations, including unbalanced loads. However, for balanced conditions, the expression reduces to simply:

$$Z_{an} = \frac{Z_{ab}}{3} \tag{4.9a}$$

or

$$Z_{ab} = 3Z_{an} \tag{4.9b}$$

which states that each branch of a balanced delta has three times the impedance of a balanced wye.

Now that voltages, current, and equivalent load impedances of balanced three-phase systems have been covered, it is good to compare these values for delta and wye loads. If the load is wye-connected, the line current and load current per phase are the same, but the voltage across each load impedance is line-to-neutral, $1/\sqrt{3}$ that of line-to-line. When the load is delta-connected, the voltage across one load impedance is line-to-line, while the line current is larger than the current through each load impedance by a factor of $\sqrt{3}$. These concepts are illustrated in Figure 4.9 for equivalent delta and wye loads. It is significant to note that the three line-to-line voltages and three line currents for either connection are identical in either case and that line-to-line voltages and line currents are standard measurement values. This information is of great importance in balanced three-phase circuit analysis.

Three-Phase Power. Because the voltage and current in every impedance of a balanced delta or wye load are the same, the average power consumed by one impedance is one-third of total power to the load. In a delta load (for instance, Figure 4.9a), current and voltage are line-to-line, and the angle between them is the angle of the impedance. Thus, considering phases a and b, the average power consumed by one element is:

$$P_p = V_{ab}\, I_{ab} \cos\theta \qquad (4.10)$$

and total power is

$$P_T = 3V_{ab}\, I_{ab} \cos\theta \qquad (4.11a)$$

or in general

$$P_T = 3V_{LL}\, I_{LL} \cos\theta \qquad (4.11b)$$

where,

P_p = average power consumed by each element of a delta load (W)

P_T = total power consumed by the delta load (W)

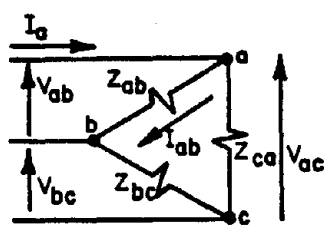
V_{LL} = the line-to-line (or "system") voltage rms magnitude (V)

I_{LL} = the magnitude of line-to-line rms current through the load (A)

$\cos\theta$ = the power factor of the load.

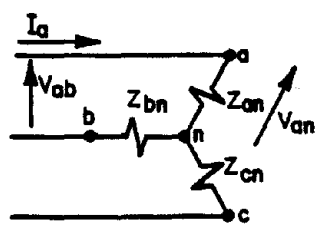
When the load is wye-connected, line current is through each load, while the voltage is line-to-neutral. Hence, taking phase a (see Figure 4.9b), the average power to one element is:

$$P_p = V_{an}\, I_a \cos\theta \qquad (4.12)$$



If $Z_{ab} = Z_{ca} = Z_{bc}$, $V_{ab} = \sqrt{3}\, V_{an}$, $Z_{an} = Z_{ab}/3$, and $I_a = \sqrt{3}\, I_{ab}$

(a) Delta Load



If $Z_{an} = Z_{bn} = Z_{cn}$, $V_{an} = V_{ab}/\sqrt{3}$, $Z_{ab} = 3Z_{an}$, and $I_{ab} = I_a/\sqrt{3}$

(b) Wye Load

Figure 4.9. Comparison of Equivalent Delta and Wye Loads.

and total power is

$$P_T = 3V_{an}\, I_a \cos\theta \qquad (4.13a)$$

or

$$P_T = 3V_{Ln}\, I_L \cos\theta \qquad (4.13b)$$

in which

P_p = average power consumed by each element of a wye load (W)

P_T = total power consumed by the wye load (W)

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

I_L = the line rms current magnitude (A)

$\cos\theta$ = the power factor of the load.

It is important to note that, again, the power factor angle, θ, is referenced to the sinusoidal voltage across one load and the current through that load.

As stated earlier, the standard values for three-phase circuits are line-to-line voltage and line current; often, these are the known quantities. Since for balanced systems,

$$V_{LL} = \sqrt{3}\, V_{Ln}$$

and

$$I_L = \sqrt{3}\, I_{LL},$$

both equations 4.11b and 4.13b are also identical to:

$$P_T = \sqrt{3}\, V_{LL} I_L \text{ (load p.f.)} \qquad (4.14)$$

where the power-factor angle is that of a load impedance or an equivalent impedance. (It is important to realize that this angle has nothing to do with the angle between V_{LL} and V_L, for example, $\overline{V}_{ab}$ and $\overline{I}_a$.)

Following the single-phase presentation of Chapter 3, a balanced three-phase load also has (in addition to average power, P_T) apparent power, S_T, and reactive power, Q_T; the following expressions apply:

$$Q_T = \sqrt{3}\, V_{LL}\, I_L \sin\theta \tag{4.15a}$$

or

$$Q_T = 3\, V_{Ln}\, I_L \sin\theta \tag{4.15b}$$

or

$$Q_T = 3\, V_{LL}\, I_{LL} \sin\theta \tag{4.15c}$$

and

$$S_T = \sqrt{3}\, V_{LL}\, I_L = 3\, V_{LL}\, I_{LL} = 3\, V_{Ln}\, I_L. \tag{4.16}$$

Complex power, $\bar{S}_T$, is therefore,

$$\bar{S}_T = P_T + jQ_T = S_T \angle\theta \tag{4.17a}$$

or for phase a,

$$\bar{S}_T = 3\, \bar{V}_{an}\, \bar{I}_a^* \tag{4.17b}$$

for phases a and b,

$$\bar{S}_T = 3\, \bar{V}_{ab}\, \bar{I}_{ab}^*. \tag{4.18b}$$

It should be evident for balanced three-phase systems that complex power, $\bar{S}_T$, does not equal $\sqrt{3}\, \bar{V}_{ab}\, \bar{I}_a^*$.

Basically, all other considerations of power that were presented in Chapter 3 for single-phase a-c also apply to balanced three-phase power. Poor power factor is worthy of critical attention. It affects the entire system operation. For example, poor power factor limits the available power from transformers, worsens voltage regulation, and limits current-carrying ability of conductors and cables. Simply, the result is poor system operation and economy. Thus, power factor can be equated to an indicator of system efficiency.

4.3-2 Three-Phase Transformers

Considerable information about transformers has already been covered in Chapter 3 and most of that theory is also applicable to three-phase transformers. As with single-phase systems, the prime purpose is the same, a need for differing voltages for three-phase distribution then equipment operation. The following discussion will, therefore, be pointed at three-phase transformers.

The usual connections of three-phase transformers are wye-to-wye, delta-to-delta, delta-to-wye, and wye-to-delta. In each case, transformer construction can be either a three-phase unit or a "bank" of three single-phase units; the only difference between the two is that the three-phase unit has all windings placed on a common core. Until recently, single-phase transformer banks have been more popular (see Chapter 11, Substations, for more details). Nevertheless, the description of connections is easier and more illustrative using single-transformers.

If these single-phase two-winding transformers are examined, every coil is insulated from the rest, and there are three primary and three secondary windings which can be interconnected independently. Thus, the primary windings or the secondary windings can be connected delta or wye, while retaining complete electrical separation of the primary and secondary windings of all three transformers. Figure 4.10 illustrates the physical connections of each combination, and Figure 4.11 shows the corresponding common symbols used in three-phase circuit diagrams. Any one of these can be found in or about mine installations. The advantages and disadvantages of a specific combination will be discussed in subsequent report chapters. However, because of significance, two combinations should be discussed here.

Mine power transformers are practically always delta-to-wye. Among the reasons for this popularity are:

1. The primary, in essence, is the load for the incoming power. A delta connection here affords the same load advantages that were just covered.
2. The wye-secondary neutral provides a good grounding point for the outgoing system (from the transformer). This neutral does not shift potential under unbalanced load conditions.
3. The delta-wye winding combination is free (or does not generate) third-harmonic (180 Hz for 60 Hz systems) voltages and currents. Delta-delta and wye-wye do generate these.

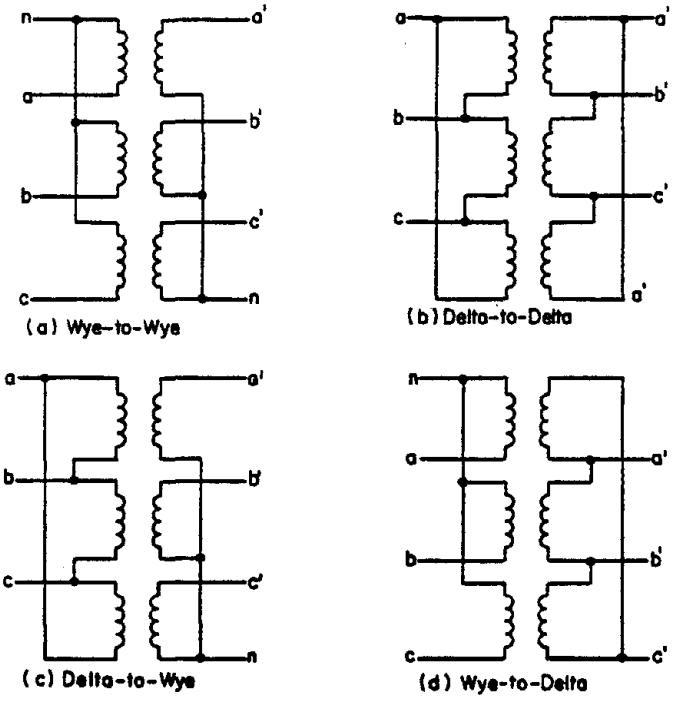


Figure 4.10. Three Single-Phase Transformers Connected for Three-Phase Operation.

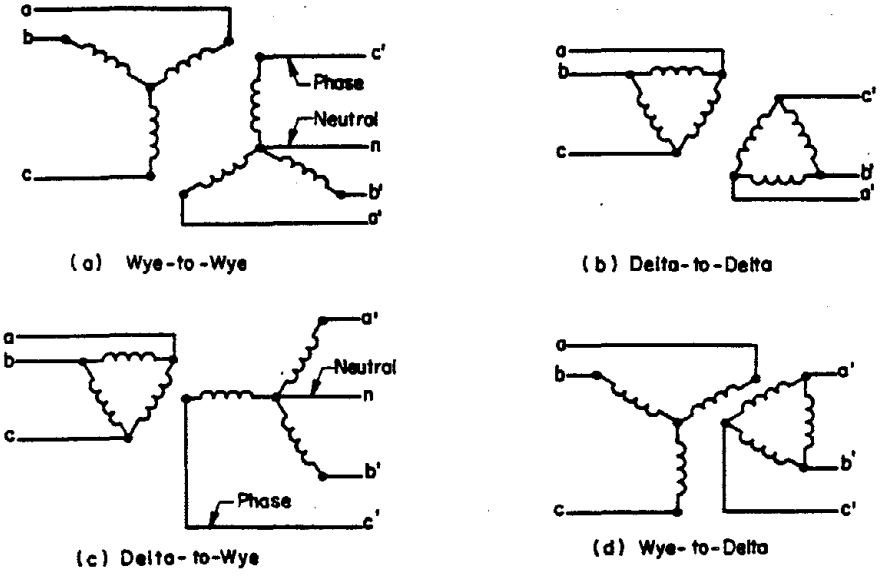


Figure 4.11. Three-Phase Diagrams for the Transformers of Figure 4.10.

The majority of the balance (not delta-to-wye) are delta-to-delta. Although systems requiring a grounding neutral point create some difficulty for delta secondaries, they provide a substantial advantage. If one of the single-phase transformers fails, operation can be continued by removing the defective unit and then operating the transformer "open-delta".

The open-delta or "V-connection" of two single-phase transformers, shown in Figure 4.12, is an unsymmetrical connection. However, it does provide a symmetrical three-phase power input and output, but the normal capacity is reduced to 57.7% of its delta kVA rating (using all three transformers). In addition to being an emergency measure, the open-delta configuration is sometimes a temporary set-up; the completion of delta is held until load conditions warrant the third unit. Because of economics, open-delta is also used extensively to monitor the three system voltages.

Transformation using delta-to-delta or wye-to-wye is straight-forward and easy to comprehend. With delta-to-delta, primary line-to-line voltages and currents are transformed to secondary line-to-line values; while for wye-to-wye, line-to-neutral voltages and line-currents transfer directly. Delta-to-wye and wye-to-delta combinations are different. For instance, consider delta-to-wye. Primary line-to-line voltages become secondary line-to-neutral, and primary line-to-line currents transform to secondary line currents. Through this, the current and voltage for all three phases shift phase 30° across the transformer. The change can be demonstrated using one transformer of the delta-to-wye bank and applying equations 4.3d and 4.7b.

4.3-3 Balanced Three-Phase Circuit Analysis

Per-Phase Reduction. By definition, any element in one phase of a balanced three-phase system is duplicated in the other two phases. Furthermore, from delta-wye transformations, reactions between phases such as phase-to-phase currents, voltages, or connected impedances, may be represented by an equivalent

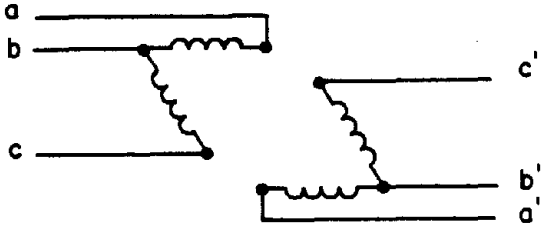


Figure 4.12. Open-Delta Three-Phase Transformer Operation.

phase-to-neutral value. Therefore, analysis of voltage, current, impedance, and power in only one phase can provide complete knowledge about the entire balanced three-phase system. In other words, currents and voltages for the other phases are equal in magnitude to those analyzed but displaced symmetrically in phase position. This balanced three-phase solution technique is termed "per-phase" or "single-phase" analysis. It is significant because almost all normally-operating three-phase power systems are approximately balanced.

As a simple demonstration of the concept consider Figure 4.13a, which illustrates a wye generator connected through line resistance to a wye-connected load. In Figure 4.13b, one phase of this circuit is extracted where:

1. V is one leg of the wye-connected source,
2. R is the line resistance per phase, and
3. Z is a "single-leg" impedance of the wye-connected load.

The unconnected points, n and n', are the neutrals of the source and load, respectively.

For the balanced or "symmetrical" system, the vectorial sum of all three phase currents is zero. Hence, the current between n and n' is zero, and the potential at n equals that at n'. Accordingly, the two neutrals can be joined as shown in Figure 4.13c. This last diagram is the "single-phase equivalent circuit" or the "per-phase reduction" of Figure 4.13a. It should be noted that Figure 4.13c is indeed a basic power circuit, identical to Figure 4.1.

The same reduction of circuits containing delta-connected sources and loads is almost as easy. Only one additional step is involved and uses the delta-wye transformations discussed earlier. Figure 4.14 demonstrates a simple example. The prime worry is to convert delta connections to wye using equations 4.9 and line-to-line voltages and currents to line-to-neutral. Thus, Figure 4.14b becomes the per-phase equivalent of Figure 4.14a.

Analysis now can be performed on the simplified representative of the balanced three-phase circuit employing all the single-phase techniques previously discussed. After solution, the three-phase parameters can be determined by reversing the reduction. This only needs to be done on the per-phase results (which are either line or line-to-neutral values) when phase-to-phase (or line-to-line) values are required. As shown in Figure 4.13, no changes are necessary with line-to-neutral parameters.

Solution problems exist when delta-wye or wye-delta transformers are in the system, due to the 30° phase shift of voltage and current across them. The other words, a line-to-neutral transformer secondary voltage transfers to line-to-line primary

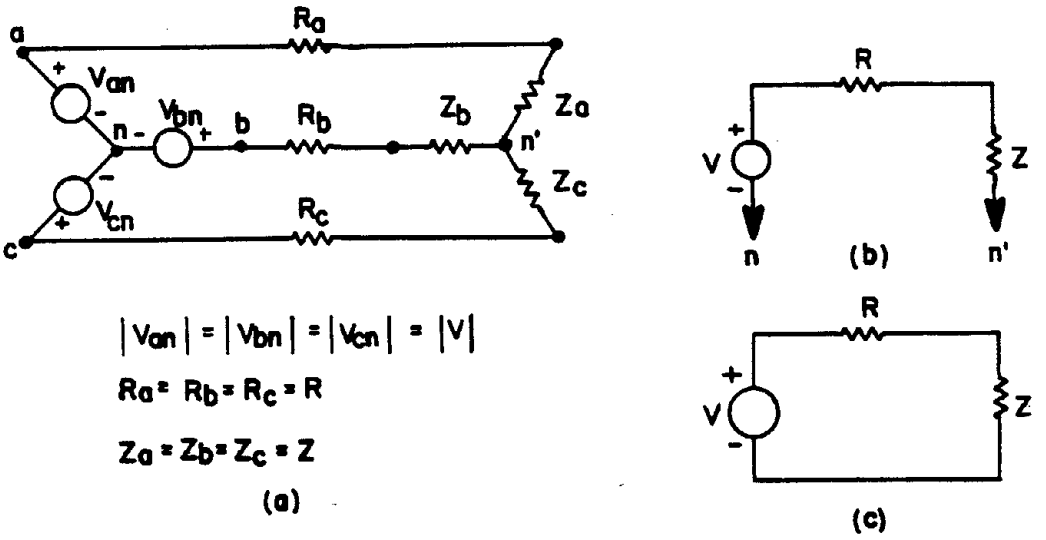


Figure 4.13. Per-Phase Reduction of a Wye-to-Wye System.

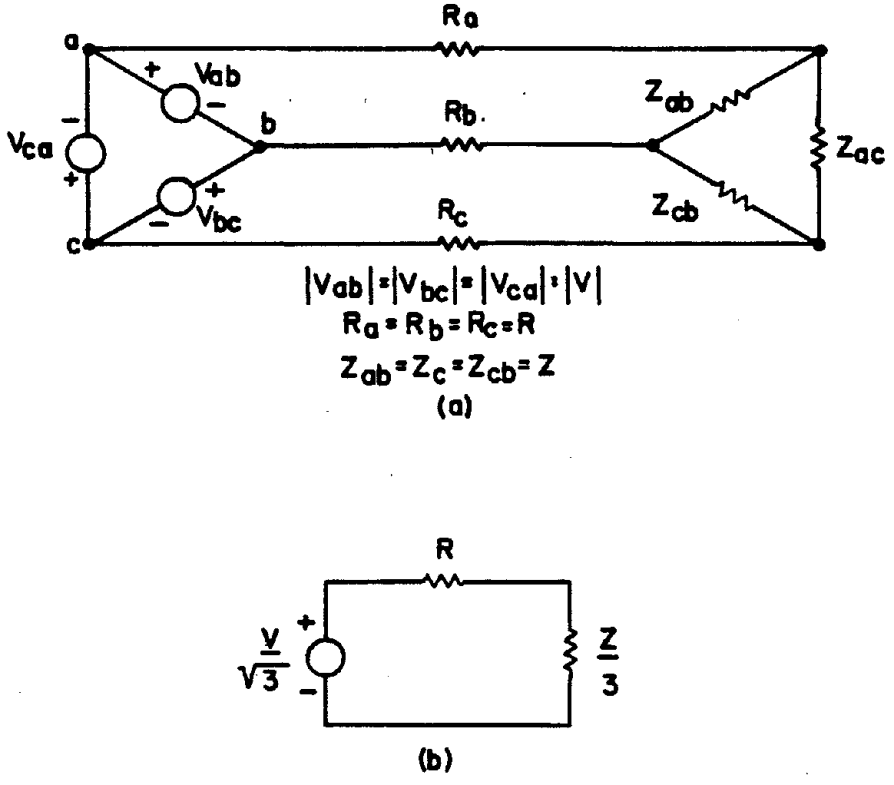


Figure 4.14. Per-Phase Reduction of a Delta-to-Delta System.

value and vice-versa. The situation will be discussed later in this section. Furthermore, when the three-phase system is not balanced, the solution does not permit the same simplification covered here. The methods needed are specialized and, thus, are provided in Sections 4.6 and 4.7.

One-Line and Three-Line Diagrams. It is apparent so far in this chapter that practically all power circuits consist of three conductors, three transformers, three switches, and so forth. Simply, each phase must have its own device, which is duplicated in each other phase. When all these components are shown in a schematic, the drawing is called a "three-phase diagram," and an example is given in Figure 4.15. Such diagrams can be extremely helpful, especially when the circuits are concentrated, for instance in a piece of machinery or power equipment. They allow a complete view of component interconnections and are imperative in manufacturing or troubleshooting.

However when the circuits are large, as in a complete mine power system, three-line diagrams are not only cumbersome to draw but also to read and interpret. Furthermore, if the power system is normally balanced (or approximately so), a three-line diagram is usually unnecessary since the system is always solved as a single-phase circuit composed of only one line conductor and a neutral return.

When the interconnections or, in fact, the conductors between components are represented by single lines and specific conventions are followed to signify these components, the illustration becomes a "one-line diagram." This is a further simplification of the per-phase diagram because the completed circuit through the neutral is omitted. The usefulness of one-line diagrams is practically endless, especially in analysis, and they are an invaluable tool in designing new power systems or modernizing existing ones. Furthermore, as circuit diagrams of mine power systems are required by federal law[1] in coal mines, a one-line diagram is the most practical way to comply.

Figure 4.16 shows a one-line diagram; its reference is the three-line diagram in Figure 4.15. The diagram purpose is to convey in concise form, the significant information about the system. All information is implied per-phase unless otherwise stated. The conventional notations are, therefore, line or line-to-neutral impedance, line current, and line-to-neutral voltage. If line-to-line values are listed, they must be stated as such. It must be realized when viewing a one-line diagram, that each device shown is really installed in triplicate (again, unless otherwise stated). Every line, symbol, figure, and letter has

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1. Title 30, Code of Federal Regulations, Parts 75 and 77.

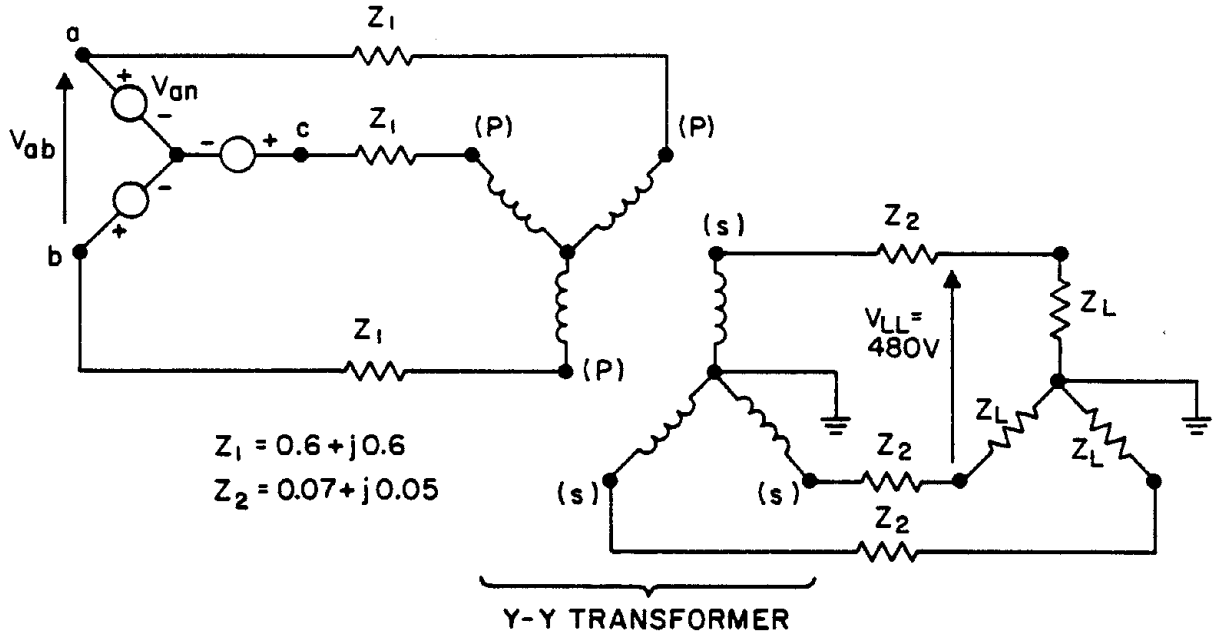


Figure 4.15. A Three-Line Diagram.

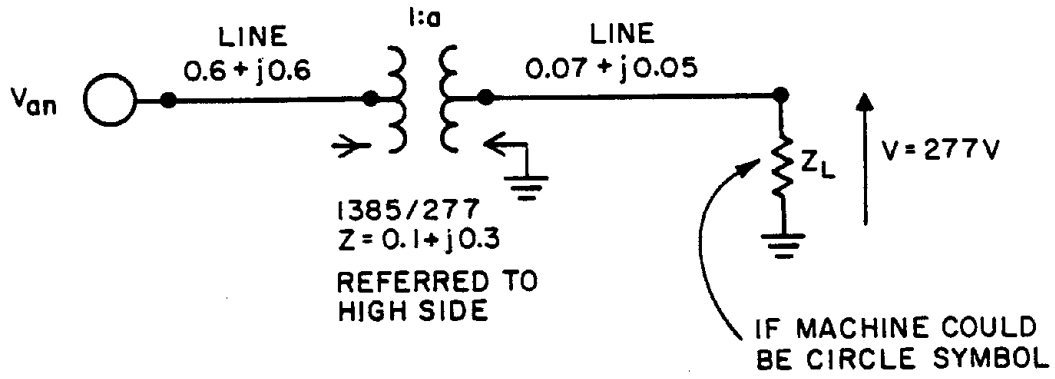


Figure 4.16. A One-Line Diagram of the Circuit Shown in Figure 4.15.

a definite meaning. Consequently, when a one-line diagram is constructed, specific conventions[2,3] must be followed to insure that the result will be complete, accurate, and correctly interpreted by anyone. The guidelines which follow should insure these objectives.

Relative geographic relationships should be maintained as far as practical. An excellent layout guide in mining is, therefore, a mine map. Because of the "short-hand" form and definite meaning of every entry, duplication must be avoided; for example, using a three-line diagram format for a system segment on a one-line diagram could imply three separate three-phase circuits. Standard numbers[2] and symbols[3] are mandatory, and those commonly used in mining are available in Tables 4.1 through 4.4. Many of the devices listed have not yet been covered in the report but are provided here for completeness.

All know facts about the power system should be shown on the diagram. This includes but is not excluded to:

1. apparatus ratings (volts, amperes, power, and so on),
2. ratios and taps of current and potential transformers,
3. power transformer winding connections,
4. relay functions, and
5. size and type of conductors.

The amount of information included depends on the purpose for which the diagram is intended. For instance, if the diagram is to assist in studying the power flow to loads throughout the system (called a "load-flow" study), circuit-breaker and relay location is unimportant. However, for the solution of other power problems, complete knowledge of these devices is mandatory. It is important that the one-line diagram contains only known facts because implications and guesses can lead to disastrous results.

On many one-line diagrams, knowledge of future electrical plans is very helpful. This should be entered either diagrammatically (say, using dashed lines) or through explanatory notes.

Finally, the diagram should include correct title data. The installation is thus clearly identified without confusing it with another mine or portion thereof.

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2. "Device Numbers," ANSI Standard C37.2-1970.
3. "Graphic Symbols for Electrical Diagrams," ANSI Standard Y32.2-1970.

Table 4.1. Commonly Used Symbols for One-Line Electrical Diagrams.

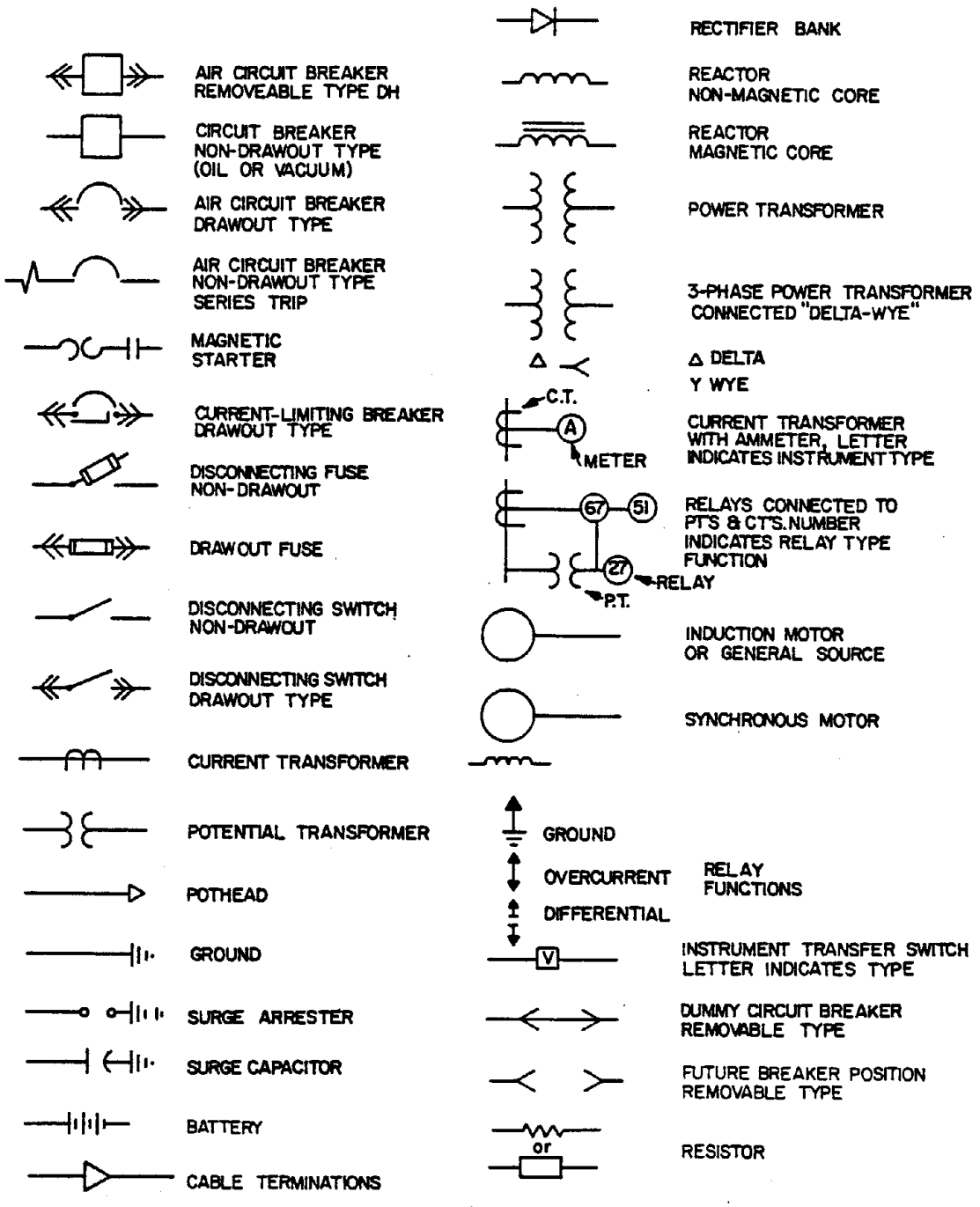


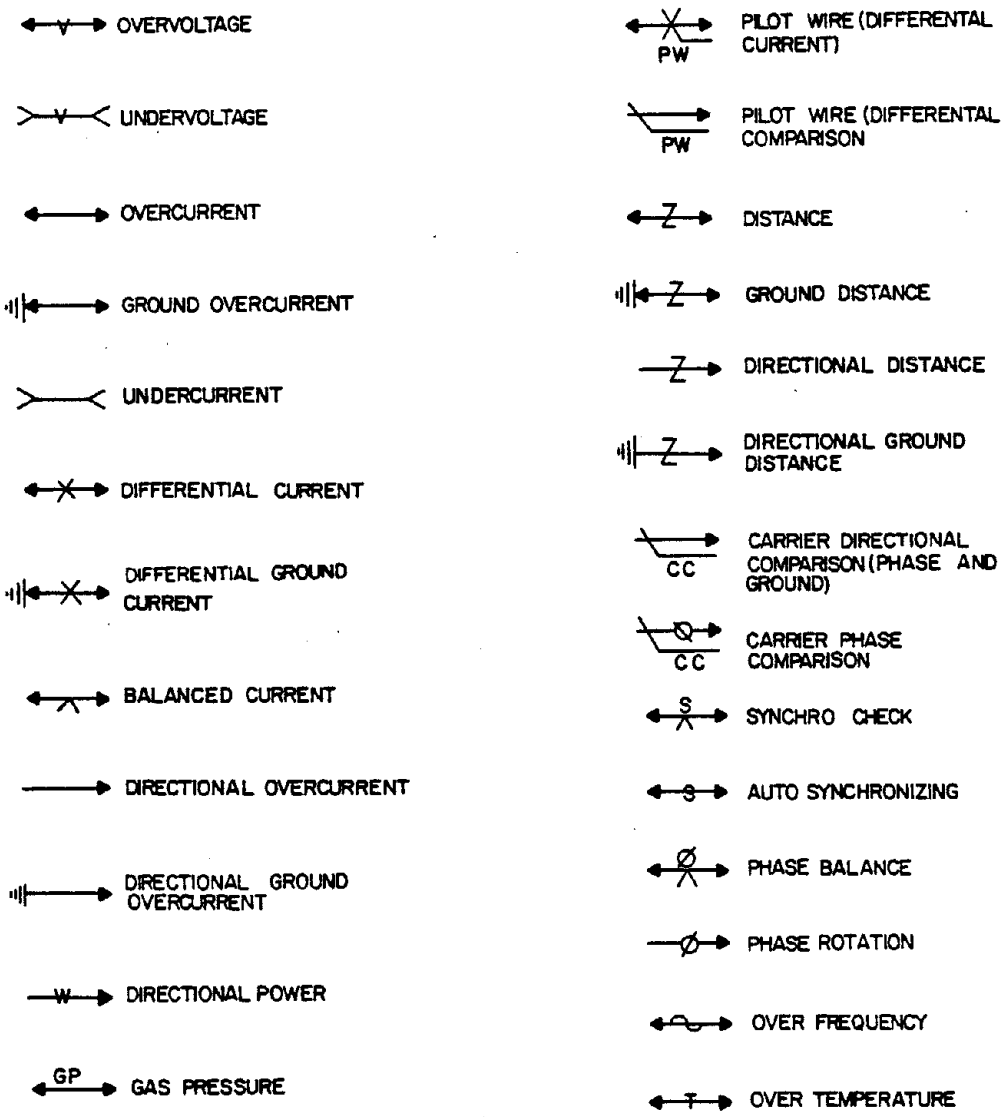
Table 4.2. IEEE Device Numbers and Functions.

DEVICE NO.	FUNCTION
1	Master Element
2	Time-Delay Starting Or Closing Relay
3	Checking Or Interlocking Relay
4	Master
5	Stopping Device
6	Starting Circuit Breaker
7	Anode Circuit Breaker
8	Control Power Disconnecting Device
9	Reversing Device
10	Unit Sequence Switch
11	(Reserved For Future Application)
12	Overspeed Device
13	Synchronous-Speed Device
14	Underspeed Device
15	Speed, Or Frequency Matching Device
16	(Reserved For Future Application)
17	Shunting Or Discharge-Switch
18	Accelerating Or
19	Starting to Running Transition Contactor
20	Electrically Operated Valve
21	Distance Relay
22	Equalizer Circuit Breaker
23	Temperature Control Device
24	(Reserved For Future Application)
25	Synchronzing Or Synchronism Check
26	Apparatus Thermal Device
27	Undervoltage Relay
28	(Reserved For Future Application)
29	Isolating Contactor
30	Annunciator Relay
31	Separate Excitation Device
32	Directional Power Relay
33	Position Switch
34	Motor-Operated Sequence Switch
35	Brush-Operating or Slip-Ring Short-Circuiting Device
36	Polarity Device
37	Undercurrent Or Underpower Relay
38	Bearing Protective Device
39	(Reserved For Future Application)
40	Field Relay
41	Field Circuit Breaker
42	Running Circuit Breaker
43	Manual Transfer Or Selector Device
44	Unit Sequence Starting Relay
45	(Reserved For Future Application)
46	Reverse-Phase-Balance Current Relay
47	Phase-Sequence Voltage Relay
48	Incomplete Sequence Relay
49	Machine Or Transformer Thermal Relay
50	Instantaneous Overcurrent Or Rate-Of-Rise Relay
51	AC Time Overcurrent Relay
52	AC Circuit Breaker
53	Exciter Or DC Generator Relay
54	High-Speed DC Circuit Breaker
55	Power-Factor Relay
56	Field Application Relay
57	Short-Circuiting Or Grounding Device
58	Power Rectifier Misfire Relay
59	Overvoltage Relay
60	Voltage Balance Relay
61	Current Balance Relay
62	Time Delay Stopping or Opening Relay
63	Liquid Or Gas Pressure Level Or Flow Relay
64	Ground Protective Relay
65	Governor
66	Notching Or Jogging Device
67	AC Directional Overcurrent Relay
68	Blocking Relay
69	Permissive Control Device
70	Electrically Operated Rheostat
71	(Reserved For Future Application)
72	DC Circuit Breaker
73	Load Resistor Contactor
74	Alarm Relay
75	Position-Changing Mechanism
76	DC Overcurrent Relay
77	Pulse Transmitter
78	Phase-Angle Measuring Or Out-Of-Step Protective Relay
79	AC Reclosing Relay
80	(Reserved For Future Application)
81	Frequency Relay
82	DC Reclosing Relay
83	Automatic Selective Control Or Transfer Relay
84	Operating Mechanism
85	Carrier Or Pilot-Wire Receiver Relay
86	Locking-Out Relay
87	Differential Protective Relay
88	Auxiliary Motor Or Motor Generator
89	Line Switch
90	Regulating Device
91	Voltage Directional Relay
92	Voltage And Power Directional Relay
93	Field-Changing Contactor
94	Tripping Or Trip-Free Relay
95, 96, 97, 98, 99	(Reserved For Special Application)

Table 4.3. Device Numbers Common to Mining.

1	Control switch
3	Plug interlock relay
37	Ground-continuity check undercurrent relay
49 D	Diode thermal relay
49 GR	Grounding resistor thermal relay
49 T	Transformer thermal relay
50	Instantaneous overcurrent relay - a-c
51	Time delay overcurrent relay - a-c
50 G	Instantaneous overcurrent relay - d-c - connected in ground wire
50 N	Instantaneous overcurrent relay - a-c - connected to neutral
51 N	Time-delay overcurrent relay - a-c - connected to neutral
50 Z	Instantaneous current balance relay - a-c - zero sequence
51 Z	Time-delay current-balance relay - a-c - zero sequence
52	a-c circuit breaker
59 GR	Ground protective relay - d-c unbalance relay
72	d-c circuit breaker
76	d-c overcurrent relay
A	Ammeter
D	Demand Meter
GD	Ground Detector
PF	Power Factor
V	Voltmeter
VA	Volt-ammeter
VAR	Varmeter
W	Wattmeter
WH	Watthour meter

Table 4.4. Relay Functions.



The balance of the report will employ one-line and per-phase diagrams almost exclusively. The main thing to remember when using them is that practically every item in these illustrations represents three identical (or corresponding) items in the actual system. Even when the normally balanced system becomes unbalanced from component failures, the same diagram is used, the only change being the notation for the specific failure. These unbalanced conditions will be covered in Section 4.6.

Transformer Considerations. As previously stated, solving a balanced three-phase system problem by per-phase analysis is as simple as the single-phase techniques covered in Chapter 3 (in fact, they are basically identical). The solution is not as clear, however, when delta-wye or wye-delta transformers are involved. Perhaps, the best approach to showing these perplexities is to first illustrate a problem solution where the per-phase reduction of the transformer is straight-forward (i.e., a wye-wye transformer), then change the transformer to delta-delta or delta-wye and show the complications that arise.

Consider Figure 4.17, which shows a one-line diagram of a substation supplying power through about one mile of No. 1 AWG copper overhead line (power conductors on poles) to a three-phase wye-wye transformer bank, then through a trailing cable to a three-phase induction motor. The motor consumes an average three-phase power of 150 kW, operating at 0.8 lagging power factor. The problem is to find the rms voltage necessary at the substation output to provide the rated motor terminal voltage of 480 V line-to-line.

A three-phase diagram of the circuit is shown in Figure 4.18 for reference. However, the first step in the solution is usually to develop a per-phase circuit as shown in Figure 4.19. Although the solution could be performed directly from the one-line diagram, this allows direct application of single-phase techniques. The following should be noted in Figure 4.19.

1. The line and trailing-cable conductor impedances are now illustrated as circuit elements.
2. Only one phase of the transformer bank is shown, represented as an impedance in series with the primary of an ideal transformer. The transformer turns ratio is computed from:

$$a = \frac{V_2}{V_1} = \frac{277}{1385} = \frac{1}{5}$$

where these rated voltages are line-to-neutral rms.

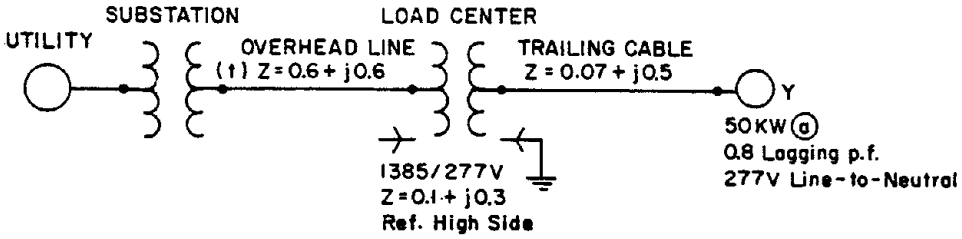


Figure 4.17. One-Line Diagram of the Wye-Wye Transformer Problem.

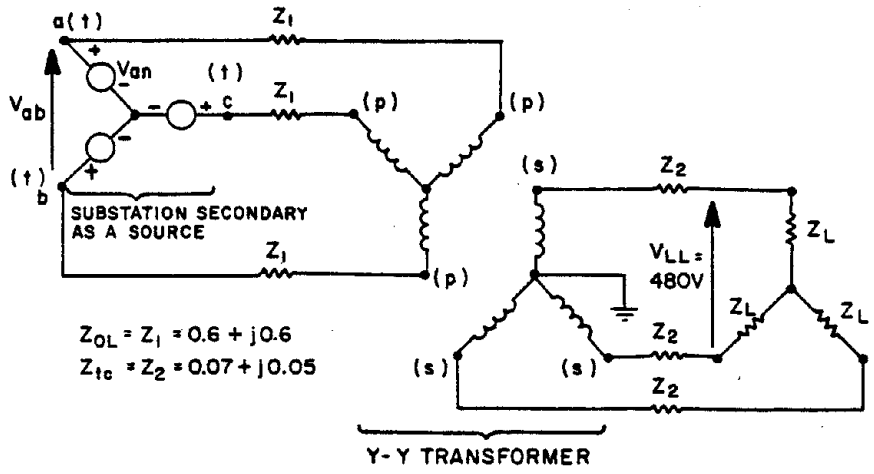


Figure 4.18. Three-Phase Diagram of Figure 4.17.

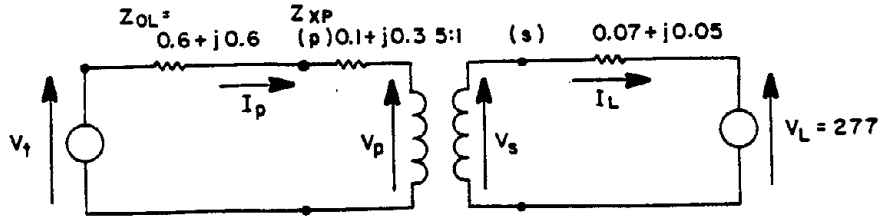


Figure 4.19. Per-Phase Diagram of Figure 4.17.

3. The induction motor is represented by its single-phase equivalent, P_p, where:

$$P_p = \frac{P_T}{3} = \frac{150}{3} = 50 \text{ kW}.$$

The solution now can follow the step-wise process.

1. Assume the motor terminal voltage, V_L, is the rated 277-V rms line-to-neutral $(480/\sqrt{3})$,
2. Compute motor line current magnitude, I_L, using

$$P_p = V_L \, I_L \, (\text{load p.f.})$$

or

$$I_L = \frac{P_p}{V_L \, (\text{load p.f.})} = \frac{50{,}000}{(277)(0.8)} = 225.5 \text{ A}.$$

If the motor terminal voltage is taken as the reference phasor, this current has a phase angle determined by the load power factor. Therefore, the motor current phasor is

$$\bar{I}_L = I_L \underline{|-\text{Cos}^{-1}(0.8)} = 226 \underline{|-36.9^\circ} \text{ A}.$$

3. $\bar{I}_L$ is then employed to find the voltage drop across the per-phase equivalent of the trailing cable, Z_{tc}. When this is added to the motor terminal voltage, the voltage at the ideal transformer secondary, V_s, is found:

$$\bar{V}_s = \bar{I}_L Z_{tc} + \bar{V}_L$$

or

$$\begin{aligned} \bar{V}_s &= (226 \underline{|-36.9^\circ})(0.09 \underline{|35.5^\circ}) + 277 \underline{|0^\circ} \\ &= 20.30 \underline{|-1.4^\circ} + 277 \underline{|0^\circ} \\ &= 20.29 - j\ 0.50 + 277 \\ &= 297.29 - j\ 0.50 = 297 \underline{|-0.1^\circ} \text{ V}. \end{aligned}$$

4. For the ideal transformer with turns ratio, a, of five, the voltage across the primary is

$$\bar{V}_p = \frac{\bar{V}_s}{a}$$

or

$$\bar{V}_p = 5(297\angle -0.1°) = 1486\angle -0.1° \text{ V}$$

with the primary current being

$$\bar{I}_p = a\bar{I}_L$$

or

$$I_p = (\tfrac{1}{5})(226\angle -36.9°) = 45\angle -36.9° \text{ A.}$$

Notice, there is no change in current or voltage phase angle across the transformer.

5. This primary current can now be used to find the voltage drop resulting from transformer and overhead-line impedances. Summing this voltage drop with the transformer primary voltage gives the desired answer to the problem, the substation output voltage, V_t:

$$\bar{V}_t = \bar{I}_p(Z_{OL} + Z_{XP}) + \bar{V}_p$$

where,

Z_{OL}, Z_{XP} = the overhead line and transformer impedances, respectively,

Then

$$\bar{V}_t = 45\angle -36.9°(0.6 + j\ 0.6 + 0.1 + j\ 0.03) + 1486\angle -0.1°$$

or

$$\bar{V}_t = 45\angle -36.9° \ (0.94\angle 41.99°) + 1486\angle -0.1°$$

$$\bar{V}_t = 42.39\angle 5.1° + 1486\angle -0.1°$$

$$\bar{V}_t = 1528\angle +0.04° \text{ V}.$$

Because the analysis is per-phase, the result is of course line-to-neutral. If line-to-line values are required, the above answer need only be multiplied by the $\sqrt{3}$. It is interesting that in this example the phase angle of the substation voltage is practically the same as the motor. Such is not usually the case in actual mine power systems.

The solution is practically the same when the transformer used is delta-delta connected, such as shown in the one-line diagram of Figure 4.20. When the system is represented per-phase (Figure 4.21), the only additional concern is delta-wye transformation, then the solution proceeds as before. However, such is not the case with delta-wye transformer connections (and vice versa).

Consider the one-line diagram in Figure 4.22 showing a delta-wye transformer supplying the same motor from Figure 4.17. Figure 4.23 illustrates one leg of the three-phase transformer. From this, it can be seen that secondary line currents appear as line-to-line currents on the primary, and line-to-neutral voltages become line-to-line primary voltages. Accordingly, if only the transformer is considered, a phase shift in currents and voltages is attained through the transformer. In other words, from Figure 4.23 for primary voltage in terms of secondary (the ideal transformer with turns ratio, a, only):

$$\bar{V}_{AB} = \frac{\bar{V}_{an}}{a} \angle 30°$$

where,

$\bar{V}_{AB}$ = the line-to-line primary voltage (V)

$\bar{V}_{an}$ = the line-to-neutral secondary voltage (V),

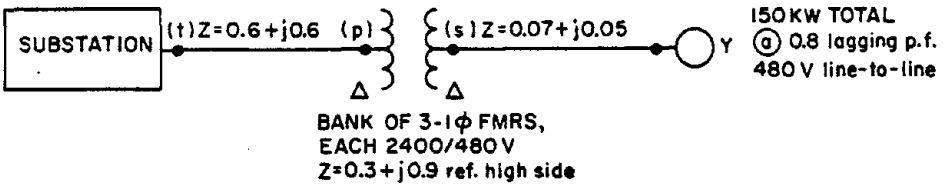


Figure 4.20. One-Line Diagram with Delta-Delta Transformer.

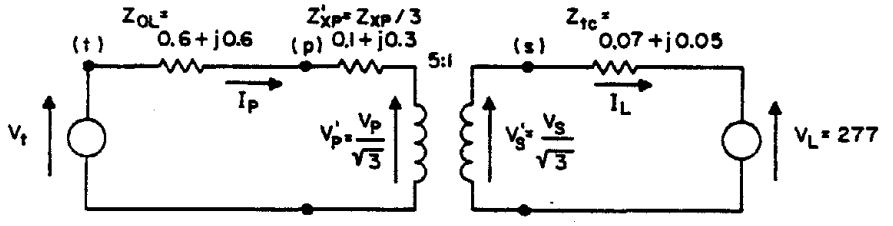


Figure 4.21. Per-Phase Diagram of Figure 4.20.

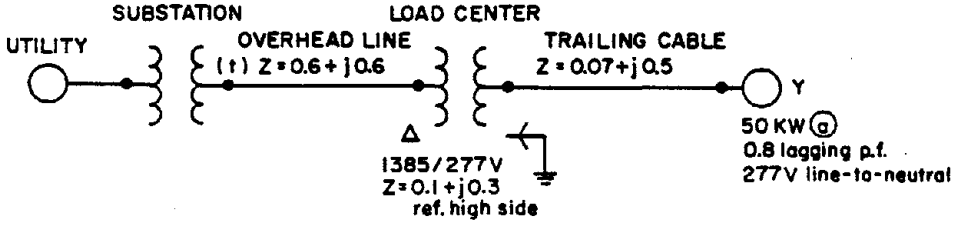


Figure 4.22. One-Line Diagram with Delta-Wye Transformer.

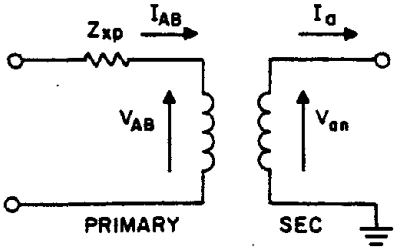


Figure 4.23. One-Leg of the Three-Phase Transformer from Figure 4.22.

and for primary and secondary current,

$$\bar{I}_{AB} = a\,\bar{I}_a \,\angle 30°$$

where

$\bar{I}_{AB}$ = the line-to-line primary current (A)

$\bar{I}_a$ = the line secondary current (A).

However, when performing balanced three-phase analysis, the parameters of interest are line-to-neutral voltages and line currents. Thus, to continue the analysis in a similar situation as the preceding example (the wye-wye transformer), $\bar{V}_{AB}$ and $\bar{I}_{AB}$ must be converted to their respective per-phase equivalents. Recalling that

$$\bar{V}_{ab} = \sqrt{3}\,\bar{V}_{an} \,\angle +30° \qquad (4.3d)$$

and applying this concept to equation 4.19, the primary line-to-neutral voltage, V_A, is

$$\bar{V}_A = \frac{\bar{V}_{an}}{a\sqrt{3}} . \qquad (4.21)$$

Employing equation 4.7b to convert equation 4.20, primary line current, $\bar{I}_A$, is:

$$\bar{I}_A = a\,\bar{I}_a . \qquad (4.22)$$

Equations 4.21 and 4.22 simply state that the phase shifts that occur across delta-wye connected transformers do not interfere with the analysis when this is performed per phase. Analysis can be enhanced by changing the delta primary or secondary to an equivalent wye connection, thus enabling construction of a per-phase diagram for the entire system.

Concerning the actual per-phase analysis, it has been shown that the three-phase circuit is reduced. The process is no more difficult than the single-phase work that was covered in Chapter 3. The next section will present a technique that further simplifies power system analysis.

4.4 The Per-Unit System

Percent and Per-Unit Quantities. Problems relating to electrical circuits should be solved in terms of volts, amperes, volt-amperes, and ohms. The answers to mine power problems (and, indeed, any electrical problem) almost always require these terms. However, in the process of computations it is often more convenient to express these quantities in "percent" or "per unit" in reference to some arbitrarily chosen base. For example, if a base voltage of 100 kV is selected, voltages of 90, 120, and 125 kV have percent representations of 90, 120, and 125% or per-unit values of 0.9, 1.2, and 1.25 pu, respectively. Both percent and per-unit values express a ratio of a specific quantity to the base quantity. Per unit is given as a decimal, whereas the ratio in percent is 100 times the per-unit value. Importantly, such expressions, especially per unit, are becoming standard for equipment specifications.

There is a definite advantage in using per-unit notation over percent. Per-unit multiplication or division yields a result in per unit. However, the product of two percent quantities must be divided by 100 to obtain a percent answer. For example, if two quantities are both 0.9 pu or 90%, then

$$(0.9 \text{ pu})(0.9 \text{ pu}) = 0.81 \text{ pu}$$

and

$$(90\%)(90\%) \neq 8100\%$$

but

$$(90\%)(90\%) = \frac{8100\%}{100} .$$

Consequently, per-unit notation will be employed almost exclusively in this report; the only exceptions being where conventions dictate otherwise.

Voltage, current, volt-amperes, and impedance are obviously interrelated for any specific circuit or system. As a result, the selection of any two determines the base values for the remaining two. For example, if the current and voltage bases are specified, the base impedance and base volt-amperes can be found. Since three-phase circuits are most often solved as a single line with a neutral, base quantities in the per unit are line current, line-to-neutral voltage, per-phase impedance, and per-phase volt-amperes. The mathematical interrelations of the bases are therefore as follows:

$$V_b = I_b Z_b \tag{4.23}$$

$$kVA_b = kV_b I_b \tag{4.24}$$

$$I_b = \frac{kVA_b}{kV_b} = \frac{V_b}{Z_b} \tag{4.25}$$

$$Z_b = \frac{V_b}{I_b} = \frac{(kV_b)^2 1000}{kVA_b} = \frac{(kV_b)^2}{MVA_b} \tag{4.26}$$

where,

V_b = the base line-to-neutral voltage (V)

kV_b = the base line-to-neutral voltage (kV)

kVA_b = the base per-phase volt-amperes (kVA)

MVA_b = the base per-phase volt-amperes (MVA)

I_b = the base line current (A)

Z_b = the base per-phase impedance (Ω).

All these formulas are just adaptions of the fundamental material (Ohm's law and power); the last three are expressed in kilovolts and kilovolt-amperes because of the levels normally found in power systems. It should be remembered that line-to-line voltages and total power (kVA or MVA) are customarily specified; these must be changed to line-to-neutral voltages (dividing by the $\sqrt{3}$) and per-phase power (dividing by 3) before equations 4.23 through 4.26 can be applied.

To apply the per-unit system to power problems, base values for kVA and kV are normally selected first; the reason is to minimize calculations as much as possible. Then, base values for impedance and current are found. This is followed by expressing all the actual voltages, currents, impedances, and powers in the power system or system segment as a ratio to the base quantities; these are the per-unit quantities. Problems are then solved in per unit with the answers converted back to actual parameters. The actual values and per-unit quantities are related by:

$$Z_A = Z_{pu} Z_b \tag{4.27}$$

$$I_A = I_{pu}\, I_b \tag{4.28}$$

$$V_A = V_{pu}\, V_b \tag{4.29}$$

$$VA_A = VA_{pu}\, VA_b \tag{4.30}$$

in which

Z_A, I_A, V_A, VA_A = the actual values of impedance, current, voltage, and power, respectively (Ω, A, V, VA),

Z_{pu}, I_{pu}, V_{pu}, VA_{pu} = the per-unit values impedance, current, voltage, and power, respectively (puΩ, puA, puV, puVA).

It is important to note that all impedances in a problem are referenced to the same base impedance, be they resistance or pure reactance. The same holds for all powers (which can be average, reactive, or apparent) to the base kVA.

Often it is found that per-unit impedances or percent impedances of system components have already been selected for bases referenced to the specific component or power-system segment in which that component is located. These impedances can be changed to the desired base impedance by:

$$Z_{pu} = \frac{Z_{pue}\, kVA_b}{kVA_e} \left(\frac{kV_e}{kV_b}\right)^2 \tag{4.31}$$

where,

Z_{pue} = the per-unit impedance of a specified component (puΩ)

kV_e, kVA_e = the base kV and kVA used to reference Z_{pue} (V, VA)

kV_b, kVA_b = the base kV and kVA to which a new per-unit impedance is to be referenced (V, VA)

Z_{pu} = the new per-unit impedance referenced to kV_b and kVA_b (puΩ).

The most common devices in mine power systems in which the component impedance is referenced to the rated power and voltage of the

component, are transformers. Conventionally, percent impedance is specified, but this can be converted to per unit by simply dividing by 100.

Specification of Transformers. An advantage of using per-unit computations is seen when circuits are connected through transformers. Through the proper selection of voltage bases, the per-unit impedance of the transformer is the same no matter which winding is used. Consequently, if exciting and magnetizing current are ignored (as they often can be in power systems), the transformers become a simple series impedance in the per-unit calculations. In other words, the ideal transformer in the equivalent circuit is removed.

To explore this advantage, consider a 750-kVA load-center transformer, the approximate per-phase equivalent circuit for which is shown in Figure 4.24. The per-phase ratings are 250 kVA, 5000/1000 V, and 5-Ω reactance referred to the high side. Following convention, the base power, kVA_{b1} is 250 kVA and, for the high side, the base voltage kV_{b1} is 5 kV, 1 kV being selected as the low-side base voltage, kV_{b2}. With these, the high-side base quantities can be calculated using equations 4.23 through 4.26:

$$kVA_b = 250 \text{ kVA},$$

$$kV_{b1} = 5 \text{ kV},$$

$$I_{b1} = 50 \text{ A, and}$$

$$Z_{b1} = 100 \ \Omega.$$

The per-unit impedance of the transformer is thus:

$$Z_{pu} = \frac{Z_{A1}}{Z_{b1}} = \frac{5}{100} = 0.05 \text{ pu}.$$

Now consider the actual transformer impedance as it would appear referred to the low side, as in Figure 4.25.

$$Z_{A2} = Z_{A1} \left(\frac{N_2}{N_1}\right)^2 = Z_{A1} \left(\frac{V_2}{V_1}\right)^2$$

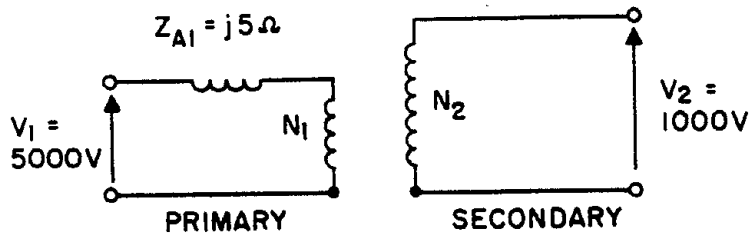


Figure 4.24. Approximate Per-Phase Equivalent Circuit for a 750 kVA Load-Center Transformer, Impedance referred to the High-Side.

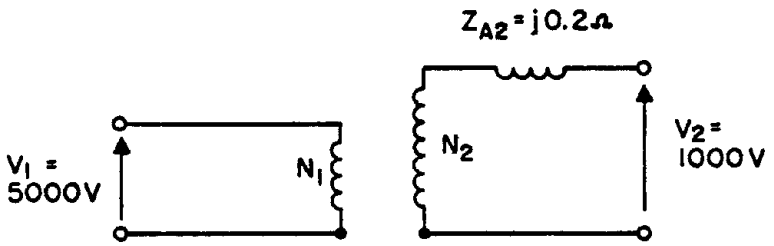


Figure 4.25. Transformer of Figure 4.24 with Impedance Transferred to the Low-Side.

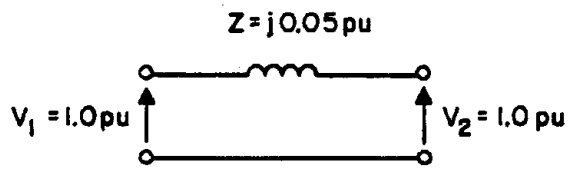


Figure 4.26. Simplified Equivalent Circuit of the Transformer Expressed in Per Unit.

or

$$Z_{A2} = 5\left(\frac{1000}{5000}\right)^2 = 0.20\ \Omega.$$

Notice that the base power does not change and the low-side base voltage defines base current and impedance when the base quantities on the low side are

$$kVA_b = 250\ kVA,$$

$$kV_{b2} = 1\ kV,$$

$$I_{b2} = 250\ A,\ \text{and}$$

$$Z_{b2} = 4\ \Omega.$$

The per-unit transformer impedance as seen for the low side is:

$$Z_{pu} = \frac{Z_{A2}}{Z_{b2}} = \frac{0.2}{4} = 0.05\ pu.$$

Therefore, the per-unit impedance of the transformer is the same, regardless of which side it is viewed, and the per-unit equivalent circuit is simply the series circuit shown in Figure 4.26. Notice that the input and output voltages are now expresed in per-unit (here, the transformer is operating at rated voltage).

Importantly, the foregoing applies in general to all two-winding transformers.

Three-Winding Transformers. In Chapter 3 and to this point in Chapter 4, equivalent circuits have only been shown for two-winding transformers (those having only one primary and one secondary winding). However, many transformers in mine power systems have three windings. Instances include load-center transformers supplying two different utilization voltages, such as 950-Vac and 550-Vac face equipment or 550-Vac and 250-Vdc machinery (the latter not only uses a three-winding transformer but also three-phase rectification, to be shown shortly).

Both the primary and secondary windings of the two-winding transformer have the same kVA capacity or rating, yet the three-windings of a three-winding transformer may have different kVA ratings.

The impedance of each winding may be given in percent or per unit based on the winding ratings, or the three-impedances can be measured by the following standard short-circuit test (rated voltage applied to primary for Z_{ps} and Z_{pt} and to the secondary for Z_{st}):

Z_{ps} = leakage impedance measured in the primary (or first winding) with the secondary (or second winding) short circuited and the tertiary (or third winding) open (Ω),

Z_{pt} = leakage impedance measured in the primary with the tertiary short circuited and the secondary open (Ω), and

Z_{st} = leakage impedance measured in the secondary with the tertiary short circuited and the primary open (Ω).

The impedances of the primary, secondary, and tertiary winding are found from:

$$Z_{ps} = Z_p + Z_s \tag{4.32a}$$

$$Z_{pt} = Z_p + Z_t \tag{4.32b}$$

$$Z_{st} = Z_s + Z_t \tag{4.32c}$$

or

$$Z_p = \frac{1}{2}(Z_{ps} + Z_{pt} - Z_{st}) \tag{4.33a}$$

$$Z_s = \frac{1}{2}(Z_{ps} + Z_{st} - Z_{pt}) \tag{4.33b}$$

$$Z_t = \frac{1}{2}(Z_{pt} + Z_{st} - Z_{ps}) \tag{4.33c}$$

where Z_p, Z_s, Z_t = the impedances of the primary, secondary, and tertiary, respectively (Ω).

In equations 4.32 and 4.33, all impedances (Z_{ps}, Z_{pt}, Z_{st}) must be referred to the primary-winding voltage. If Z_{st} is obtained from the described measurements, the impedance is referred to the secondary winding voltage, hence it must be transferred.

The approximate per-phase equivalent circuit for a three-winding transformer with the winding impedances of Z_p, Z_s, and Z_t is provided in Figure 4.27 (magnetizing and exciting currents are ignored). The terminals p, s, and t are the primary, secondary, and tertiary connections; the common point is unrelated to the system neutral. The three transfer impedances must be in the per-unit system (as was the case for the equivalent circuit in Figure 4.26), hence they must have the same kVA base. Further, voltage bases for the circuits connected through the transformer must have the same ratios as the turns ratio of the transformer windings (i.e., primary to secondary, primary to tertiary, actually the same as the ratios of the related winding voltages).

Per-Unit Method in System Analysis. As mentioned earlier, the use of per-unit equivalents in the analysis of power system problems can greatly simplify the work involved, especially where the system contains transformers and different voltage levels. However, as per-unit calculations require the change of familiar parameters (i.e., ohms, volts, amperes, and so on) to values representing a ratio, this advantage is often difficult to comprehend. To illustrate analysis simplification, consider the one-line diagram provided in Figure 4.28, which could represent a mine power system in the early stages of development. All power levels listed are given per phase; those shown for the mining equipment represent consumption. The voltages are all line-to-neutral.

Desired information from the system could be the voltage or current level at any point. No matter what the problem, to solve it by the per-unit method requires first determining the impedance of all components on the same base. The base selection is arbitrary but, for convenience, the largest kVA capacity of a system component is taken. In this case, a good base would be 1000 kVA, corresponding to the per-phase capacity of the substation. Two base parameters, however, are needed in order to define the four base quantities and, as the nominal voltage level can be considered (or can approach) a constant, the system voltages are excellent second base-parameter choices. For Figure 4.28,

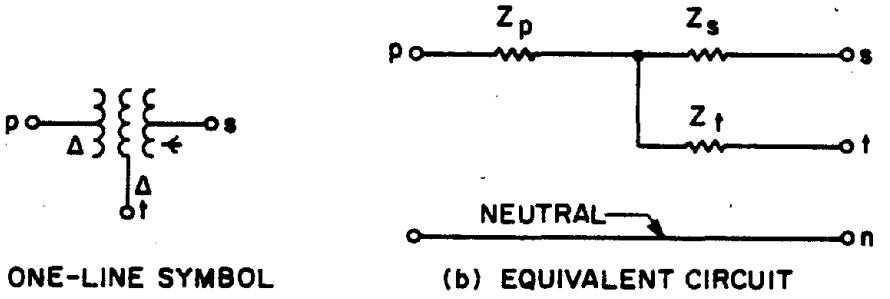


Figure 4.27. Approximate Equivalent Circuit of a Three-winding Transformer Expressed in Per-unit.

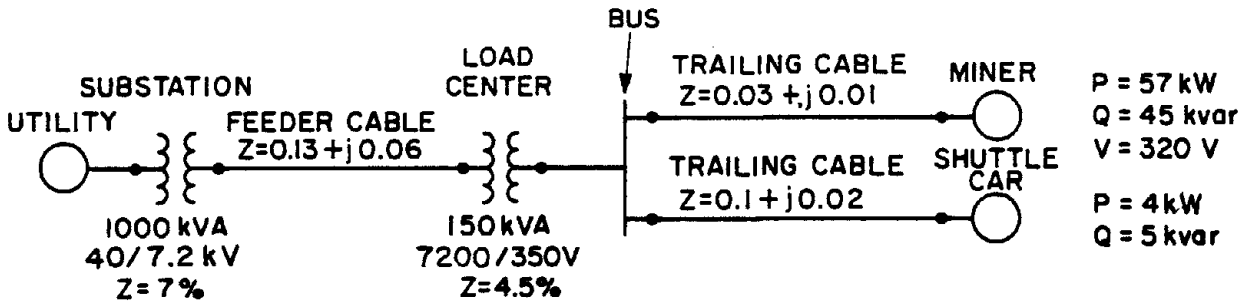


Figure 4.28. One-Line Diagram of a Small Mine Power System.

these would be the line-to-neutral voltages of 40 kV at the utility, 7.20 kV at mine distribution, and 350 kV at mine utilization. (Note that the system voltage are usually given as line-to-neutral to employ the formulas given here.) Base voltages must correspond in any event with the turns ratio of any inter-connecting transformer. The ones selected do.

With the base kVA and base kV specified, the base quantities can be calculated using equations 4.23 through 4.26.

1. For the utility:

$$kVA_b = 1000 \text{ kVA},$$

$$kV_{b1} = 40 \text{ kV}$$

$$I_{b1} = \frac{kVA_b}{kV_b} = \frac{1000}{40} = 25 \text{ A}$$

$$Z_{b1} = \frac{(kV_b)^2 1000}{kVA_b} = \frac{(40)^2 1000}{1000} = 1600 \ \Omega.$$

2. For mine distribution:

$$kVA_b = 1000 \text{ kVA}$$

$$kV_{b2} = 7.2 \text{ kV}$$

$$I_{b2} = \frac{1000}{7.2} = 139 \text{ A}$$

$$Z_{b2} = \frac{(7.2)^2 1000}{1000} = 52\ \Omega.$$

3. For mine utilization:

$$kVA_b = 1000\ kVA$$

$$kV_{b3} = 0.35\ kV$$

$$I_{b3} = \frac{1000}{0.35} = 2857\ A$$

$$Z_{b3} = \frac{(0.35)^2 1000}{1000} = 0.12\ \Omega.$$

Now the per-unit representations for all components of the mine system can be found, and the needed formulas are equations 4.27 through 4.31.

1. Substation. Percent reactance is 7% or 0.07 pu based on the transformer rated kVA, referred to the high side, 40 kV.

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

in which

$$Z_{pue} = j0.07\ pu$$

$$kVA_b = KVA_e = 1000\ kVA$$

$$kV_e = kV_b = 40\ kV$$

thus

$$Z_{pue} = j0.07\ pu.$$

2. Feeder Cable. Actual impedance is given,

$$Z_A = R_A + jX_A = 0.13 + j0.06$$

and

$$Z_{pu} = \frac{Z_A}{Z_{b2}} = \frac{0.13 + j0.06}{52}$$

$$Z_{pu} = (0.0025 + j0.0012) \text{ pu.}$$

3. Load Center. Percent reactance is 4.5% or 0.045 pu based on the transformer rated kVA, referred to the high side, 7.20 kV,

$$Z_{pu} = \frac{Z_{pue}\ kVA_b}{kVA_e} \left(\frac{kV_e}{kV_{b2}}\right)^2$$

where,

$$Z_{pue} = j0.045 \text{ pu}$$

$$kVA_b = 1000 \text{ kVA}$$

$$kVA_e = 150 \text{ kVA}$$

$$kV_{b2} = kV_e = 7.20 \text{ kV}$$

and

$$Z_{pu} = \frac{(j0.045)(1000)}{150} = j0.3 \text{ pu.}$$

4. Trailing Cables. Actual impedances are again given.

   a. Miner. $Z_A = 0.03 + j0.01$

$$Z_{pu} = \frac{Z_A}{Z_{b3}} = \frac{0.03 + j0.01}{0.12}$$

$$Z_{pu} = (0.25 + j0.083) \text{ pu.}$$

   b. Shuttle Car. $Z_A = 0.1 + j0.02$

$$Z_{pu} = \frac{Z_A}{Z_{b3}} = \frac{0.1 + j0.12}{0.12}$$

$$Z_{pu} = (0.833 + j1) \text{ pu.}$$

5. Machines. Consumption given in terms of average and reactive power.

   a. Miner. $P = 57$ kW, $Q = 45$ kvar

   or

$$kVA_A = (57 + j45) \text{ kVA}$$

   thus

$$kVA_{pu} = \frac{kVA_A}{kVA_b} = \frac{(57 + j45)}{1000}$$

$$= (0.057 + j0.045) \text{ pu.}$$

   b. Shuttle Car. $kVA_A = (4 + j5)$ kVA

   hence

$$kVA_{pu} = (0.004 + j0.005) \text{ pu.}$$

At this point the entire system of Figure 4.28 may be redrawn into the "immediate diagram" provided in Figure 4.29.

Figure 4.29, when compared to a per-phase diagram in the impedance domain such as Figure 4.19, illustrates the simplification advantage that per-unit computations lend to power system analysis. The circuit shown is merely a series-parallel arrangement of basic electrical elements and, obviously, it may be further simplified if desired, say into an equivalent per-unit impedance. This is only one example, however, and the actual appreciation of power system analysis by per-unit techniques comes through experience.

The impedance diagram can be used for the solution of most power problems. Suppose currents under normal operation are desired. One method is to apply known voltages at system points, and calculate the resulting currents and voltages. For instance, suppose the line-to-neutral at the miner is 320 V (about 555 V line-to-line), the per-unit equivalent of this is:

$$kV_{pu} = \frac{kV_A}{kV_{b3}} = \frac{0.32}{0.35} = 0.91 \text{ pu.}$$

The current through the miner trailing cable is then

$$I_{pu} = \frac{kVA_{pu}}{kV_{pu}}^*$$

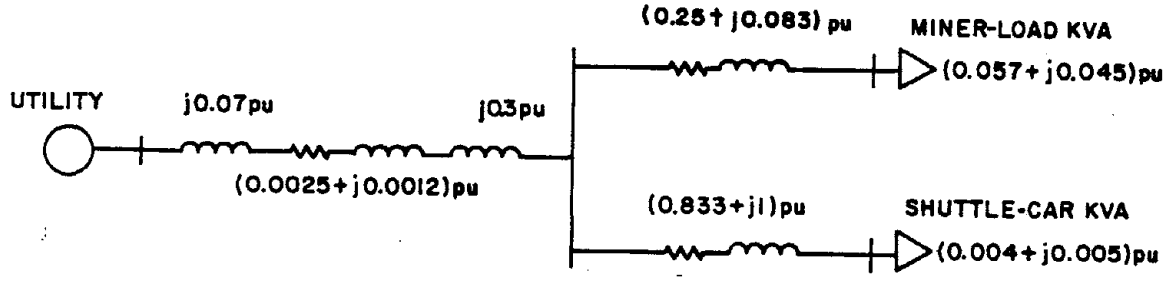


Figure 4.29. An Impedance Diagram of the System in Figure 4.28, Expressed in Per Unit on a 1000-kVA Base.

or

$$I_{pu} = \frac{(0.057 - j0.045)}{0.91} = 0.063 - j0.049 \text{ pu.}$$

The conjugate of power is employed because voltage is implied as the reference phasor (this follows the conventions stated earlier). The process is easily continued through the entire system. When the desired per-unit values are obtained, they are simply converted to actual values. Considering the current in the miner trailing cable, the actual current is:

$$I_A = I_{pu}\, I_{b3}$$

or

$$I_A = (0.063 - j0.049)(2857) = 180 - j141.3 \text{ A}$$

or

$$I_A = 229 \angle -38.1^\circ \text{ A.}$$

4.5 Three-Phase Rectification

General. Because of the advantageous use of d-c series motors on haulage, large amounts of d-c power at either 250 Vdc or 550 Vdc are required for locomotives and face equipment in many mining operations. When more than a fractional kilowatt of d-c power is needed from an a-c source, a polyphase rectifier circuit is employed and for mines the direct voltage is derived from three-phase power, most often from distribution voltages. The section covers the fundamentals of three-phase rectification and actually serves as an introduction to the Chapter-11 section on direct-current power centers.

There are specific advantages when using polyphase rectifier circuits for d-c power. As the number of a-c phases driving the rectifier is increased (say, above single-phase a-c), the frequency of output ripple is increased, the interval between rectifier conduction is decreased, and the ripple magnitude in the d-c voltage and current waves decreases.

Transformers are almost always used between the a-c source and the rectifiers. The rectifier transformer provides one or more of the following functions:

1. to transform the available a-c supply voltage to a value needed for the desired d-c voltage;
2. to provide the number of phases required to obtain the desired waveshapes of d-c voltage, d-c current, and a-c supply current;
3. to isolate the d-c circuit from the a-c source; and
4. to limit, through transformer impedance, damaging overcurrent that might flow during malfunctions.

It is important to note that the decrease in rectifier-conduction interval also increases the required transformer rating. Transformer "utilization factor" can be defined as the ratio of d-c power delivered to the required transformer secondary volt-ampere rating. Utilization factor has been found to have a maximum value of 0.520 when three-phase a-c input is used. This implies that from a transformer utilization standpoint, the most economic rectifier-conduction angle is 120°.

When power rectifiers are mentioned today, it is a very rare instance if the reference is not to solid-state rectifiers using silicon rectifiers as the rectifying elements. The silicon rectifier is virtually the only type considered for mine power installations.

There are a large number of possible rectifier circuits; however only two or three are found in mining equipment. With silicon rectifiers, circuits are selected to make the most efficient use of the transformer. This usually means the single-phase full-wave bridge or the three-phase full-wave bridge. The next section will discuss three fundamental three-phase rectifier circuits; it will be seen why the full-wave bridge is popular.

Rectifier Circuits. Rectifier circuits can be classified as "single-way" or "double-way." The phase currents of the transformer secondary (also termed the d-c winding) are unidirectional in a single-way circuit, while the phase currents are alternating in the double-way circuit.

The most simple three-phase rectifier circuit is the "three-phase half-wave" as shown in Figure 4.30a. A delta-wye transformer is used with each leg connected to a rectifier anode. The three rectifier cathodes are tied together, forming the positive d-c "bus," and the d-c winding neutral point serves as the negative connection for the load (in this case resistance R). Being a single-way rectifier, each leg of the transformer secondary conducts current unidirectionally. If the load is pure resistance, the relationship of output voltage (that across the load) versus time is as shown in Figure 4.30b. Each rectifier conducts for that cycle portion where its anode is more positive than the anode of either other rectifier. Therefore, one

rectifier passes current for 120° of the input three-phase cycle. Since the current through the load is directly proportional to the output voltage, load current also has the same waveform as voltage.

An inspection of the three-phase half-wave output voltage shows that the ripple voltage is much lower than the single-phase full-wave rectifier circuit. Actually, the rms value of the ripple voltage magnetic is only 18% of the average output voltage; this average voltage is the average d-c load voltage, V_{dc}. If rectifier losses are ignored as they are very small for silicon diodes, the d-c output voltage and the transformer secondary voltage are related by:

$$V_{dc} = 0.827V_{max} = 1.17V_{rms} \qquad (4.35)$$

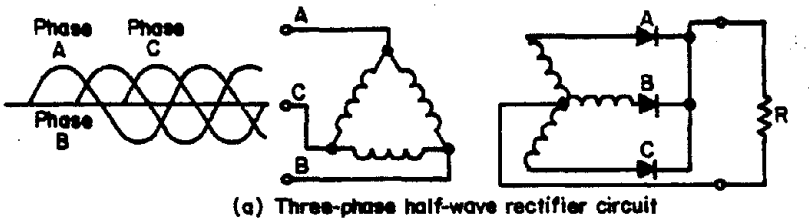
where,

V_{dc} = the average d-c output voltage (V)

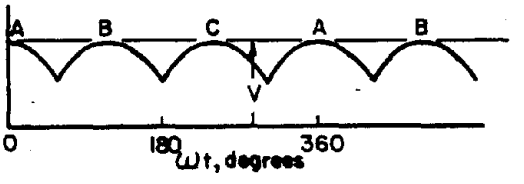
V_{max} = the peak value of the voltage applied to the rectifier circuit (V)

V_{rms} = the rms value of voltage applied to the rectifier circuit (V).

Note that V_{max} and V_{rms} are line-to-neutral voltages. In addition, the fundamental frequency is three times the a-c line frequency. This gives another advantage over single-phase rectifiers in that the size of any required filter components (to further lower the ripple voltage) are much smaller in size.



(a) Three-phase half-wave rectifier circuit



(b) Three-phase half-wave rectifier voltage waveform

Figure 4.30.. Three-Phase Half-Wave Rectifier Circuit and Output Voltage Waveform.

The relationships just presented for the three-phase half-wave rectifier hold only for ideal transformers and rectifiers. However, in actual circuits, the voltage drop, caused d-c current and the transformer secondary winding resistance, creates a d-c component that makes transformer magnetic operation move towards saturation. Consequently, this simple three-phase rectifier circuit is seldomly used.

Output ripple can be further reduced by a "three-phase full-wave" rectifier circuit, connected as shown in Figure 4.31a. Being a two-way rectifier, the transformer magnetic saturation problem with the half-wave rectifier is not present. Furthermore, the advantages of 120° conduction on transformer economy plus the fundamental ripple frequency of six times the a-c source frequency make this double-way rectifier circuit of great practical value. Also called "three-phase bridge" or "six-phase rectifier" circuit, as mentioned earlier, it is the most popular configuration for d-c power in mining. The transformer d-c winding may be either wye or delta connected, with the latter more popular.

In the full-wave rectifier circuit, each terminal of the transformer secondary is connected to two diodes, one at the anode and the other at the cathode. The cathodes of three rectifiers are common forming the positive d-c voltage bus, while the common anode connection of the other three rectifiers represents the negative d-c voltage bus. The load is connected between these two common points.

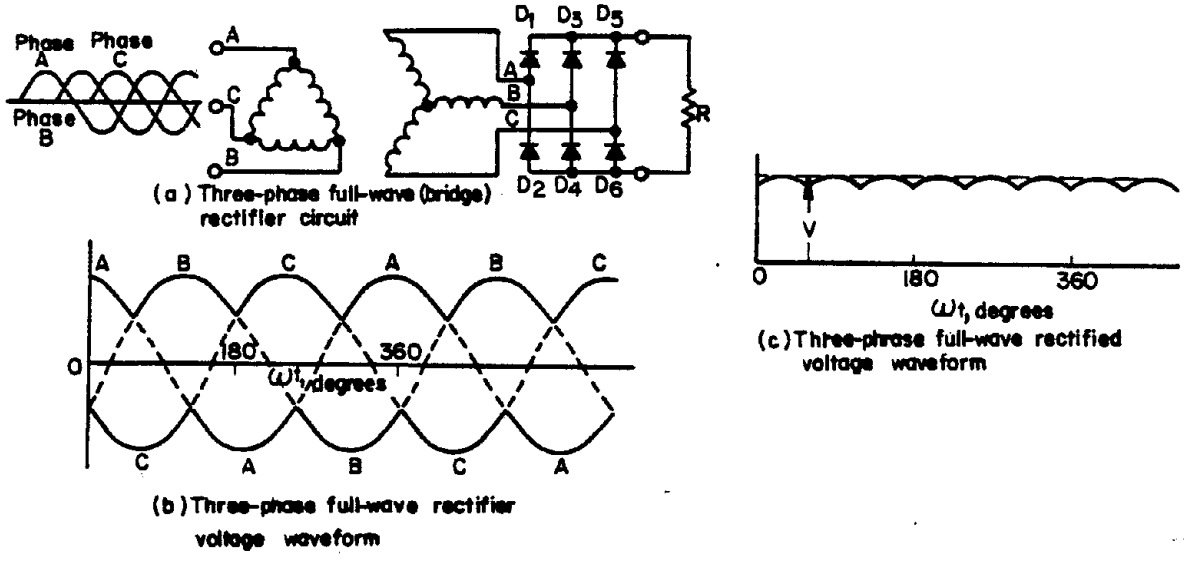


Figure 4.31. Three-Phase Full-Wave Rectifier Circuit with Input and Output Voltage Waveforms.

Each rectifier conducts for 120° of one input cycle, and current alternates in each transformer winding. However, current flows through a specific combination of rectifiers (say, D_1 and D_4 in combination with transformer secondary terminals A and B) for only 60° of the input cycle. Therefore, the peak-to-peak voltage across the load resistance appears as six-phase ripple (see Figure 4.31c).

Analysis of Figure 4.31c shows that the rms value of the fundamental component of the ripple voltage is now only 4.2% of the average d-c output voltage. In addition, for ideal rectifiers, the average d-c output voltage is:

$$V_{dc} = 0.95V_{max} = 1.34V_{rms} \qquad (4.36)$$

in which

V_{dc} = the average output d-c voltage (V),

V_{max} = the peak phase-to-phase voltage applied to the rectifiers (V),

V_{rms} = the rms value of phase-to-phase voltage applied to the rectifiers (V).

The foregoing circuits are indicative of most polyphase rectifier circuits, and many additional configurations are available. However, because mining almost always employs full-wave rectifier circuits, coverage of more circuits is beyond the scope of the report, but the references can be consulted if desired.

Parallel Rectifier Operation. Commonly, the current requirements of a rectifier circuit are too large to be handled by one rectifier per circuit element. Two or more rectifiers must then be connected in parallel. Direct operation of two silicon rectifiers in parallel is extremely difficult. Unbalance between the parallel paths can be easily caused by unequal rectifier characteristics (mainly the forward voltage) and by unequal impedance in the bus bars or cables. The result is that the rectifier with the least forward voltage will be destroyed by overcurrent. To eliminate this, parallel rectifiers must be forced into sharing the current equally.

The almost exclusive method used in mining equipment to force current sharing is "paralleling reactors," sometimes called current-balancing transformers. Figure 4.32 shows how several rectifiers are paralleled using reactors; the combination would act as one rectifying element in a rectifier circuit such as

Figure 4.31a. In Figure 4.32, each reactor is a laminated magnetic core linked in opposing polarity by the anode currents of two rectifiers. The cores are designed not to saturate at the highest expected current. If the two rectifier currents become unequal, the current difference excites a magnetic flux, which induces an aiding voltage. This voltage is induced in the rectifier leads in such a direction as to equalize the currents.

Comments. Most of the information that is covered in Chapter 3, "Semiconductor Devices," applies to three-phase as well as single-phase rectifier circuits; a good example is rectifier cooling. Many additional points have yet to be entertained but because they are directed to rectifier-circuit design the subject is continued in Chapter 11.

4.6 Unbalanced Three-Phase Circuits

Unbalanced Conditions and Faults. The solution of balanced three-phase circuit problems is commonly accomplished by converting the constants and applied voltages to per-phase values. Because symmetry determines the magnitude and phase position of all phase currents and voltages, actions occurring between phases can be represented by equivalent impedances. Furthermore, currents and voltages for the other phases are equal in magnitude to those in the per-phase solution but are simply displaced symmetrically in phase position. This is extremely important because normally-operating three-phase power systems can usually be approximated as balanced. However, as has been mentioned, the solution of unbalanced three-phase circuits or balanced circuits with unbalanced loads does not permit the same simplification.

Mine power systems are designed to have a high degree of reliability and therefore operate balanced. However, at times, equipment failures and unintentional or intentional disturbances

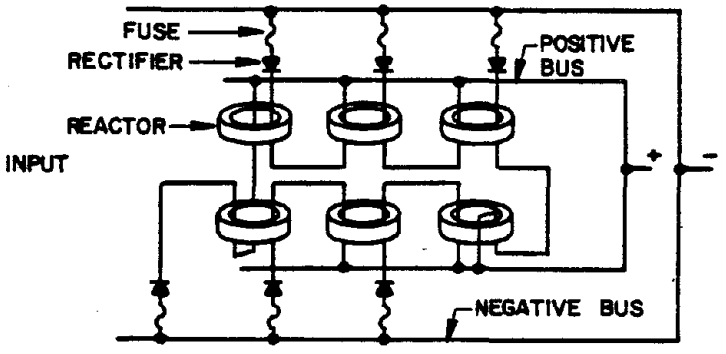


Figure 4.32. Parallel Operation of Rectifiers Using Paralleling Reactors.

from outside sources can result in unbalanced operation. The consequence is abnormal currents and voltages. If safeguards are not designed into the system to protect against these anomalies, personnel as well as equipment safety can easily be compromised. The protective circuitry within the mine power system serves as the safety-value for such hazardous malfunctions.

Power system unbalance can occur either from open-circuits or faults. A "fault" occurs whenever electricity strays from its proper path; they can be visualized as the connecting together of two or more conductors which normally operate with a voltage between them. A short circuit is a fault form, but the connection creating a fault can be from physical contact or an arc (current flow through a gaseous medium). Currents in the power system resulting from an open circuit or a fault can often be exceedingly large. The most common sites for mine power system unbalance are equipment trailing cables.

An "overload" is not a fault. The term, overload, implies only that currents exceed those for which the power system was designed. Such currents are substantially less than fault currents. Nevertheless, overloads can create equipment failures by exceeding the system thermal-design limits. If not corrected, the overload can result in a personnel hazard. However, such problems only happen from unattended overload operation for an extended time period, whereas faults can create an unsafe condition almost instantaneously.

Both "circuit breakers" and "fuses" are used to protect circuits from excessive current flow, be it a result of faulting or overloading. The "circuit-interrupting" operation consists of parting a pair of contacts. As an arc is drawn between the contacts, the process must include extinguishing the arc. The interruption is handled mechanically in the circuit breaker, but the excessive current is monitored electrically and/or thermally. Fuse operation is based on simple thermal operation. The fusible element, responsive to the heat of an overload or fault current, melts open, and the fuse jacket is employed to extinguish the subsequent arc. A complete discussion of interrupting devices, as well as the associated protective circuitry, is presented in Chapter 8.

Fault Types. The fault type often seen in literature is called a "bolted fault," which can be described as a zero-resistance short circuit between two or more conductors. In reality, however, most faults are not dead shorts but have some finite value of resistance.

Faults may be classed as permanent or temporary. A "permanent fault" is one where equipment operation is impossible and repairs are mandatory. A "temporary fault" is simply intermittant in nature. For instance, two close-spaced overhead

conductors may only cause trouble on windy days, when they can be forced into contact or close proximity by the wind.

A very sinister fault type is the "arcing fault." This condition, once poorly understood, is now believed to be the most common. When two conductors of different potential are in very close proximity, the intervening space between them can be considered a spark gap. Consider that the conductors are part of an a-c power system. As the sinusoidal waveform reaches a certain value, the insulating material between the conductors may break down, and fault current will then flow. The potential drop across the conducting gap (actually, a resistance) remains at a nearly constant level, and it is this energy source releasing terrific quantities of heat which causes the devastation that is typical of an arcing fault. Soon after the sinusoid reverses polarity, the arc quenches until the spark-gap breakdown voltage or "restrike potential" is reached once more. This repetitive arcing is almost always self-sustaining at a-c voltage levels of 480V and above.

Depending on how the fault occurs, it may be described as three phase, line-to-line, or line-to-neutral. Due to the presence of cable shields and grounded equipment in mining, the shields and the grounding system are at the same potential as are the system neutral, and line-to-neutral faults are the most prevalent. Line-to-line faults and line-to-neutral faults are unbalanced or "unsymmetrical," but the three-phase fault is balanced or "symmetrical." These three basic fault descriptions are illustrated in Figure 4.33. The resistance, albeit very small, is shown to signify its finite value.

Fault Analysis. Fault analysis is a desirable if not mandatory part of any mine power system analysis, as faulting of some nature can occur at any time. Knowledge of how faults

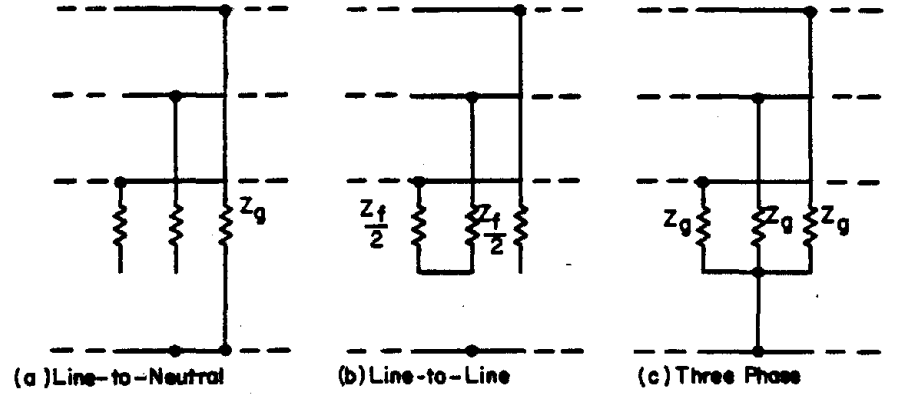


Figure 4.33. Basic Fault Descriptions.

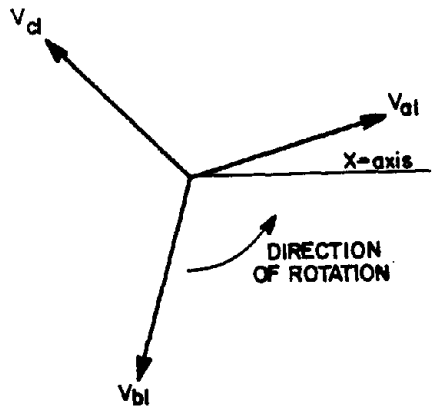
affect currents and voltages is necessary to design proper protection, thus insure personnel protection. Although faults most often occur in trailing cables on mine systems, the actual fault location, as well as the time of occurrence, is unpredictable. Consequently, fault analysis can be on a trial-and-error basis, searching for a worst-case solution. It is necessary to assume a fault location, the configuration of power-system components prior to the fault, and sometimes system loads. Such an effort can result in numerous calculations to the point where digital computers can be extremely advantageous, but the result provides invaluable information on which the mine power system must be designed.

Though not particularly common, fault analysis using three-phase faults has distinct advantages. Balanced faults, like balanced loads, can be investigated on an equivalent per-phase basis and therefore are as simple as faults on single-phase lines. Bolted three-phase faults also result in more fault current than line-to-line or line-to-neutral in the majority of cases. (See Chapter 9.)

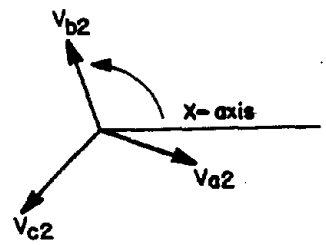
Unsymmetrical faults are often of high interest in mine power systems. Instances include finding a minimum fault current or current flowing in the system neutral conductors. When an unsymmetrical fault is placed on the system, the balance is disrupted. It is possible to solve an unbalanced power system using a three-phase diagram by assigning symbols to the quantities in all phases and carrying the phase solutions simultaneously. This complicates the problem enormously. The "Method of Symmetrical Components" reduces the solution of such problems to a systematic form and results in much simplification. The reduction is especially true for balanced systems operating under unsymmetrical faults.

4.7 Symmetrical Components

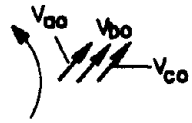
General. The Method of Symmetrical Components provides a means for determining the currents and voltages at any point of an unbalanced three-phase power system. In the method, the unsymmetrical vectors representing the unbalanced voltage or current are expressed as the sum of three symmetrical vector sets. These vector sets are designed as the "positive sequence," "negative sequence," and "zero sequence." The first two have been described in an earlier report section and consist of three balanced vectors with equal magnitude set 120° apart. The zero sequence set is three vectors equal in magnitude but operating at the same direction. These sequences are illustrated in Figure 4.34, where the instantaneous values may be represented by projection upon the x-axis. The positive, negative, and zero sequence vectors are then employed to solve the unbalanced system problem; they are so common in power system terminology that each is often used to describe the quality of system operation.



Positive Sequence. With conventional counterclockwise rotation , instantaneous maximum values result in the sequence, abcabc----.



Negative Sequence. Vectors result in a maxima sequence of acbacb----or cbacba---.



Zero Sequence. All maxima occur simultaneously.

Figure 4.34. Positive, Negative, and Zero Sequence Vector Sets.

The following presentation has two purposes; to show how any three unbalanced currents or voltages can be resolved into three sets of three balanced or symmetrical components and to show how three unbalanced voltages or currents can be constructed in an analytical manner from the three fundamental sequences.

It might be asked, why should the resolution of three vectors into nine vectors simplify the solution of unbalanced power systems? The answer is straightforward. The resolution results in three symmetrical systems, and each one of the balanced vector systems can be treated separately just as balanced three-phase systems. In other words, the power system can be reduced to per-phase values then separately analyzed for each symmetrical component. This hinges on the fact that currents and voltages of different sequences do not react upon each other. For instance, currents of the positive sequence produce only positive-sequence voltage drops; the same is true for negative and zero sequences.

The type of resolution provided by symmetrical components isolates electrical parameters into components which, at times, represent a better criterion of the controlling factor or factors for certain phenomena. For example, the presence of negative-sequence current or voltage immediately implies that the system is unbalanced, and such is utilized to detect malfunctioning power systems. Grounding phenomena is another good criterion example; neutral current is very closely related to zero-sequence components.

Sequence Components. The positive sequence for voltage is composed of the symmetrical vectors, V_{a1}, V_{b1}, and V_{c1} (see Figure 4.34). The quantities have equal magnitude but are displaced by 120° from each other. Therefore, following equation 4.2b,

$$V_{a1} = V_{b1} \angle 120° = V_{c1} \angle 240° \tag{4.37}$$

or rewriting in exponential form,

$$V_{a1} = V_{a1} \tag{4.38a}$$

$$V_{b1} = e^{j240} V_{a1} \tag{4.38b}$$

$$V_{c1} = e^{j120} V_{a1}. \tag{4.38c}$$

The unit vector, e^{j120}, is used so frequently that it is given the symbol "a" (not to be confused with a transformer turns ratio) where

$$a = e^{j120} = 1 \angle 120°. \tag{4.39a}$$

and

$$a^2 = e^{j120} e^{j120} = e^{j240}. \tag{4.39b}$$

Thus, the positive-sequence vectors (equations 4.38) are customarily written as:

$$V_{a1} = V_{a1} \tag{4.40a}$$

$$V_{b1} = a^2 V_{a1} \tag{4.40b}$$

$$V_{c1} = aV_{a1}. \tag{4.40c}$$

Equations 4.38 and 4.40 also relate to standard practice of symmetrical-component calculation; equations are always expressed in terms of the "phase a" quantities.

There are several mathematical properties of the unit vector "a" which are handy in computations:

$$1 = e^{j0} = 1.0 + j0.0$$

$$a = e^{j120} = -0.5 + j0.866$$

$$a^2 = e^{j240} = -0.5 - j0.866$$

$$a^3 = e^{j360} = 1.0$$

$$a^4 = e^{j480} = e^{j120} = a$$

$$a^5 = e^{j600} = e^{j240} = a^2$$

and for specific calculations:

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

$$a - a^2 = \sqrt{3}e^{j90} = j\sqrt{3}$$

$$a^2 - a = \sqrt{3}e^{-j90} = -j\sqrt{3}$$

$$1 - a = \sqrt{3}e^{-j30} = 1.5 - j0.866$$

$$1 - a^2 = \sqrt{3}e^{j30} = 1.5 + j0.866.$$

These allow easy conversion to simpler forms as symmetrical components are being mathematically manipulated.

Considering the symmetrical voltage vectors for the negative and zero sequences, these can be written, respectively (again, see Figure 4.34):

$$V_{a2} = V_{b2}\angle -120° = V_{c2}\angle 120° \tag{4.41}$$

and

$$V_{ao} = V_{bo} = V_{co}. \tag{4.42}$$

Rewritting these equations in terms of the unit vector "a," it is found for the negative sequence:

$$V_{a2} = V_{a2} \tag{4.43a}$$

$$V_{b2} = aV_{a2} \tag{4.43b}$$

$$V_{c2} = a^2V_{a2} \tag{4.43c}$$

and for the zero sequence:

$$V_{ao} = V_{ao} \tag{4.44a}$$

$$V_{bo} = V_{ao} \tag{4.44b}$$

$$V_{co} = V_{ao}. \tag{4.44c}$$

It is important to note that in all three sequence systems, the subscripts denote specific components in each phase (a, b,

or c). Furthermore, the subscripts 1, 2, and 0 signify if that component is part of the positive, negative, or zero sequence set. Using the same reasoning for voltages, symmetrical-component equations can also be written for current.

Sequence-Quantity Combinations. The total voltage or current of any phase is equal to the vectorial sum of the corresponding components in that phase. Figure 4.35 illustrates this concept for three unbalanced voltage vectors, V_a, V_b, and V_c. Expressed mathematically,

$$V_a = V_{ao} + V_{a1} + V_{a2} \tag{4.45a}$$

$$V_b = V_{bo} + V_{b1} + V_{b2} \tag{4.45b}$$

$$V_c = V_{co} + V_{c1} + V_{c2}. \tag{4.45c}$$

Substituting in the equivalent values given by equations 4.40, 4.43, and 4.44; equations 4.45 become:

$$V_a = V_{ao} + V_{a1} + V_{a2} \tag{4.46a}$$

$$V_b = V_{ao} + a^2V_{a1} + aV_{a2} \tag{4.46b}$$

$$V_c = V_{ao} + aV_{a1} + a^2V_{a2}. \tag{4.46c}$$

These equations state that an unbalanced system can be defined in terms of three balanced vector sets (they are expressed in only "phase a" quantities following convention). In other words,

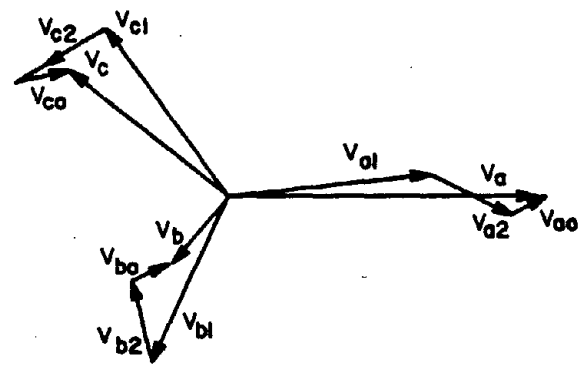


Figure 4.35. Symmetrical Component Addition to Obtain an Unbalanced Three-Phase Set.

positive-, negative-, and zero-sequence components of "phase a" can be added to obtain the unbalanced vectors.

Similarly, three unbalanced voltages or currents may be resolved into their symmetrical components. First, consider the zero sequence. By adding equations 4.46a, 4.46b, and 4.46c together,

$$V_a + V_b + V_c = 3V_{ao} + (1 + a^2 + a)V_{a1} + (1 + a + a^2)V_{a2}.$$

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

$$V_{ao} = \frac{1}{3}(V_a + V_b + V_c). \qquad (4.47a)$$

If equation 4.46b is multiplied by "a" and equation 4.46c by "a^2," then these results are added to equation 4.45a,

$$V_a + aV_b + a^2V_c = (1 + a + a^2)V_{ao} + 3V_{a1} + (1 + a^2 + a)V_{a2}.$$

Therefore

$$V_{a1} = \frac{1}{3}(V_a + aV_b + a^2V_c) \qquad (4.47b)$$

which relates the positive-sequence component of "phase a" to the unbalanced vectors. Finally, for the negative sequence, if equation 4.46b is multiplied by "a^2" with equation 4.46c by "a,"

$$V_a + a^2V_b + aV_c = (1 + a^2 + a)V_{ao} + (1 + a + a^2)V_{a1} + 3V_{a2}.$$

Then

$$V_{a2} = \frac{1}{3}(V_a + a^2V_b + aV_c). \qquad (4.47c)$$

Equations 4.47a, 4.47b, and 4.47c are therefore the reverse of equations 4.46a, 4.46b, and 4.46c; they will allow the balanced vectors to be written in terms of the unbalanced system.

Symmetrical-Component Relationships. To illustrate the existence of symmetrical components in three-phase circuits, the comparison of currents in equivalent delta-connected and wye-connected loads or sources forms a good basis. Take the two

loads shown in Figure 4.36, where I_{ab}, I_{bc}, and I_{ca} are the three line-to-line currents and I_a, I_b, and I_c are the line currents. All these may be assumed to result from an unbalanced condition.

At the three terminals of the delta load, the following relationships are satisfied by Kirchhoff's current law:

$$I_a = I_{ab} - I_{ca} \tag{4.48a}$$

$$I_b = I_{bc} - I_{ab} \tag{4.48b}$$

$$I_c = I_{ca} - I_{bc}. \tag{4.48c}$$

The zero-sequence currents of the wye-connected load are (using equation 4.47a):

$$I_{ao} = \frac{1}{3} (I_a + I_b + I_c). \tag{4.49}$$

Substituting equations 4.48 into equation 4.49, it is found that

$$I_{ao} = \frac{1}{3} [(I_{ca} + I_{ab} + I_{bc}) - (I_{ab} + I_{bc} + I_{ca})] = 0. \tag{4.50}$$

This shows that the zero-sequence current of a three-phase circuit feeding into a delta connection is always zero. In addition, the currents to a three-phase wye-connected load with a floating neutral (Figure 4.36b) can have no zero-sequence components. Simply, a neutral-return circuit must be available for zero-sequence currents to flow. However, zero-sequence current may circulate in a delta connection without getting out into a neutral conductor (see Figure 4.36a, note directions of I_{ab}, I_{bc}, and I_{ca}).

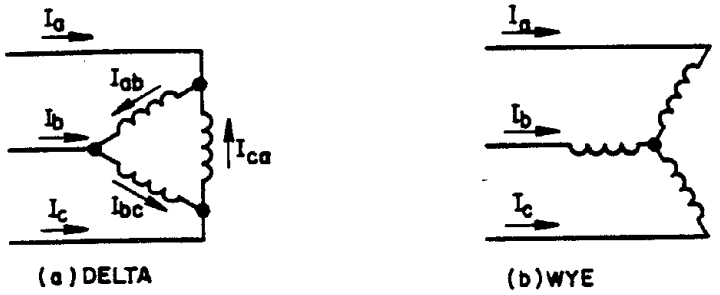


Figure 4.36. Equivalent Delta-Connected and Wye-Connected Loads.

For transforming positive-sequence line currents to line-to-line current, it can be shown that from

$$I_{a1} = \frac{1}{3} (I_a + aI_b + a^2Ic), \tag{4.51}$$

which applies equation 4.47b to current, that

$$I_{ab1} = \frac{j}{\sqrt{3}} I_{a1}. \tag{4.52}$$

Using a similar process for negative-sequence currents,

$$I_{ab2} = \frac{-j}{\sqrt{3}} I_{a2}. \tag{4.53}$$

When the foregoing is applied to line-to-neutral and line-to-line voltages, the transformation equations are:

$$V_{abo} = 0 \tag{4.54a}$$

$$V_{ab1} = j\sqrt{3}V_{a1} \tag{4.54b}$$

$$V_{ab2} = -j\sqrt{3}V_{a2} \tag{4.54c}$$

where,

V_{abo}, V_{ab1}, V_{ab2} = zero-, positive-, and negative-sequence line-to-line voltages

V_{ao}, V_{a1}, V_{a2} = zero-, positive-, and negative-sequence line-to-neutral voltages.

These bring out another general relationship about zero-sequence components; a line-to-line voltage, however balanced, can have no zero-sequence component. Line-to-neutral voltages, on the other hand, may have a zero-sequence value.

To use equations 4.51 through 4.54c, currents must be assumed for delta and wye connections as shown in Figure 4.36.

Symmetrical-Component Impedance. Before the solution of unbalanced system problems can be discussed, the concepts of impedance under the influence of symmetrical components need to be covered. Impedance relates the current in a circuit to the impressed voltage. "Symmetrical-component impedance" behaves in a similar manner, except it is sometimes affected by additional parameters. There are three likely cases for a power system: unbalanced static network, balanced static network, and the balanced non-static network. All these impedance values are created by the fact the positive- and negative-sequence currents produce only positive- and negative-sequence voltage drops, respectively. The flow of zero-sequence currents in a neutral can result in an impedance that is apparently greater than the actual impedance.

In an unbalanced static network, the sequence impedances in a particular phase are equal, but not necessarily equal to those in another phase:

$$Z_{ao} = Z_{a1} = Z_{a2} \tag{4.55a}$$

$$Z_{bo} = Z_{b1} = Z_{b2} \tag{4.55b}$$

$$Z_{co} = Z_{c1} = Z_{c2} \tag{4.55c}$$

where Z_{ao}, Z_{bo}, Z_{co}; Z_{a1}, Z_{b1}, Z_{c1}; and Z_{a2}, Z_{b2}, Z_{c2} are symmetrical-component impedances for the zero, positive, and negative sequences in phase a, b, and c, respectively.

The balanced non-static network is given by:

$$Z_{ao} = Z_{bo} = Z_{co} \tag{4.56a}$$

$$Z_{a1} = Z_{b1} = Z_{c1} \tag{4.56b}$$

$$Z_{a2} = Z_{b2} = Z_{c2}. \tag{4.56c}$$

This states that the impedances in a sequence are equal, but not necessarily equal to the other sequence-component impedances. Trailing cables and power lines are included in this case and specifically:

$$Z_{a1} = Z_{a2} \neq Z_{ao}. \tag{4.57}$$

The last likely case is the balanced static network where:

$$Z_a = Z_b = Z_c. \tag{4.58}$$

This is a situation where symmetrical components would not normally be applied.

As a general statement, positive- and negative-sequence impendances of a power system usually are on the same order of magnitude, but the system zero-sequence impedance may vary through a very wide range. This range is dependent upon the resistance-to-reactance ratio as seen by the zero-sequence current. The next report section will continue this subject for a specific example.

Fault Calculations. One of the most significant uses for the Method of Symmetrical Components is the computations of voltages and currents resulting from unbalanced faults. The three-phase diagram in Figure 4.37 represents a simple power system with a four-wire wye-connected source. The impedance of each phase conductor is Z, while Z_o is the neutral-conductor impedance. A bolted line-to-neutral fault is occurring at point a on phase a (an "x" signifies the fault). The resulting current in the fault, I_f, is of interest, and the following shows how symmetrical components can be used to find its value.

It is apparent from Figure 4.37 that the line currents, under the fault condition, are

$$I_a = I_f,\ I_b = 0,\ I_c = 0 \tag{4.59}$$

in which

I_f = the current in the fault

I_a, I_b, I_c = the unbalanced phase currents.

Applying equations 4.46, the symmetrical components of these currents are:

$$I_{a1} = \frac{1}{3}\,(I_a + aI_b + a^2I_c) = \frac{1}{3}\,I_f \tag{4.60a}$$

$$I_{a2} = \frac{1}{3}\,(I_a + a^2I_b + aI_c) = \frac{1}{3}\,I_f \tag{4.60b}$$

$$I_{ao} = \frac{1}{3} (I_a + I_b + I_c) = \frac{1}{3} I_f . \qquad (4.60c)$$

Therefore

$$I_{a1} = I_{a2} = I_{ao} = \frac{1}{3} I_f . \qquad (4.61)$$

To completely define the fault, it must be known whether the fault between line a and the neutral is a "dead" short or exhibits an impedance. Although all faults have a finite impedance, the faulting assumption states that it is bolted. Therefore, fault impedance is zero, and the voltage across the fault, V_{fn}, is also zero. With this, the current through the fault, I_f, can be described. However, to perform the required computations, it is necessary to know the force driving the fault current and the impedance existing between this "driving potential" and the fault location.

The source, V, is the driving potential, and it can be assumed as purely positive sequence. It is also assumed, from Figure 4.37 that the source has negligible internal impedance (in practical situations, however, the source impedance is of great importance). Therefore, the source line-to-neutral potentials are equal to the terminal voltages:

$$V_{an} = V_a, \; V_{bn} = V_b, \; V_{cn} = V_c$$

where V_{an}, V_{bn}, V_{cn} are the terminal line-to-neutral voltages and V_a, V_b, V_c are the corresponding ideal-source potentials. The impedances involved are simply the line impedance of phase a, Z, and the neutral impedance, Z_n. With these parameters known, the

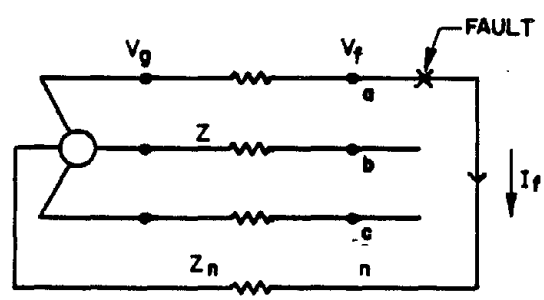


Figure 4.37. A Three-Phase System with a Line-to-Neutral Fault.

process now is to convert the unbalanced system to symmetrical components, solve the problem in terms of these balanced vectors, then reconstruct the result for the fault current.

Following convention, all work is performed in "phase a" quantities. Notwithstanding, phase a contains the line-to-neutral fault, thus it is the only phase involved. Since only positive-sequence voltage is supplied by the source, the symmetrical components of the driving potential are

$$V_{an1} = V_{an},\ V_{an2} = 0,\ V_{ano} = 0. \tag{4.61}$$

The impedance to positive-sequence or negative-sequence current in any one of the three lines is equal, thus for phase a,

$$Z_{a1} = Z,\ Z_{a2} = Z.$$

Zero-sequence current follows a different path than positive or negative sequence. From the source to the fault, zero-sequence current, I_o, exists in each line but, from the fault back to the source (through the neutral conductor), the current is $3I_o$. Zero-sequence impedance, Z_{ao}, is therefore greater than Z. As was inferred in the preceding section, the quantification of Z_{ao}, or just simply Z_o, is not an easy matter. However, in order to limit the amount of fault current flowing in mine power system neutrals, large resistances are placed in the neutral circuit. With this in mind, the resistance-to-reactance ratio of the neutral impedance, Z_n, is very large and, for mine power systems under line-to-neutral faults, the impedance seen by the zero-sequence current can be approximated for this instance as:

$$Z_o = Z + 3Z_n. \tag{4.62}$$

Loop equations for each sequence current can now be expressed for Figure 4.37. If a voltage is assumed to exist across the fault, for phase a,

$$V_{an1} = Z_{a1}\ I_{a1} + V_{f1} \tag{4.63a}$$

$$V_{an2} = Z_{a2}\ I_{a2} + V_{f2} = 0 \tag{4.63b}$$

$$V_{ano} = Z_o\ I_{ao} + V_{fo} = 0 \tag{4.63c}$$

where,

V_{an1}, V_{an2}, V_{ano} = the sequence voltages for the source

I_{a1}, I_{a2}, I_{ao} = the sequence components of the fault current

V_{f1}, V_{f2}, V_{fo} = the sequence components of the voltage across the fault

Z_{a1}, Z_{a2}, Z_o = the sequence impedance seen by the fault current.

Equations 4.62 generalize the fault condition and are practical because of fault impedance. However, a bolted fault has been assumed to exist, thus

$$V_{f1} = V_{f2} = V_{fo} = 0. \tag{4.64}$$

All input to the problem is now available, and simultaneous solution of equations 4.60 through 4.64 shows that:

$$V_{an} = V_{an1} = \frac{1}{3} ZI_f + \frac{1}{3} ZI_f + \frac{1}{3} Z_o I_f \tag{4.64a}$$

or

$$I_f = \frac{V_{an}}{\frac{1}{3}(2Z + Z_o)} \tag{4.64b}$$

or

$$I_f = \frac{V_{an}}{Z + Z_n}. \tag{4.64c}$$

Consequently, symmetrical components have been employed to solve this unbalanced faulting problem.

This work can be easily expanded to cover other unbalanced faulting problems, and the process can be employed to solve any

unbalanced three-phase, or even polyphase, condition. Because fault analysis is imperative in protective-device sizing, additional discussion can be found in Chapter 9.

4.8 Power Terminology

If the sum of the electrical ratings is made for all equipment in a power complex, the result will provide a total connected load. The measure could be expressed in horsepower, but the electrical quantities of kilowatts, kilovolt-amperes, or amperes are more suitable units. (Note: connected horsepower can be converted to connected kilowatt by simply multiplying by 0.746.) Many loads, especially mining production equipment, operate intermittently with others at less than full load. Accordingly, the demand upon the power source is less than the connected load. This fact has principal input in the design of any mine power system as the system should not be designed to the connected load, rather it should be planned to what the connected load actually uses. Obviously, this situation has great impact on power-system investment or the capital required to build the system.

Because of their importance, the IEEE has standard definitions for load combinations and their ratios. The important ones follow (4).

1. "Demand" is the electrical load for an entire complex (or even one piece of equipment) average over a specified interval of time. The time or demand interval is generally 15 min, 30 min, or 1.0 hr, and demand is generally expressed in kilowatts, kilovolt-amperes, and amperes.
2. "Peak load" is the maximum load consumed or produced by one piece or a group of equipment in a stated time period. It can be the maximum instantaneous load, the maximum average load, or (loosely) the maximum connected load over the time period.
3. "Maximum demand" is largest demand that has occurred during a specified time period.
4. "Demand factor" is the ratio of the maximum demand to the total connected load.
5. "Diversity factor" is the ratio of the sum of the individual maximum demands for each system part or subdivision to the complete-system maximum demand.
6. "Load factor" is the ratio of the average load to the peak load, both occurring in the same designated time period. This can be implied as also equal to the ratio of actual power consumed to total connected load (same time period).
7. "Coincident demand" is any demand that occurs simultaneously with any other demand.

As noted with the first definition, all these definitions may be employed on the units of average power, apparent power, or current. Thus, they are invaluable in power system design. A few examples are in order to illustrate the usefulness.

Consider a feeder cable supplying several mining sections in an underground mine. The sum of the connected loads on the cable, multiplied by the demand factor of these loads, yields the maximum demand which the cable must carry. When applied to current, this would be the maximum amperage. Good demand factors for mine power systems range from 0.8 to 0.7 depending upon the number of operating sections. The lower value is used when there are fewer producing units (i.e., from two to four). Demand factor can be extended to include estimations of average load. For instance, the sum of the average loads on the cable, multiplied by the demand factor, provides the average load on the cable. A prime application for this concept is approximating the current a conductor is expected to carry. Say ten identical mining sections draw 53 A each; the conductors feeding all these sections would then be expected to carry:

$$\text{(total average load)(demand factor)} = \text{(average load)}$$

or

$$(10)(53\text{A})(0.8) = 424 \text{ A}.$$

Demand factor, and similarly diversity factor, can be applied to many other mine electrical areas: estimating transformer capacities, protective-circuitry continuous ratings, and the load that a utility company must supply, just to name a few.

Load factor provides an additional example of the utility of these definitions; this one can be used to estimate actual loads required by equipment. Here, the total-connected load times the load factor is an approximation of the actual power consumed. Interestingly, average load factors for underground coal mining are rather low, mainly due to the cyclic nature of their operation and also, at times, to high horsepower motors which are needed to perform specific functions but only for a small fraction of the operating time. For instance, when cutting and loading, a continuous miner will have all motors operating, thus have a total connected load of 385 hp or (0.746) 385 = 287 kW. The average load factor might be 0.6; therefore, the average consumed power is (0.6) 287 or 172 kW. Load factor can also be applied to equipment combinations.

The maximum power demand is normally used by utility companies to determine power bills; most often, one month is the specified time period. Demand meters are occasionally or continuously installed at the utility company's "metering point" for this purpose. A description of this instrumentation is contained in the next section.

4.9 Instrumentation

General. Much has been said in the preceding material about electrical parameters and their quantification: voltage, current, power factor, power, and so on. Instruments which measure these quantities are necessary to monitor and troubleshoot the operation of a power system; they can be used to ensure optimum operations as well as to find malfunctions. The devices may be "indicating" or "recording," and each can be permanently installed in major equipment or be self-contained and portable. Often, every piece of power equipment in or about the mine has some form of enclosed instrumentation. The devices can range from basic meter movements to sensors which are connected to on-line computers that monitor the status of entire power-system complexes.

The word, "meter" is often used to describe instrumentation as a suffix or part of a compound word. Of all the instruments designed to measure electrical quantities, the voltmeter and ammeter are basic, "Voltmeters" measure the potential difference or voltage between two points and, so as not to interfere with normal circuit operation, they must present a very high impedance to the circuit. "Ammeters" measure current flow and must have a near zero impedance. Direct-current voltmeters and ammeters sense average quantities, while their a-c counterparts usually provide rms voltage and current values. Normally, instrument current coils are rated at 5 A with potential coils at 120 V.

This chapter section will explore the various instruments available to the mining industry in an elementary level. The content will commence with description of basic instrument or meter types then show how the devices are employed to monitor system quantities.

4.9-1 Basic Instrument Types

Meter Movements. A "meter movement" is an electromechanical device that provides a mechanical motion to an indicator in response to an applied electrical signal. Usually, regardless of the meter movement type, opposing magnetic fields are employed to activate the indicator or pointer. These movements can be classified as electrostatic, dynamometer, moving iron vane, and permanent-magnet moving coil.

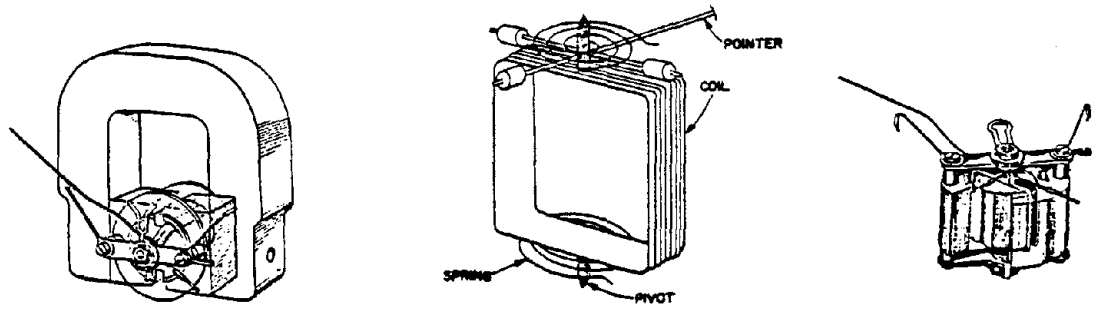
An "electrostatic" movement is the only type which measures voltage directly as opposed to a voltage-produced current.

Basically, this meter is a variable capacitor with a "restoring" resistor connected between a fixed and a movable plate or vane. When a potential difference exists between the plates, the opposing charges produce a mutual attraction. The moveable vane will move towards the fixed vane with the deflection proportional to the applied voltage. Upon removal or change in potential, the resistor discharges the capacitance. Thus, any current through the movement is just incidental to the operation. Electrostatic instruments can measure either a-c or d-c potentials; they have true rms response to a-c regardless of waveform shape. Full-scale readings (or maximum meter deflection) range from 100 V to 10 kV depending on the movement, with measurement precisions of 1/2 to 2%.

"Dynamometer" movement consist of two coils, one fixed and the other movable. The movable coil rotates in the magnetic field produced by current through the stationary coil. If the current being measured flows through both coils (i.e., they are in series), the resulting torque is proportional to that current, and displacement is proportional to the square of current. Thus, pointer deflection indicates the rms value of current. The movement can be designed to measure d-c or a-c current very precisely (0.1%). However, the dynamometer is not commonly employed as an ammeter. The prime application is as a wattmeter; this will be described shortly.

"Moving iron-vane" movements are similar to the dynamometer, except the moving coil is replaced by a soft iron vane with no permanent magnetization. Here, current through the fixed coil produces a magnetic field which induces magnetism in the soft iron vane. The magnetic fields oppose each other, producing torque that deflects the iron vane. The force is proportional to the square of current. The instrument can therefore measure d-c or the rms value of a-c current but with less precision (1/2%) than the dynamometer.

The last basic type of meter movement is the "permanent-magnet moving-coil" or "d'Arsonval," which is a d-c ammeter. The moving element is a coil of fine wire suspended so that it is free to rotate in the field of a permanent magnet. Sketches of typical movements are provided in Figure 4.38. When direct current flows in the coil, a torque is produced that tends to rotate the coil. The rotation is opposed by some form of spring restraint (usually a helical spring) so coil motion and thus pointer position is proportional to coil current. If the direct current through the coil is varying too fast so that the pointer cannot follow the fluctuations, the pointer will assume a position relative to average torque and, therefore, indicate the average value of current. However, if the current is a sinusoid, the average of moving-coil torque is zero, and the pointer will not be deflected. Nevertheless, precision of d'Arsonval movements can obtain 0.1%.



(a) External Magnet (b) Moving-Coil Construction (c) Internal Magnet

Figure 4.38. Permanent-Magnet Moving-Coil Movements.

For measuring current, both dynamometer and moving-iron-vane types are often restricted to frequencies less than 200 Hz, yet both these yield true rms readings within their frequency range. For observing voltage, electrostatic instruments can be extremely precise, but they are often very delicate, being considered for laboratory use only. Interestingly, even though d'Arsonval movements measure only direct current, they are the most common type in use, be the application d-c or a-c voltage or current. Hence, the following discussion will primarily address this type movement; the main exception will be dynamometers as wattmeters.

Meter-Movement Applications. When a d'Arsonval meter is used as an ammeter, it is inserted in series with the circuit being measured. The current range for this direct application is obviously restricted by the maximum scale reading or maximum current of the movement. D'Arsonval meters can have full scale limits from 1.0 μA to 50 mA although the basic movement is considered 1.0 mA (which allows measurements from zero to 1.0 mA). For higher current requirements, the meter is shunted with a low resistance as shown in Figure 4.39. Such shunts can be tapped to provide several current ranges, or several shunts might be available, each selected by a switch to provide a specific current range. Commercially-available ammeters of this type are available up to a 50-A full-scale reading.

To measure d-c voltages, a d'Arsonval movement is simply placed in series with a selected high resistance, and the combination is connected between the two points where a voltage measurement is desired (see Figure 4.40). Here, because meter deflection is still proportional to current, the meter scale can be calibrated to read the voltage required to produce a

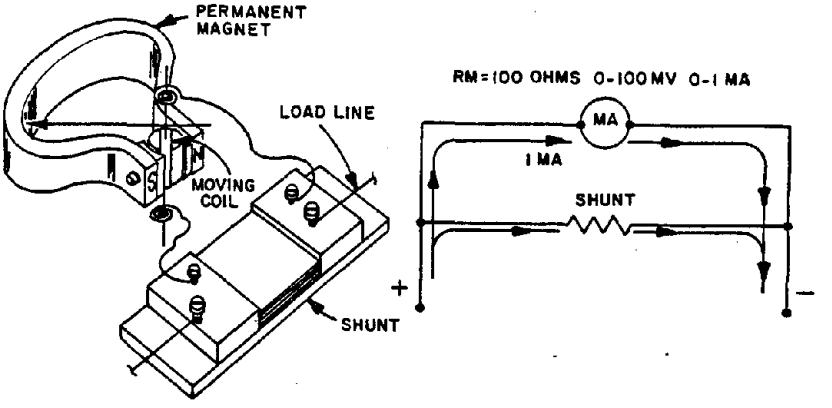


Figure 4.39. Shunting a d'Arsonval Meter for High-Current Tests.

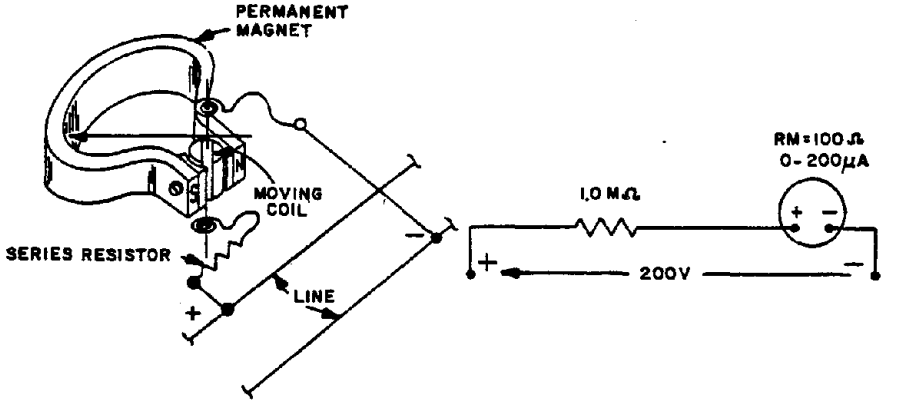


Figure 4.40. The d'Arsonval Meter Used to Measure d-c Potentials.

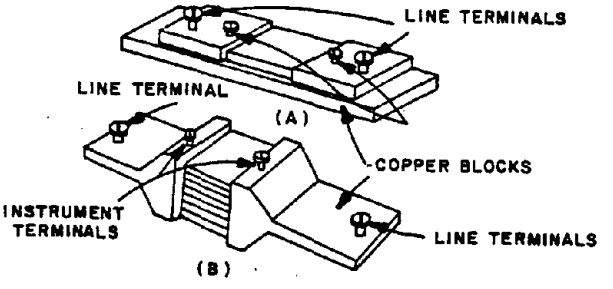


Figure 4.41. External Shunts Used for High-Current Measurements.

specific current. The "sensitivity" of such voltmeters is stated in ohms per volt (Ω/V). For instance, if a meter has a range of 0-200 μA and if the movement is to be used to measure 0-200 V, the total meter resistance must be:

$$R = \frac{200\ V}{200\mu A} = 1.0\ M\Omega.$$

As moving-coil resistance, R_m, is generally on the order of 50 to 100Ω, it can be neglected in this case. Sensitivity of the combination is therefore,

$$\frac{1,000,000\Omega}{200\ V} = 5000\ \Omega/V.$$

A higher value of sensitivity for a specific meter implies higher quality; presently, the upper limit for the commercially-available d'Arsonval voltmeter is 50 kΩ/V. It is interesting to note that the standard d'Arsonval movement of 0-1 mA has a coil resistance of 100 Ω, hence it can be employed to read 0-100 mV directly.

For high-current applications greater than possible with normal instruments with internal shunts, external shunts are utilized for a desired maximum current. Figure 4.41 provides a couple of typical constructions; terminals are available for circuit as well as meter connections. They are simply standard-resistance units, designed to be used with either 50 mV (0-50 mA) or 100 mV (0-100 mA) movements, such that a specific voltage drop across the shunt indicates a related current through the shunts. For example, if a shunt is designated 100 mV, 600 A, a reading of 50 mV across the shunt signifies that 300 A is flowing in the circuit. Any time that "metering" or instrumentation is part of d-c mine power equipment, it can almost be assumed that external shunts are involved.

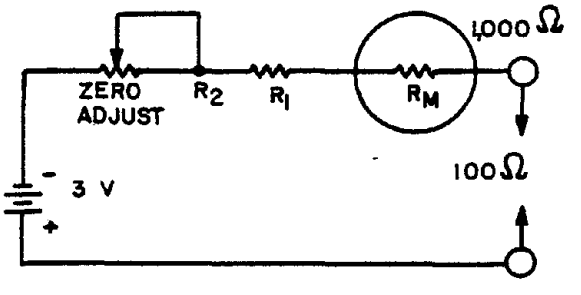


Figure 4.42. A Simple Ohmmeter Circuit.

To this point, the measurement of circuit operation has only been considered. By the addition of a d-c source in the aforementioned d-c voltmeter circuit, a d'Arsonval meter can be used to measure resistance. Consider the circuit shown in Figure 4.42, which has a d-c movement in series with a d-c source (usually a battery) and one or more resistors (one of these is usually variable for calibration). An unknown resistance (that to be measured) completes the loop. Meter deflection is still proportional to d-c through the loop and, therefore, a function of the known resistance. Using known resistances, the meter scale can be calibrated to read resistance directly, and different fixed resistors or multipliers can be used to extend the single scale. The combination is easily calibrated before each use by adjusting the pointer to zero with the variable resistance. The resistance desired could be a simple component or a complete circuit, but the ohmmeter should never be used on an energized circuit because of the internal source.

Combining the d'Arsonval movement with a half-wave or full-wave rectifier allows the reading of a-c values in terms of d-c through the coil. The full-wave or "rectifier ammeter" circuit, as shown in Figure 4.43, is the most common. Here, current through the movement is I_d and thus meter deflection is proportional to the average of I_d. This reading is the half-cycle average if the a-c is symmetrical (i.e., the d-c scale of the meter will read the half-cycle average sinusoidal current). As the rms value of current is usually desired, the scale is calibrated in rms by multiplying the average current by 1.11. This is the rms value only for a sinusoidal waveform; for any other waveshape, relying on the rectifier circuit can produce large errors.

It is interesting to note that moving-iron (as well as dynamometer) movements record rms current automatically. However, the greater sensitivity of d'Arsonval meters often makes their use in a-c desirable, but many permanent meters in power equipment to measure a-c voltage and current are moving-iron types. For a-c measurements of voltage or high current, the concepts of high series resistance and low parallel resistance also can be applied to rectifier, moving-iron, and dynamometer movements, but such practices are not common except in small portable test equipment.

It can be seen in the foregoing that the d'Arsonval meter can be used to measure a-c or d-c voltage or current as well as resistance. An instrument incorporating all these functions is called a "multimeter." The selection of a specific parallel or series resistance combination provides the needed measurement function and parameter range.

Wattmeters. As mentioned earlier, the main application for dynamometer movements is for wattmeters. Figure 4.44 illustrates the wattmeter connection. Typically, the fixed coil carries circuit current, while the moving coil is connected in series with a high resistance and attached across the terminals of the circuit (the moving coil can itself be of high resistance). With this, circuit current flows through the fixed (or "current") coil, and the current through the moving (or "potential") coil is proportional to circuit voltage. Therefore, the movement torque is proportional to the product of instantaneous voltage and current, with the indication relative to the product average or average power. The dynamometer connected as such will measure correctly the average power of a d-c or a-c circuit of any waveform, even when a power factor is involved.

Varmeters. The dynamometer movement, in addition to being used to measure watts, has wide application in measuring reactive power or vars. In single-phase instruments, this is done by shifting the phase of the voltage coil by 90°. Therefore, the voltage-coil flux is in phase with the flux produced by the reactive-current component in the current coil. Such "varmeters" are installed in the same manner as a wattmeter.

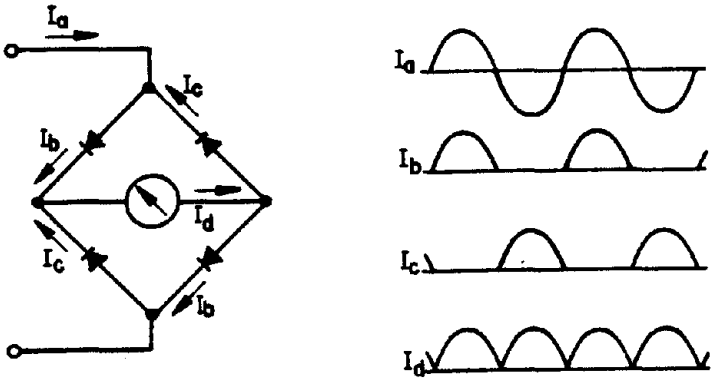


Figure 4.43. The Rectifier Ammeter.

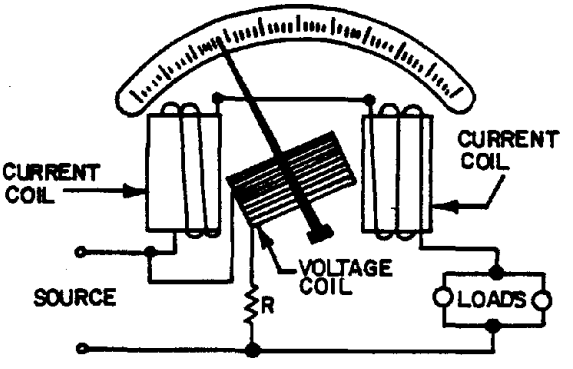


Figure 4.44. A Dynamometer Connected as a Wattmeter.

Power-Factor Meters. A "power-factor meter" indicates the power factor continuously as well as whether the current is leading or lagging the voltage. The movement resembles a single-phase wattmeter but has no control spring and has two moving potential coils mounted on the same shaft 90° apart. One potential coil (B of Figure 4.45) is in series with a noninductive resistor so it produces torque proportional to the line voltage and in-phase with the real component of line current. The other coil (coil A) is in series with a higher quality inductance so its torque is in proportion to the line-current reactive component. The fixed coil (coil C) again is the current coil. With unity power factor, the average torque between coils A and C is zero as the currents are 90° apart, but the currents through coils B and C are in phase so torque produced aligns their axes, and the pointer indicates 1.0 pf. For leading or lagging power factors, the net torque created by currents in coils A, B, and C will swing the moving coils to the right or left, aligning the pointer in a position relative to the power factor. Meter scales are therefore calibrated so the center position is unity power factor and, to the left and right of center, lagging and leading power factors from unity to zero.

This section has shown some direct applications of the basic meter movements. Some concepts shown here apply to all electrical parameter measurements. However for a-c power systems additional components are normally employed.

Power-System Instrumentation. In Chapter 3, the subject of current transformers (C.T.s) and potential transformers (P.T.s) was introduced. These devices actually fall under the general category of "instrument transformers" and serve two main functions:

1. to isolate instruments, relays, and meters from line voltage, and
2. to transform line currents and voltages into values suitable for measurement by standard instruments.

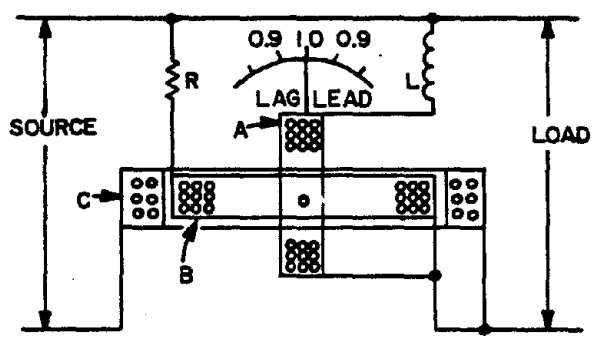


Figure 4.45. Power-factor Movement.

Thus, the normal ratings of instrument transformer secondaries are 5.0 A for current transformers and 120 V for potential transformers. The measurement referred to implies not only "metering" or actual visual readings but also "sensing" for purposes such as protective relaying. The following material will cover specifics of C.T.s and P.T.s as they apply to instrumentation of mine power systems. Chapter 8 will continue the discussion to the application of these transformers to protective relaying.

Instrument Transformers. Instrument transformers are tied into the power system in a manner directly connected to the function they help observe. Therefore, the primary winding of a C.T. is placed in series with the line conductor to be measured or may be the line conductor itself, while a P.T. is placed across the line voltage to be measured (see Figure 4.46). The transformers can then be used to extend the application of a-c instruments in the same manner that shunts and series resistors do for d-c instruments. In this case, however, the ratio of a C.T. (or P.T.) is the ratio of primary current (or voltage) to secondary current (or voltage) under specified conditions. The secondary winding parameter is coordinated with the connected instrumentation.

To operate reliably, an instrument must receive information that "accurately" represents conditions that exist in the power system. However, instrument transformers are significantly nonlinear devices when used outside the range for which they were intended. The amount of deviation is a function of the transformer input level, secondary load, and design. Instrument transformer designs are called "accuracy classes;" the load imposed on the secondary is termed "burden." Thus, ANSI C57.13-1968 et seq. "Requirements for Instrument Transformers"[1]

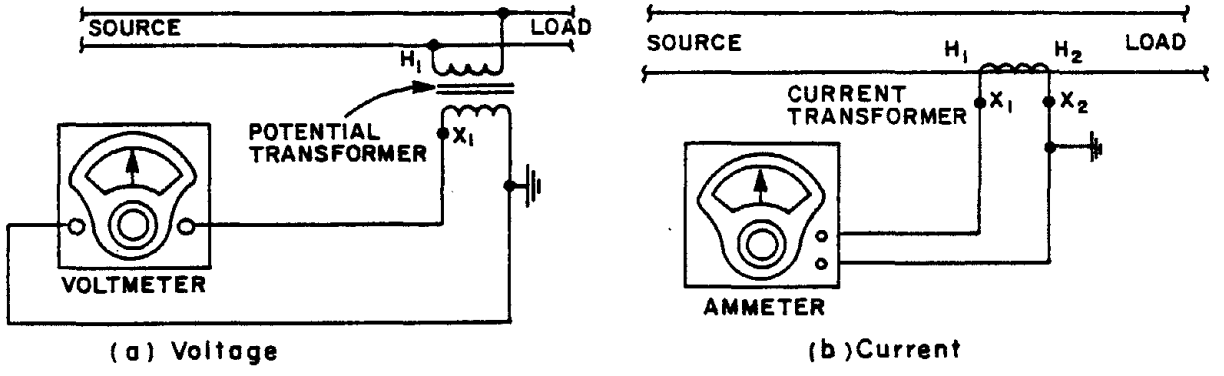


Figure 4.46. Simple Instrument-transformer Connections.

[1]American National Standards Institute, "Requirements for Instrument Transformers," Publ. C57.13-1968, 1430 Broadway, N.Y. 10018.

classifies potential-transformer and current-transformer performance in terms of an accuracy class and a burden.

The effects of burden changes are typically more pronounced with C.T.s than P.T.s. Preferably, C.T. burden is expressed as a standard load impedance or its resistance and reactance components. In the past, the practice was to specify the value as an apparent power (in VA) at a power factor, the angle of which referenced to a rated secondary current (e.g., 0.9 pf current lagging). Consequently, a C.T. burden of 0.5-Ω impedance could be expressed as 12.5 VA at 5 A, assuming the usual 5-A current. However, because of the non-linear nature of transformers, burden impedance decreases as the secondary current increases, and a specific burden may apply only to one level of secondary current. Through this, the now-standard volt-ampere ratings are confusing. Furthermore, C.T. burden must be applied not only to the external load but also to all elements of that load, including the interconnecting loads. As the total burden most often needs calculation, manufacturer publications usually provide the burdens of individual components.

Potential transformer burden is normally stated as the total external volt-ampere load on the secondary at rated secondary voltage.

For best accuracy with either P.T.s or C.T.s, the impedance of the burden should be identical to that of the instrumentation. In these cases, the accuracy limits stated in ANSI C57.13-1968 will apply. As a general rule for C.T.s, if silicon steel is used for the core, the "ampere-turns" should be at least 100 for good accuracy under normal conditions. When a P.T. has acceptable accuracy at its related voltage, it normally can be used over a range from zero to 110% of rated voltage. Operation greater than 10% overvoltage will often produce excessive errors.

Some special precautions are in order whenever current transformers are in use. A C.T. secondary should always be shorted or properly connected to the instrumentation (meters, relays, etc.). Otherwise, dangerous potentials can occur at the secondary terminals, and the core can become magnetized. The flux density in the core is normally very low and can easily rise to saturation without a secondary current. The core can also become easily magnetized if d-c is passed through the secondary. In either situation, the transformer ratio can be seriously changed. Furthermore, it is possible for a C.T. to become damaged through insulation breakdown from surges, overloads, and other occurrences. Therefore, good practice dictates conducting tests prior to installation and periodically thereafter to verify operation. If magnetization is suspected, the

core can be "demagnetized" by passing rated 60-Hz current through the secondary (primary open), gradually reducing the current to zero.

When a fault occurs on a line inby where a C.T. is coupled, the transformer primary current may reach several times the rated value for short periods of time. Two different designs are available to protect against C.T. damage. One defense is to overdesign the primary winding so the transformer is not damaged by the mechanical and thermal effects of moderate overload. The other design is perhaps more desirable. Here, the C.T. is selected such that its core is near the saturation point with normal operating primary current. When a surge current occurs, the secondary current cannot increase in proportion to primary current, and the burden is thus spared much of the shock. (See Chapters 8 and 9 for further details as core saturation can seriously effect protective-relay operation.)

Single-Phase Connections. Figure 4.47 illustrates the measurement connections for a single-phase circuit in order to observe voltage, current, and average power (indeed, this is a simple extension of Figure 4.46). Only two instrument transformers are required with the P.T. driving the voltmeter and the wattmeter voltage coil and the C.T. supplying current to the ammeter and the wattmeter current coil. For this arrangement, the ammeter and voltmeter would likely be moving-iron movements with the wattmeter being a dynamometer. Many times, however, a different instrument arrangement is used as illustrated in Figure 4.48. Here, "transducers" are placed between the instrument transformers and the meter movements. Transducers are electronic devices which present a standard burden to the transformer and provide an output compatible with the standard d'Arsonval movement, 0-1 mA (0-50 mV and 0-100 mV are also usually available). This output will also work on a range of load impedances. With either arrangement, three a-c power parameters can be measured, and the fourth, power factor, can be calculated if desired.

Regardless of the instrument arrangement, whenever meter movements are employed, the normal reading of the meter should be one-half to three-quarters of the full-scale value. Such provides the best precision.

It should be noticed in both Figures 4.47 and 4.48 that the instrument transformer secondaries are grounded (see Chapter 8 for full comprehension on why). The grounding is necessary to prevent a high static potential which can cause a higher voltage than normal to appear on the secondaries. Without grounding, the transformer insulation can possibly fail. The transformer case should be grounded for the same safety reason.

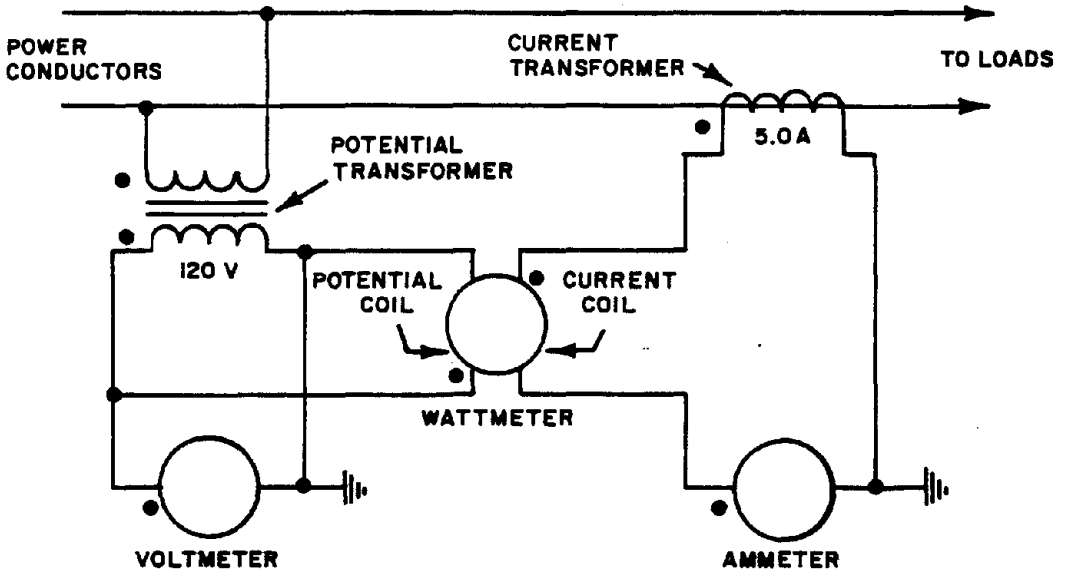


Figure 4.47. A Voltmeter, Ammeter, and Wattmeter Arrangement as a Single-Phase System.

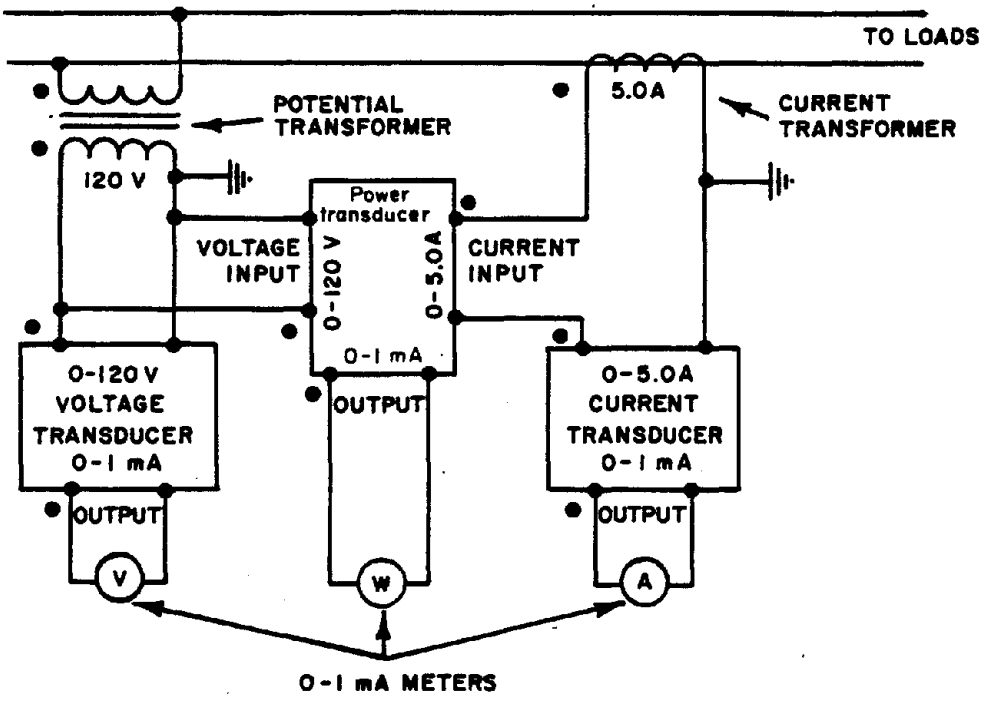


Figure 4.48. The Use of Transducers with Standard d'Arsonval Movements.

Three-Phase Connections. When the measurement of average power in a three-phase system is desired, it seems obvious to simply place one dynamometer wattmeter in each phase and add the results. Such is shown in Figures 4.49 a and b for a four-wire wye load and a three-wire wye or delta load. For either connection the meter-reading sum is total power whether the system is balanced or not and voltage and current are of any waveform. Importantly, the common connection of the three wattmeter potential coils may be placed at any potential without affecting the total power readings. If the point is at one phase conductor (see Figure 4.50), one wattmeter becomes inoperative and thus may be omitted. The result is the "two-wattmeter method" of three-phase power measurements. Instead of the two wattmeters, commercially-available transducers can be used with inputs being two line-to-line voltages and two line currents. The single transducer output, which is proportional to total power as before, can be used with a standard d'Arsonval movement. A circuit arrangement for this method is shown in Figure 4.51.

Under balanced conditions, the readings from the two-wattmeter method can be used not only for total power but also to determine the power-factor angle. It can be shown that:

$$\tan \theta = \sqrt{3}\, \frac{P_2 - P_1}{P_2 + P_1} \qquad (4.56)$$

where,

P_1, P_2 = the two power readings, corresponding to the arrangement in Figure 4.50.

θ = the load power-factor angle.

If P_1 represents a measurement of phase, a current (equation 4.65) provides the correct power-factor angle sign, thereby relating that the load is capacitive or inductive. In practice, phase sequence is at times hard to distinguish, but the equation yields the angle magnitude. This is often sufficient information as the reactive characteristics of the load are usually known.

If the system is balanced or can be approximated as such, the circuit shown in Figure 4.52 can be employed to measure the line-to-line voltage, line current, power factor, and total average power. The two-wattmeter approach calls for the two P.T.s and two C.T.s. One P.T. also supplies the voltmeter, while one C.T. provides information to the ammeter. The remaining P.T. and C.T. supplies the power-factor meter so the transformer burdens are balanced.

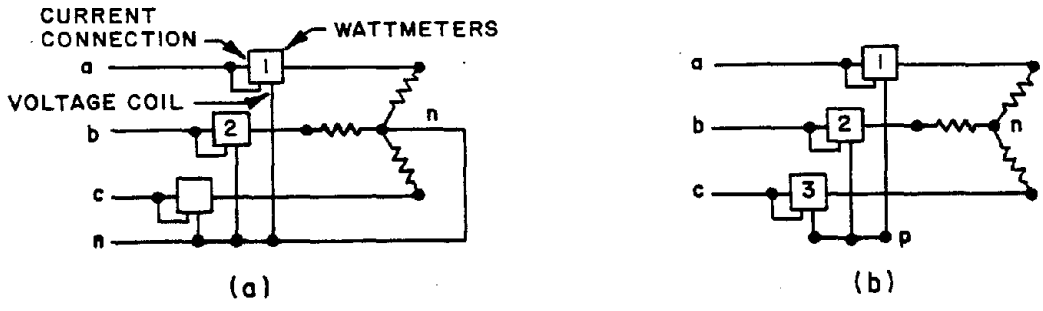


Figure 4.49. Three-Phase Wattmeter Connections.

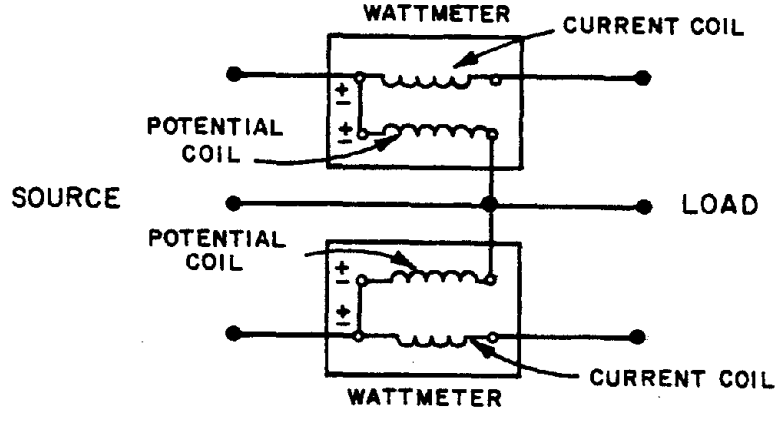


Figure 4.50. Two-Wattmeter Method.

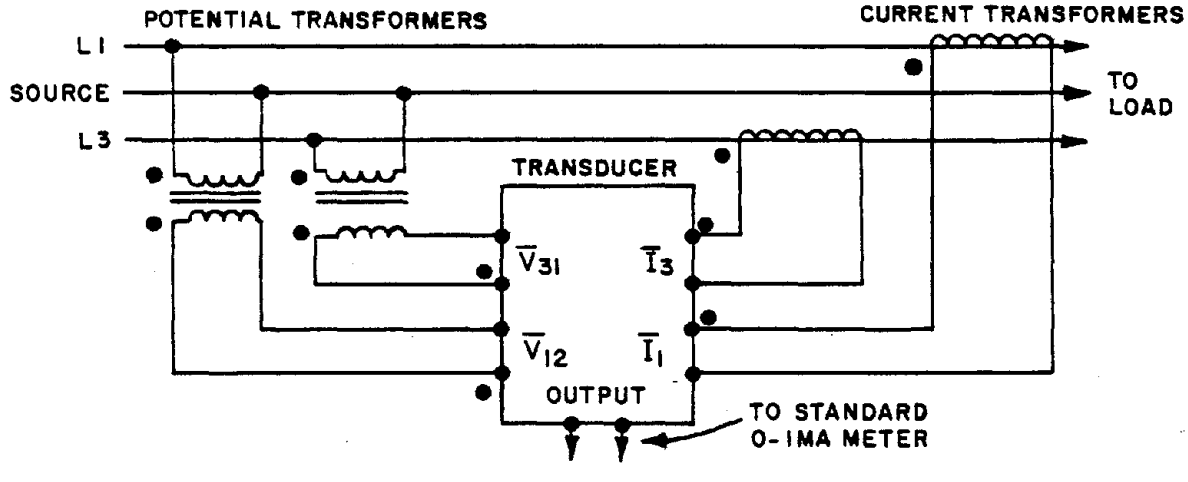


Figure 4.51. Three-Phase Power Measurement with a Transducer.

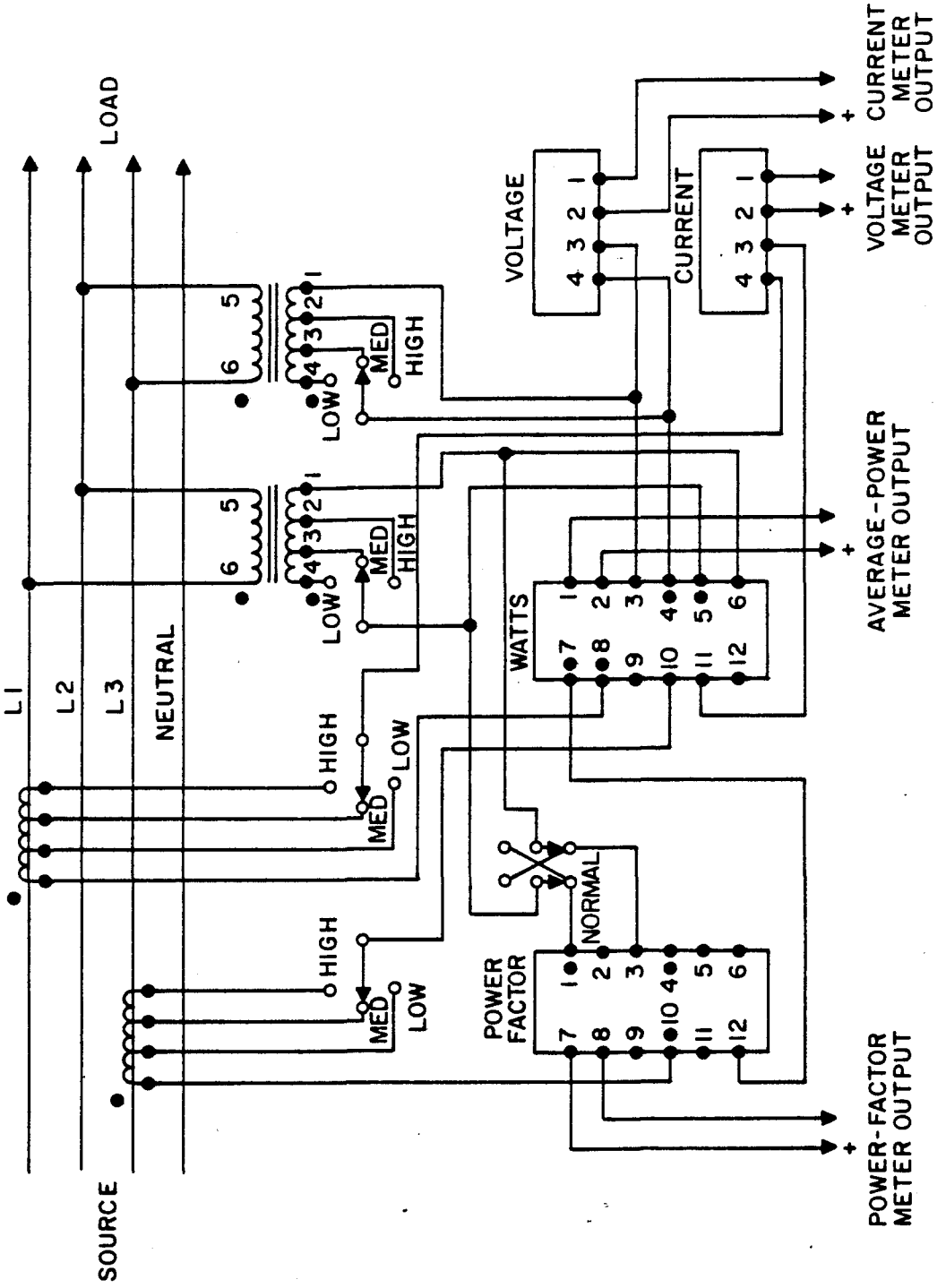


Figure 4.52. Balanced Three-Phase Measurement of Voltage, Current, and Average Power.

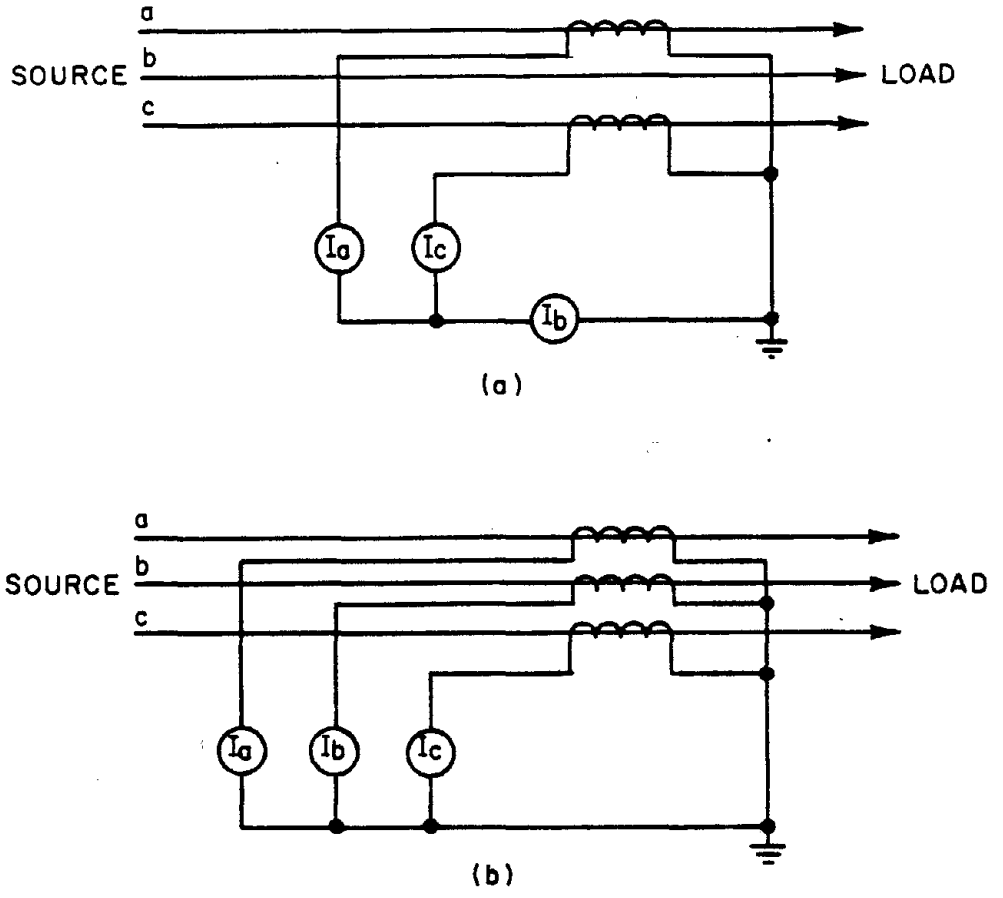


Figure 4.53. Line Current Measurements with Two or Three Current Transformers.

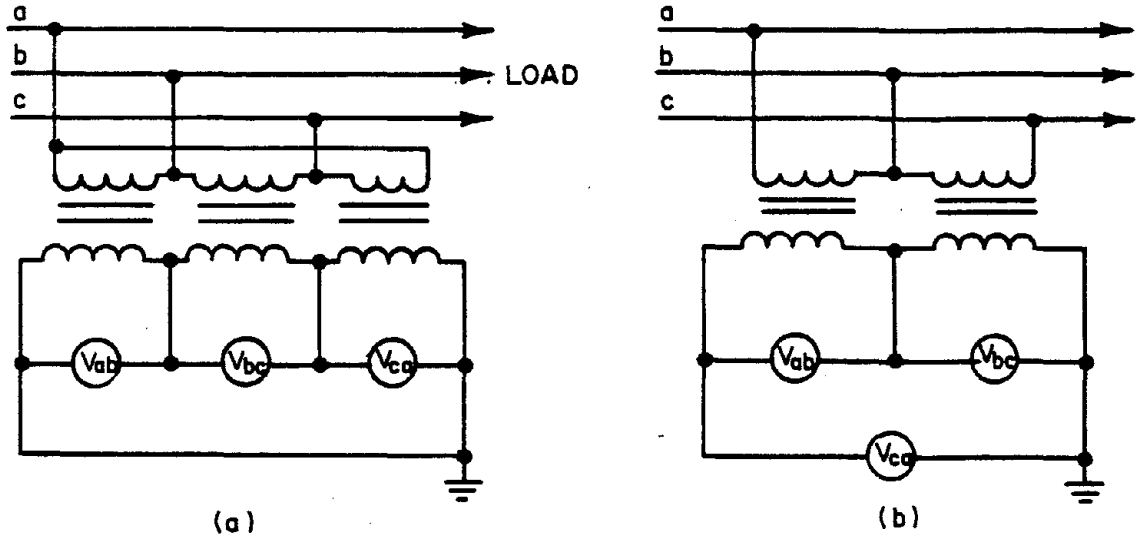


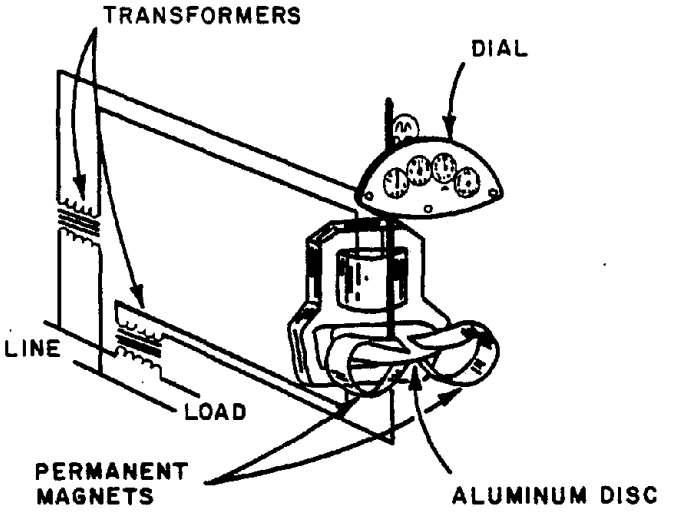
Figure 4.54. Line-to-Line Voltage Measurements with Three or Two Potential Transformers.

Oftentimes, it is very handy to observe each phase current or line-to-line voltage in major power equipment. Figure 4.53a provides an economical method for line currents where only two C.T.s are needed. If one C.T. secondary is measured, the current will correspond to the C.T. phase (i.e., a or c) but, if both C.T. secondaries are paralleled, the current reading is for the phase without the C.T. (i.e., phase b). This metering is theoretically correct only for balanced voltages, but the voltage balance on most systems is close enough that the two C.T. approach give acceptable precision. If more accuracy is desired, three C.T.s should be used as shown in Figure 4.53b. It is possible to connect the C.T. secondaries in delta or wye but, whatever the case, the burden impedances should always be wye connected. To observe all three line-to-line voltages, three potential transformers can be used as in Figure 4.54a. However, although not as accurate, the open-delta arrangement shown in Figure 4.54b gives satisfactory precision and uses just two P.T.s. For either current or voltage with either two or three instrument transformers, metering in power equipment is performed with one voltmeter or ammeter (or both); and the phase desired is switch-selected by connecting the transformer combination with the meter.

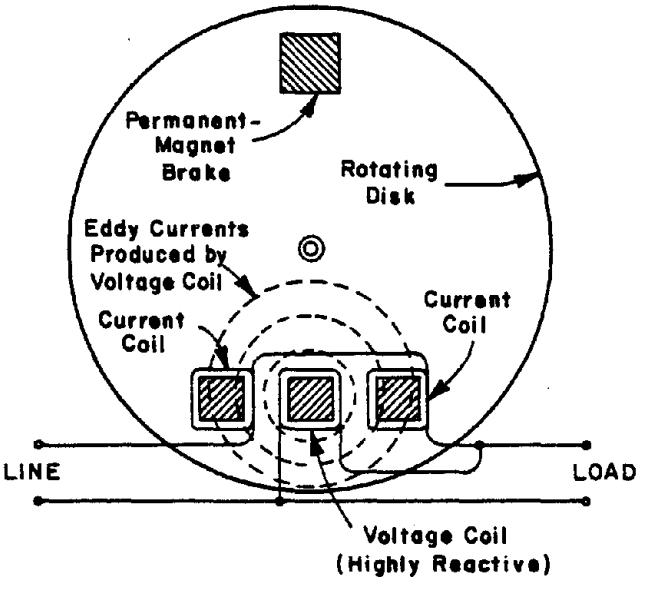
Special Instruments. Several special, if not very common, instruments are available to perform measurements on specific electrical quantities. These include but are not limited to watthour meters, demand meters, bridges, Meggers, and phase-sequence indicators. Each of these is described in the following paragraphs.

Watthour Meters. The "watthour meter" is a very common power instrument, as it is used in nearly every house and other building to measure consumed electrical energy. The typical watthour meter is essentially a small induction motor, where an aluminum disk is rotated by a torque proportional at every instant to voltage times current. The principle of operation is similar to the dynamometer wattmeter, except the disk is allowed to turn continually with its speed being proportional to average power. The number of turns is counted by a train of clock-like gears. The counter thus indicates the product of power and time, or energy, which is measured in kilowatt-hours. A simplified sketch of the induction mechanism is shown in Figure 4.55.

Demand Meters. Demand meters are usually of two types (although there are others): integrated demand or lagged demand. The readings may be indicating or recording. Integrated-demand meters consist of an integrating-meter element (such as the watt-hour meter just described) which totalizes the energy used over the demand interval and drives a maximum indicating device (a passive pointer, display, or chart). The meter can be manually reset or a timing device can be used to return the drive to zero



(a) Simple Schematic



(b) Disk Plan View

Figure 4.55. Simplified Sketch of a Watthour-Meter Induction Mechanism.

at the end of the recording period, thus leaving an indication of maximum demand. Lagged-demand meters provide a maximum demand indication subject to a characteristic time lag by either mechanical or thermal means, but usually the exponential heating curve of electrical equipment is followed. The demand interval is then defined as the time required to indicate 90% of maximum value of a suddenly applied steady load, thus maximum demand can be observed. Demand meters, whatever the type, can provide input to the power-system studies discussed in the preceding report section.

Bridges. Bridge circuits yield the most precise measurements of impedance, be it resistance, capacitance, or inductance. The reasons are two-fold:

1. the measurements rely on null methods and
2. comparisons are made directly with standardized impedances that are precisely known.

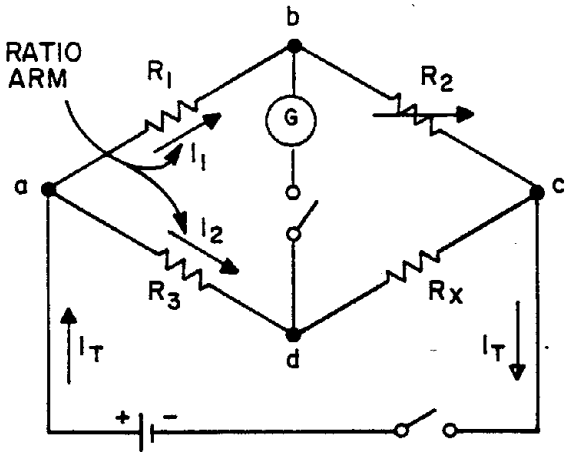
"Null methods" mean that a zero reading or "null" indicates the correct value.

The "Wheatstone Bridge" is the most widely used of these circuits. Shown in Figure 4.56, the bridge is dedicated to measure resistance, capacitance, or inductance depending on its internal components.

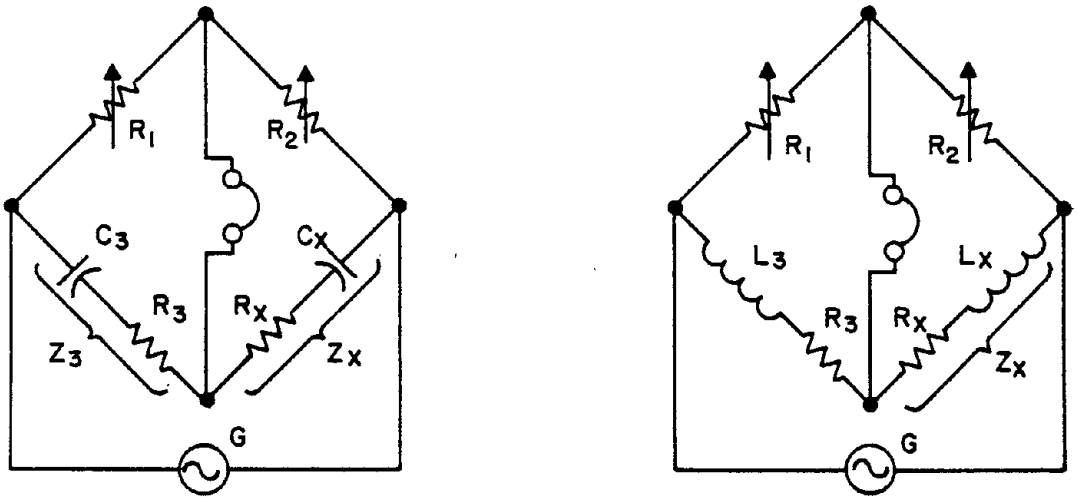
When the Wheatstone bridge is intended to measure resistance (Figure 4.56a), the circuit consists of two "fixed" precision resistances, R_1 and R_3, known as the "ratio arm;" a variable precision resistance, R_2; and the unknown R_x. A d-c source supplies current to the arrangement and a galvanometer, G, is in the center of the bridge across points b and d. The "galvanometer" is simply a very sensitive ammeter with a center-scale zero-reading pointer and the ability to read very small currents in either direction. R_2 is adjusted to provide a null-reading on the galvanometer, which means the potential between b and d must be zero. With this "balanced" condition, the unknown resistance can be calculated by

$$R_x = \frac{R_2}{R_1} R_3. \qquad (4.66)$$

In commercially-available bridges, R_1, R_2 and R_3 are all variable, and the value of each is readily determined by calibrated dials. Thus, the bridge can precisely measure resistances over a broad range.



(a) A Wheatstone Bridge for Resistance



(b) Impedance Measurements with a Wheatstone Bridge

Figure 4.56. Wheatstone-Bridge Circuits.

To measure impedance, R_3 of the resistance bridge is replaced by Z_3, and the unknown is now Z_x. An a-c source is used, along with some means of measuring the potential between points b and d. The latter could be a sensitive a-c ammeter or an audible device (e.g., a set of headphones). R_1 and R_2 are then adjusted to provide a null, and the balanced condition means:

$$Z_x = Z_3 \frac{R_2}{R_1} . \tag{4.67}$$

Obviously, the values of Z_x and Z_3 depend upon the frequency of the a-c source. The most typical value used is 1000 H_z.

If very low resistances, in the order of 10 μΩ to 1.0 mΩ, must be measured, "Kelvin double bridge" shown in Figure 4.57 provides satisfactory results. The circuit consists of ratio arms R_A, R_B and R_α, R_β; a connecting link (or conductor) R_ℓ; a known resistance R_s; the unknown R_x; an adjustable d-c source; and a null indicator. The latter could again be a galvanometer. The resistances, r_1, r_2, r_3, and r_4, are that of the connecting leads between the four-terminal bridge and the resistances to be compared (R_x and R_s). These lead resistances should be in the same ratio as the bridge arms to which they are connected; otherwise the ratio unbalance will cause incorrect measurements. A small adjustable resistor can be used to balance the lead resistances. The balance equation is thus:

$$\frac{R_x}{R_s} = \frac{R_A}{R_B} + \frac{R_\ell}{R_s} \left(\frac{R_\beta}{R_\alpha + R_\beta + R_\ell}\right)\left(\frac{R_A}{R_B} - \frac{R_x}{R_\beta}\right). \tag{4.68}$$

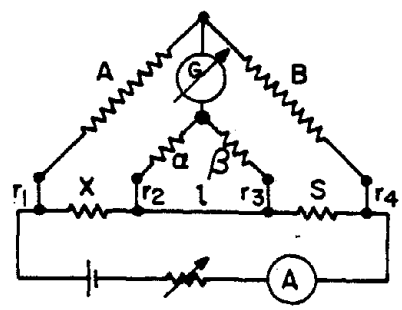


Figure 4.57. Kelvin Double Bridge.

When R_x and R_s are so small that R_ℓ is comparable, the term in equation 4.68 involving R_ℓ can be significant. However, if

$$\frac{R_A}{R_B} = \frac{R_\alpha}{R_\beta}$$

then the R_ℓ term becomes zero. The source is adjustable so the current through R_x, R_ℓ, and R_s (the series resistance of which is small in comparison to the bridge) is large enough to allow a measurable milling current through the indicating device, G. An application for the Kelvin double bridge is in the measurement of cable and conductor resistances.

Megohmmeters. The preceding resistance-measuring devices are often not effective for observing resistance in the many millions of ohms. An important area here is the resistance of insulation, such as around conductors (see Figure 4.58). One main problem in these and other high-resistance measurements is providing sufficient potential so the resulting current is detectable and an indicating device can provide resistance readings. Instruments designed to perform these tests are called "megohmmeters," the internal construction of which is depicted in Figure 4.59. The unknown resistance is R_x, and R_1 and R_2 serve as current-limiting resistors to protect the meter from damage.

In comparing the megohmmeter with the instruments that have preceded, the most evident difference is the hand-driven generator, which supplies the needed measurement d-c potential. This applies from 500 to 2500 V, depending on the instrument, and is tied to the resistance range desired (the higher the measured resistance, the higher the required voltage). Typically, a friction clutch is employed to restrict the generator to rated output voltage. In some Meggers, the potential is from batteries via an electronic power supply located within the instrument.

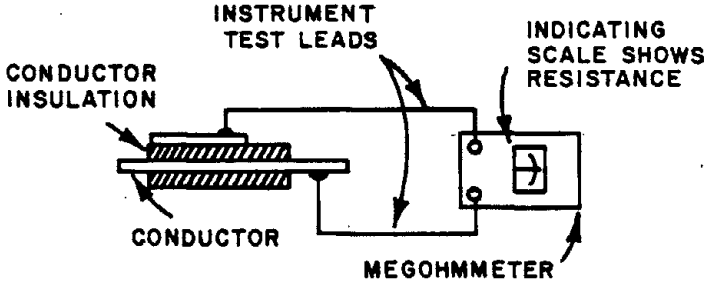


Figure 4.58. A Megohmmeter Testing Insulation Resistance.

As shown in Figure 4.59, the meter has two coils mounted over a gapped core. The movement is similar to the d'Arsonval, but there are no restraining springs. Consequently, the indicator is free to move when there is no output from the generator. If the instrument terminals are open (i.e., R_X is infinite) and the generator is operated, current will flow through R_2 and coil A_1, and the torque produced will force the pointer counterclockwise to the infinite scale reading. When the terminals are shorted (R_X is zero), the torque produced by coil B, being greater than that from coil A, moves the pointer to a zero reading. For measuring an unknown resistance, therefore, the pointer location is dependent upon the opposing torques from the two coils, and the position is a function of R_X.

Another prime application for megohmmeters is in the measurement of ground-bed resistances. The specialized testing procedures are covered in the subsequent chapter on "Grounding."

Phase-Sequence Indicators. In order to prevent damage or incorrect operation, all conductors in a three-phase distribution system must be properly connected; this provides the same phase sequence to all equipment. Such correct interconnections can, at times, be difficult to accomplish in mine power systems, especially with feeder and trailing cables (there exists at present no standard color coding of phase conductors). A "phase-sequence indicator," illustrated in Figure 4.60, can be used to determine the phase relationship of energized three-phase conductors. It falls in the most simple class of testing devices, "indicating instruments;" other examples include a light bulb with leads to test for the presence of potential, or a battery in series with a light bulb with leads to check continuity by completing the series circuit. The phase-sequence indicator consists of two light bulbs and a capacitor connected in wye, and the lamps are labeled in the two possible phase combinations. Because of the arrangement, one lamp will burn brighter than the other depending on the connections to the power system.

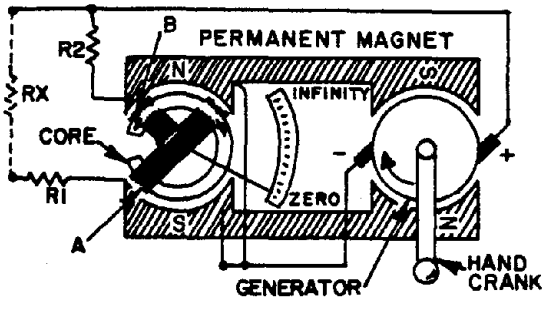


Figure 4.59. Internal Components of a Megohmmeter.

Other Instruments. The foregoing has provided information on several devices that are helpful in measuring mine electrical systems. Other instruments are available which are equally useful for specific applications and include:

1. split-core a-c ammeter, a hand-held a-c ammeter that has its own C.T.;
2. synchroscope, measures proper phase connections and correct speed of parallel a-c generators; and
3. frequency meter, indicates the frequency of an electrical supply in Hz.

Oftentimes, there is also a need to get a continuous record of an electrical parameter; the next section discusses the popular devices.

Recording Instruments. Many of the direct-reading indicating instruments just presented are also available as recording instruments. Some devices are actually very similar to their indicating counterparts in that they can use the same electrical movements; they differ because the pointer is also used to provide a graphic record on a chart. Thus, these are termed "chart recorders," with one popular class being "strip-chart recorders" (see Figure 4.61a) so named because the electrical parameter is recorded on a strip of paper.

The similarity between strip-chart and indicating-instrument movements is illustrated in Figure 4.61b, actually a d'Arsonval type. The pen can trace on paper in several ways; among these are:

1. inking, the pen is a capillary tube through which ink flows from a well to the chart (this is perhaps the most used system);
2. inkless, the tip of the pen is a stylus which impacts the paper like a typewriter (a regular force is supplied by a cam), leaving a series of dots; and

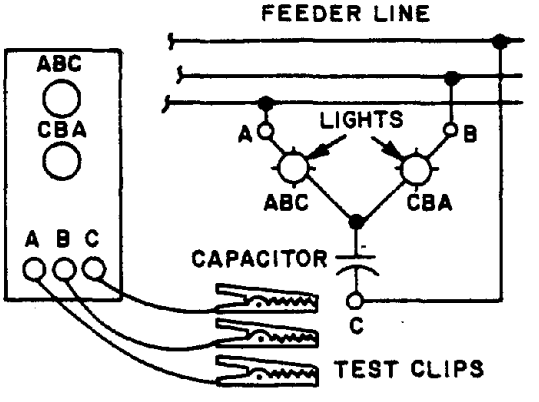


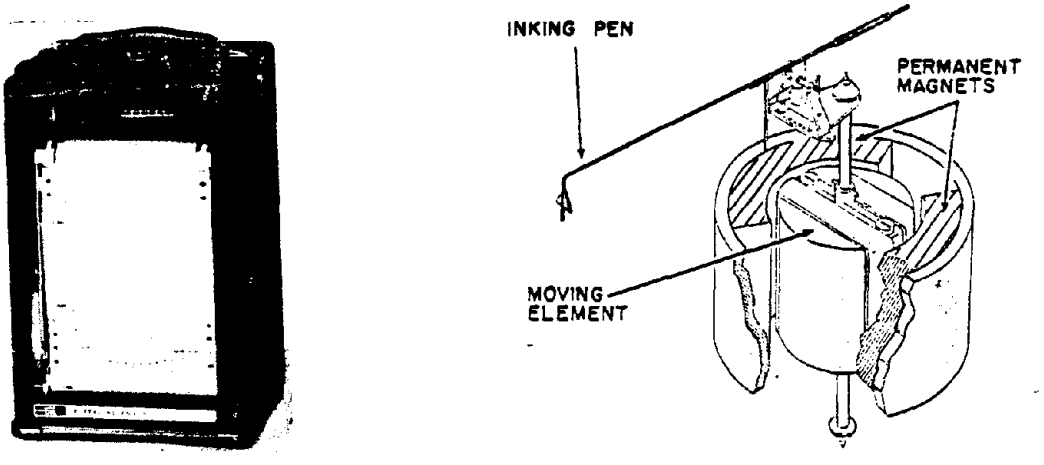
Figure 4.60. A Phase-Sequence Indicator.

3. thermal, the pen tip contains a heating element that leaves a trace by heating specially-treated paper.

The most simple units provide a curved recording as the pen swings in an arc; however, articulated pen arms are available that produce linear or rectilinear traces. The paper chart moves by the pen at a predetermined speed; the drive is by an electric-motor or a mechanical-spring clockwork mechanism. Depending on the movement, this recorder provides a continuous record of the average or rms value of the electrical parameter of interest. Such is advantageous in obtaining records of equipment operation; an example would be the electrical performance of a mining machine. (Note: a variation of these recorders uses a round chart, driven similarly to a disk on a record player, but at a very slow speed. These can be included in major equipment to provide permanent records.)

Sometimes recordings of the actual electrical waveforms are needed to study power systems. Such calls for an instrument which can resolve electrical-parameter instantaneous values. Electromechanical instruments that have this resolution are called "oscillographs." The movement in most of these is a sensitive galvanometer of low mass, and two types of writing systems are normally available.

1. Direct writing. Similar to either the inking or thermal strip-chart recorder types. The pen has high inertia, and instrument response is about 0.5 to 100 Hz (some to d-c).
2. Optical. Instead of a pen, the movement drives a low-mass mirror. A light beam is deflected by the mirror and exposes a light-sensitive paper. Developing is required to



(a) Instrument (b) Mechanism

Figure 4.61. Strip-Chart Recorder Example.

obtain the record, but the system can have resolution to 10,000 Hz.

In many applications, magnetic tape recorders and oscilloscopes, both electronic instruments, find favor over oscillographs. However, oscillographs still have some practical uses, especially where an extended-time "hard copy" is needed immediately. An example would be measuring neutral currents existing on three-phase equipment (these can have d-c as well as a-c components).

Electronic Instruments. The employment of complex and sophisticated control equipment in the mining industry is continuing to increase. Instances include solid-state motor starters, electronic protective relaying, computer-logic circuits on mining machinery, and so on. This type of system requires precision voltage, current, and waveform measurements that are not possible with the preceding instruments. Certain phenomena existing on power systems, such as transients, also require such precision in addition to frequency response into the megahertz. Electronic measuring equipment answers the need. This section will briefly introduce only the more popular instruments.

Electronic Voltmeters. These instruments use many of the same basic circuits that have been described for multipliers, in other words, series resistances for voltage (see Figure 4.62a), voltage-drop for resistance (Figure 4.62b), and shunts for current. The prime difference is that a "scaled-down" d-c voltage, which is proportional to the actual circuit voltage, current, or resistance, is amplified by electronics. When the parameter is a sinusoid, the a-c is rectified before amplification. The amplified signal then drives the indicating device. In the past, vacuum tubes performed the amplification (this is termed a vacuum-tube voltmeter or "VTVM"); lately, solid-state devices (usually FET's) are becoming the most popular. The indicating device can be of two types: the familiar d'Arsonval movement or digital.

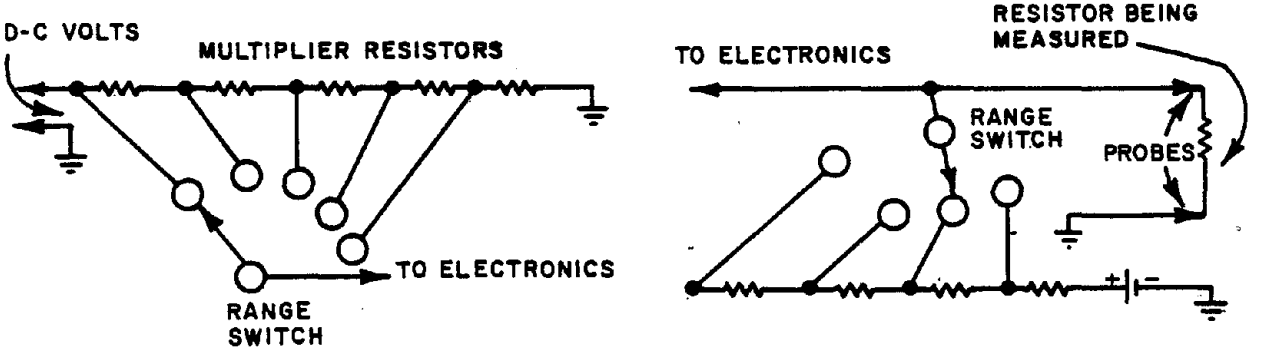


Figure 4.62. Input Circuits on an Electronic Voltmeter.

The displays or movements described thus far can be termed as "analog." The "digital" display is an indicating output assembly that takes the measurement results and, through electronics, gives a visual indication in "discrete number," as shown in Figure 4.63. The actual display can be by Nixie tube (as gas-discharge tube), seven-segment incandescent filament, light-emitting diodes (LED), or liquid-crystal decimal (LCD). The electronics in the display assembly uses "logic" or binary mathematics to convert the analog output of the measurements to drive the visual display.

Electronic voltmeters might appear rather complicated, but an important advantage is gained through the circuitry. The instrument can be made so its interference with the circuit being measured is negligible. Typical input impedance of most electronic voltmeters in 11 MΩ.

Oscilloscopes. Oscilloscopes are electronic instruments which provide a "real-time" display of waveforms and are available with responses from d-c to hundreds of megahertz. Thus, they can be used to observe a large range of electrical phenomena, including those of extremely short duration. The reason these instruments have such broad frequency range is that they are not constrained by mechanical inertia. The heart of the oscilloscope is a "cathode-ray tube" or "CRT" (see Figure 4.64a). Here, a fine beam of electrons is deflected by an electrostatic field in relationship to the voltage or current being investigated. The beam then impinges on a florescent screen to create a luminous display. The electrostatic field is normally established by two pairs of "deflecting plates," one provides deflection vertically, the other horizontally. When observing a waveform, the horizontal pair is driven electronically by a "sweep" signal to provide a "time-base," and the vertical pair creates a field in response to the electrical-parameter instantaneous value. In some CRTs, additional vertical-plate pairs are available, enabling the

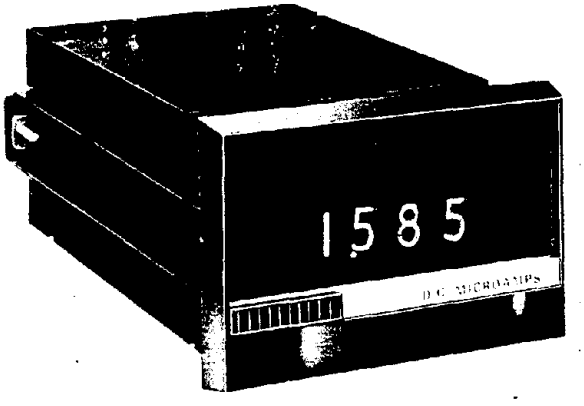
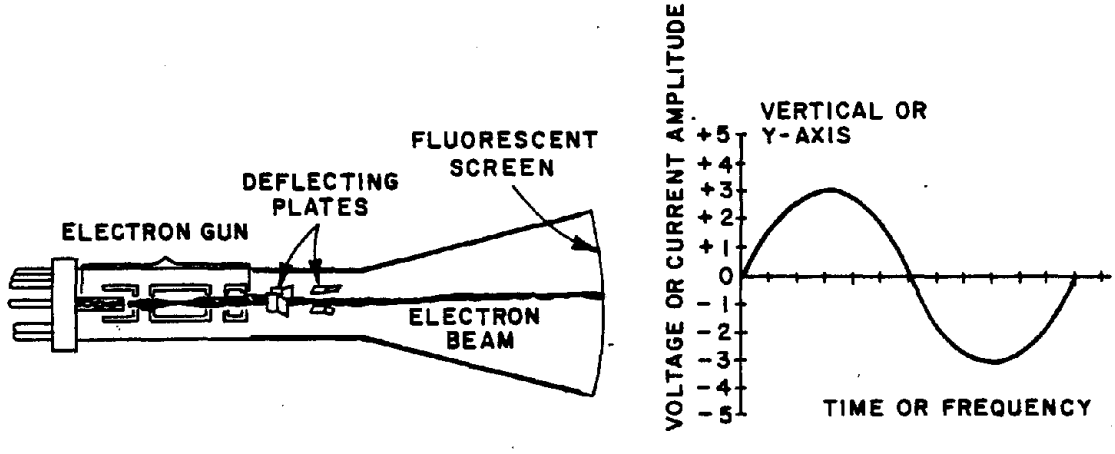


Figure 4.63. A Digital Display.

display of more-than-one "trace" on the screen. This allows direct comparison of two-or-more waveforms. To provide a permanent record, a camera can be used in conjunction with the oscilloscope.

Tape Recorders. Many other electronic instruments are available to measure a great range of electrical parameters, way too many to mention here. The magnetic tape recorder, however, does warrant a short description. This device, which is quite familiar to many people, records a signal by magnetizing a thin strip of tape. The non-metallic tape is coated with a very thin layer of magnetic material (e.g. iron oxide). Thereby, a "permanent" record of a signal can be obtained (the record can be erased magnetically, and the tape reused). The signal can be an analog recording, or in direct relationship to the measured parameter, or digital. With the latter, the signal is converted electronically to the binary system, then the binary counterpart is recorded. With either, measurement flexibility as well as precision is increased substantially. The recording can be "played back" numerous times with the output very closely matching the input that was observed. Analog tapes, which can have frequency ranges from d-c to over 20,000 Hz, can be used as input to strip-chart recorders to produce "hard copies" or to various electronic instruments to perform analysis of the electrical parameters. Digital recordings can be made compatible with digital computers that can, in turn, perform elaborate analysis on the data in very short time periods.



(a) CRT (b) Sinusoidal Display with Sweep.

Figure 4.64. Cathode-Ray Tube.

Sensors. Input from the power system to electronic instruments, such as the tape recorder, is via sensors. A "sensor" can be described as a device that provides an electrical signal output in response to a specific measurement. This definition, therefore, could also be used for the previously mentioned transducers, but the word "transducer" is normally reserved for devices that convert energy from one form into another, such as mechanical into electrical energy. Thus, potential transformers and series-dropping resistors can be considered voltage sensors with current transformers and shunts as current sensors. Another popular current-sensing device employs the "Hall-effect" principle.

Hall-effect current transducers measure the effect of an electromagnetic field on a semiconductor. Basically, such devices operate on the interaction of magnetic force and the movement of charge through a semiconductor. Consider Figure 4.65 where a current, I_c, is flowing and a magnetic field is acting at a right angle to the current. The magnetic field will deflect the charge carriers in proportion to the field strength. This action produces a "Hall-effect voltage," as shown, which is in proportion to the magnetic field. Current flow in a conductor produces an electromagnetic field which can be measured by a Hall-effect device, thus producing a voltage output in proportion to the current. Most times, the magnetic field needs concentration. In some Hall-effect instruments, this is performed by a core of magnetic, low-retentivity material which can be clipped around a conductor; the semiconductor is mounted on the core oriented at right angles to the induced magnetic field. The combined unit appears much like a split-core C.T. and through this method d-c as well as a-c currents can be measured with high precision. Many instruments used for precise power-system measurements employ Hall-effect devices.

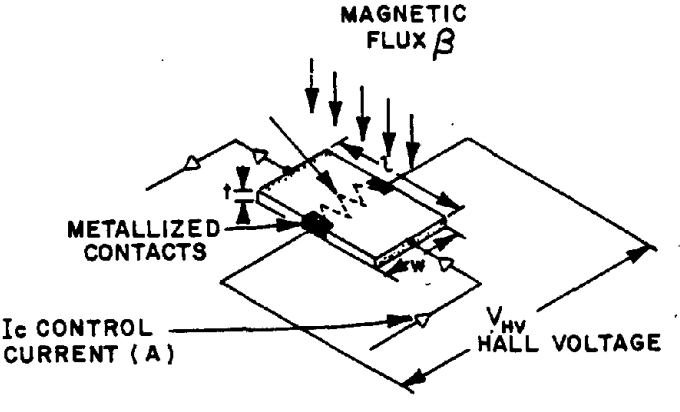


Figure 4.65. A Semiconductor Illustrating Hall Effect.

Oftentimes the output from a sensor is not compatible with the input of the instrument or, for safety reasons, is not "isolated" from the power system. In these instances, the signal requires conditioning, and electronic circuitry, usually amplifiers, is called upon to perform the task. This circuitry can itself be termed a transducer, as was the case earlier in this section.

Instrument Installations. Several instruments are included as part of major power equipment. The following can be used as a guide for installation of specific instruments.

1. The termination of utility transmission lines:
   a. voltmeters,
   b. ammeters,
   c. wattmeters,
   d. varmeters or power-factor meters,
   e. watthour meters,
   f. demand meters, and
   g. frequency meters.
2. Substation secondaries (i.e., outgoing distribution):
   a. voltmeters,
   b. ammeters,
   c. wattmeters,
   d. varmeters or power-factor meters,
   e. watthour meter (demand attachment optional), and
   f. test blocks (or connection points) for portable instruments.
3. Switchhouses, load centers, and rectifiers:
   a. voltmeters,
   b. ammeters, and
   c. test blocks for portable instruments.
4. Machinery:
   a. voltmeters (optional),
   b. ammeters,
   c. elapsed-time meters (optional), and
   d. watthour meters (also optional).

Two points must be considered in the application of the above listing. At the higher transmission voltages, say 69 kV and up, it is sometimes advantageous to have the utility-metering point at the substation transformer secondary, such would eliminate item 1 and might add additional instruments to item 2. The reason is economics; the capital required for high-voltage metering can prohibit its use. The test blocks for power equipment are necessary as they provide an easy avenue for maintenance and trouble-shooting problems. In general, they consist of a series of terminals to which permanent connections are made to important circuit portions, such as major components. The block is located on the surface of the equipment, accessible only to maintenance personnel, and can eliminate the need for some permanent instruments. However, as was mentioned at the beginning of this section, voltmeters and ammeters are considered minimum permanent instrumentation, unless otherwise stated above.

This section has covered just the elementary concepts of instrumentation in mine power systems. Specific portions of forthcoming chapters will elaborate on this vital subject.

4.10 Summary

Chapter 4 has covered a broad range of electrical fundamentals projected towards three-phase power systems in mining. Important items have included balanced three-phase circuit analysis, the per-unit system, three-phase rectification, unbalanced polyphase circuits, and instrumentation. When combined with Chapter 3, the material forms the major base for the report balance. The next chapter, "Motors and Motor Control," concludes the report fundamentals by discussing the most important loads in the mine electrical complex.

4.11 References

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Chapter 5

MOTORS AND MOTOR CONTROL

5.1 General

From the chapter title, the subject is electromechanical-conversion equipment; these link electrical and mechanical systems and make it possible to convert from one energy form to the other. The primary electromechanical devices are "generators" and "motors." In generators, mechanical power is used to generate electrical power, whereas electric motors can be thought of as generators in reverse; they convert electrical power into mechanical power. The word, "motor," however, can be applied to any device that converts energy of any form into mechanical power but for purposes of the chapter, the term is restricted to those machines that receive electrical energy.

Except for mines that generate their own electricity, generators have limited (but important) applications in most mining operations. The principal functions are in motor-generator (M-G) sets for surface-excavating machinery and mine hoists, as well as providing emergency power for ventilation fans and hoisting equipment. Motors, on the other hand, are used so extensively that they are the most important loads on the mine electrical system, and also the most important mechanical source in mining machinery. Without electric motors, by far the majority of mines, milling plants, preparation plants, and other related mining activities would find it near impossible to operate.

Generators and motors can be studied independently of each other, but comprehension of motor operation is more easily obtained when generation is covered first. Consequently, the chapter will follow this format. However, tied to the level of use, the generator presentation will be short whereas motors and their control will be the principal chapter discussion. The content will be mainly elementary but with the objective of providing sufficient information so the following can be understood:

1. the effect that motors have on the mine power system, and
2. the specific motor applications in mining.

5.2 Alternating-Current Generation

5.2-1 Electromagnetic Induction

In Chapter 3 it was demonstrated that a voltage is induced in a conductor when there is relative motion between the conductor and a magnetic field. This electromagnetic-induction concept, which is called "Faraday's law," is the basic principle behind the generation of voltage in electric machines. As a transition between induced voltage in inductors or transformers

and generators, the following paragraphs return to the fundamental concept but in a slightly different fashion.

In Figure 5.1, a conductor is under the influence of a magnetic field. If a force is placed on the conductor so that it moves at right angles to the magnetic-field direction, a voltage will be induced in the conductor. Obviously, when a conductor is part of a closed loop, current will flow. The direction of the current produced depends upon the directions of the magnetic flux and conductor movement. Often, "Fleming's Right-Hand Rule" is used to determine the current direction; it also helps to illustrate the interrelation among the three dependent parameters. The thumb, fore-finger, and center finger of the right hand are stretched out so they are mutually at right angles to each other. If the hand is placed such that the fore-finger points in the flux direction, with the thumb pointing in the direction of conductor motion, the center-finger points in the direction of current flow.

When the conductor cuts a magnetic field at a specific relative velocity, it has been found that the instantaneous magnitude of the voltage induced, e, can be calculated by (2):

$$e = Blv_c \qquad (5.1)$$

where,

B = magnetic-field flux density (T or Wb/m^2)

l = conductor length (m)

v_c = conductor velocity at right angles to the magnetic field (m/s).

Accordingly, the magnitude of induced potential depends upon the flux density, the conductor length, and the conductor velocity

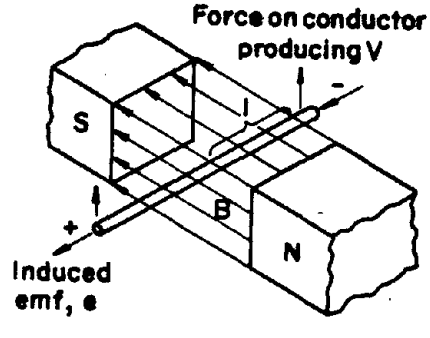


Figure 5.1. Production of a Voltage from a Magnetic Field.

(relative to the magnetic field). By varying these parameters, a voltage of almost any magnitude can be theoretically produced. It is this electromechanical principle (an adaptation of Faraday's law) that is utilized in the generation of alternating and direct currents.

5.2-2 Principle of Operation

Figure 5.2 illustrates the basic principle of alternating-current generation. A loop of conductor (say mounted on a mechanical drive shaft through an insulating block) is rotated in a magnetic field (1). A circular metallic ring, called a "slip-ring," is connected to each end of the loop, and "brushes" contact each slip-ring surface to allow the connection of stationary conductors.

When the loop is rotated by a mechanical drive, a potential is induced in each side of the loop which is proportional to the conductor velocity at right angles to the magnetic field. At the position shown in Figure 5.2, the induced voltage is at a maximum (relative right-angle velocity is maximum) but, at 90° from this position, there will be no induction (relative velocity is zero). The instantaneous voltages for the entire loop can be added algebraically as they are in series. Therefore, continued rotation will produce a sinusoidal velocity (see Figure 5.2b) and resultant sinusoidal current if the loop is part of a closed circuit.

5.2-3 Generator Construction

It has been shown that there are basically two requirements for generation. The first is a conductor or "winding" in which a desired voltage is to be induced. Such is termed an "armature

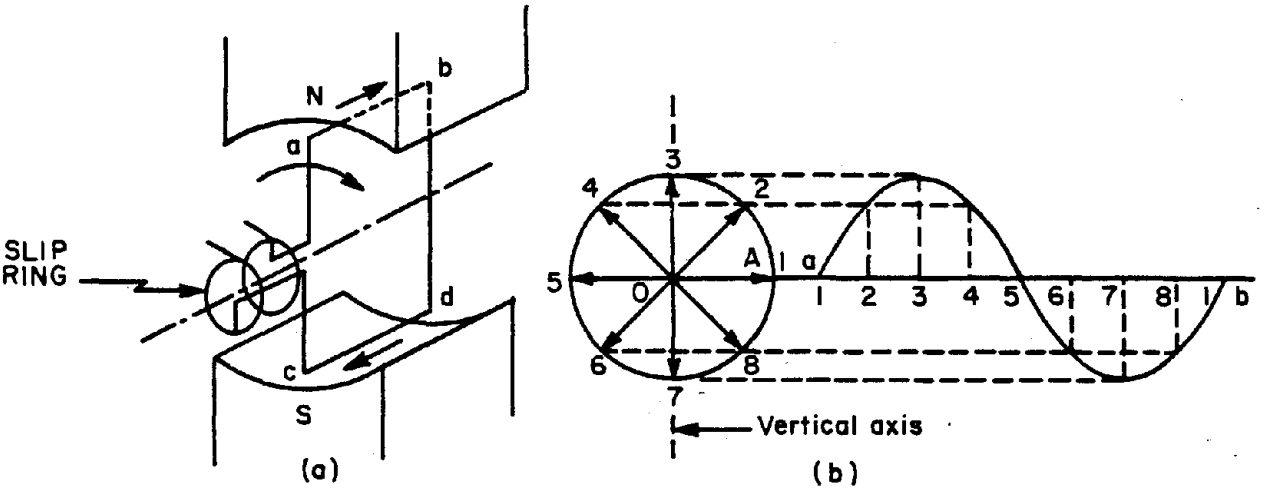


Figure 5.2. Demonstration of Alternating-Current Generation.

winding," with the structure enclosing it called an "armature." The second is a magnetic-field source and, in the majority of machines, this is created by a "field winding" (some very small machines do use permanent magnets). To classify the rotating and fixed machine portions, the rotating member is referred to as the "rotor," while the "stator" is the stationary portion.

So the flux path in the machine is as efficient as possible, the windings are placed on two concentric cylindrical iron cores with a small air gap between. Usually the inner core serves as the rotor. Similar to transformer construction, thin laminations, at times insulated from each other, are employed to minimize eddy-current loss. The structure of either core is of two types: salient poles or nonsalient poles. "Poles" form the center lines of the magnetic field. "Salient poles" physically stick out from cylinder surface (Figure 5.3); "nonsalient poles" are part of a completely cylindrical surface (Figure 5.4) (2). The windings are around salient-pole structures, but located near the core surface (in the vicinity of the air gap) and positioned in slots for nonsalient-pole cores. The conductors are usually insulated from the core. Surrounding the cores and windings is a structure called the "frame," with some form of end enclosures. The frame serves to anchor the stationary machine elements to a foundation. The end enclosure may contain bearings of either sleeve, ball, roller, or needle types that support the rotor shaft and properly position the rotor with respect to the stator. Figure 5.5 is a sketch illustrating these physical components.

The function of an electromechanical machine is commonly described in terms of the number of available magnetic poles in the field. Thus, the elementary machine in Figure 5.2 is a "two-pole" generator. Most generators, however, have more than two poles (i.e., even numbers of four, six, eight, etc.). Figure 5.6 shows an elementary "four-pole" generator (1). Here, the armature needs only to turn 180° to produce a full sinusoidal cycle in its winding output.

The foregoing terminology applies to all electromechanical rotating machinery. For practically all a-c generators (or "alternators"), the armature is contained in the stator. The field winding is part of the rotor with a d-c field current supplied through slip rings. (This is the reverse of the situation discussed previously.)

5.2-4 Three-Phase Generation

A preliminary discussion of three-phase power generation has already been presented in Section 4.3-1, but only in the context of balanced three-phase systems. This section will elaborate on its electromechanical conversion.

Consider Figure 5.7, a cross-sectional view of an elementary three-phase two-pole generator. Located in the stator, the armature has three single-conductor windings, a, b, and c, whose axes

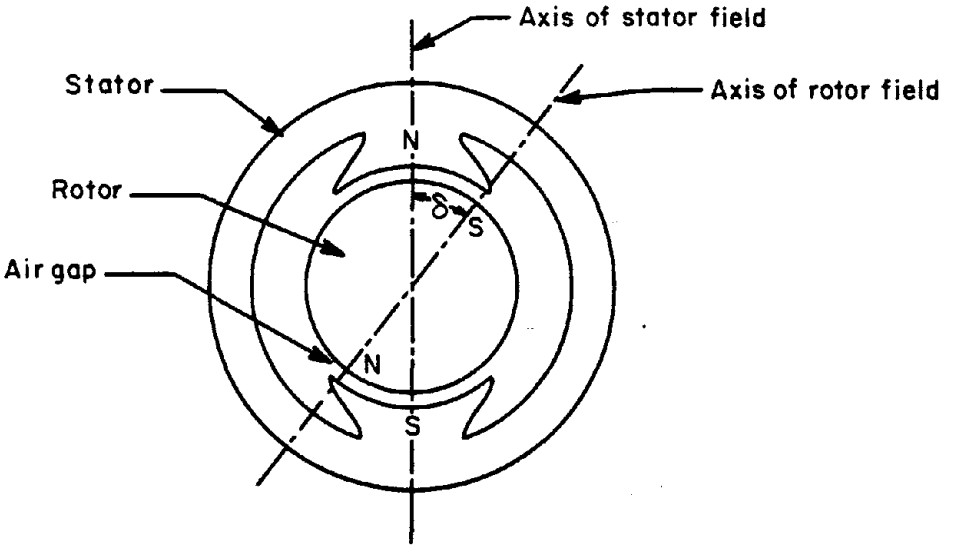


Figure 5.3. Cross Section of a Machine with Salient Poles on the Stator and Nonsalient Poles on the Rotor.

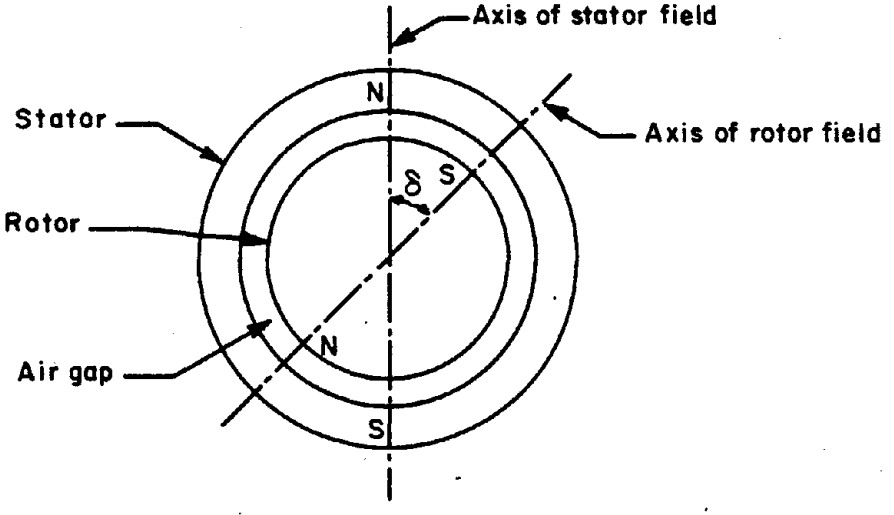


Figure 5.4. Cross Section of a Machine with Nonsalient Poles on the Stator and Rotor.

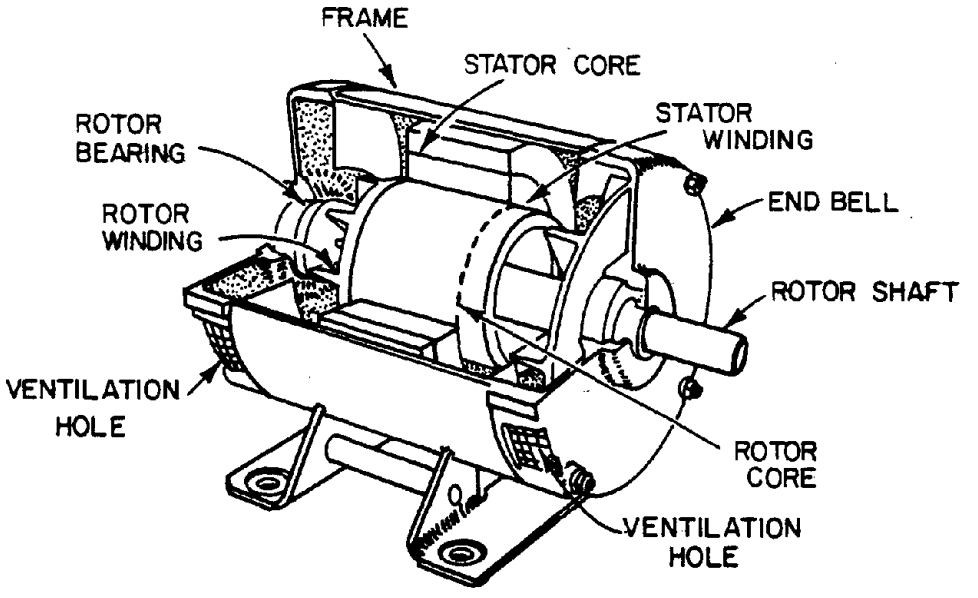


Figure 5.5. Simplified Sketch of an Electromechanical Machine Illustrating Physical Components.

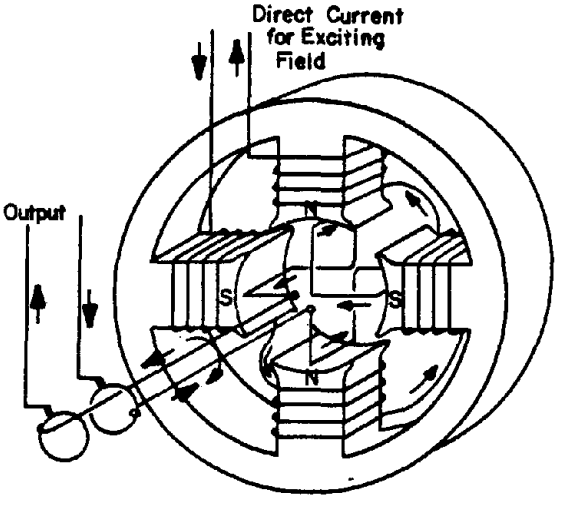


Figure 5.6. An Elementary Four-Pole Single-Phase Alternating-Current Generator.

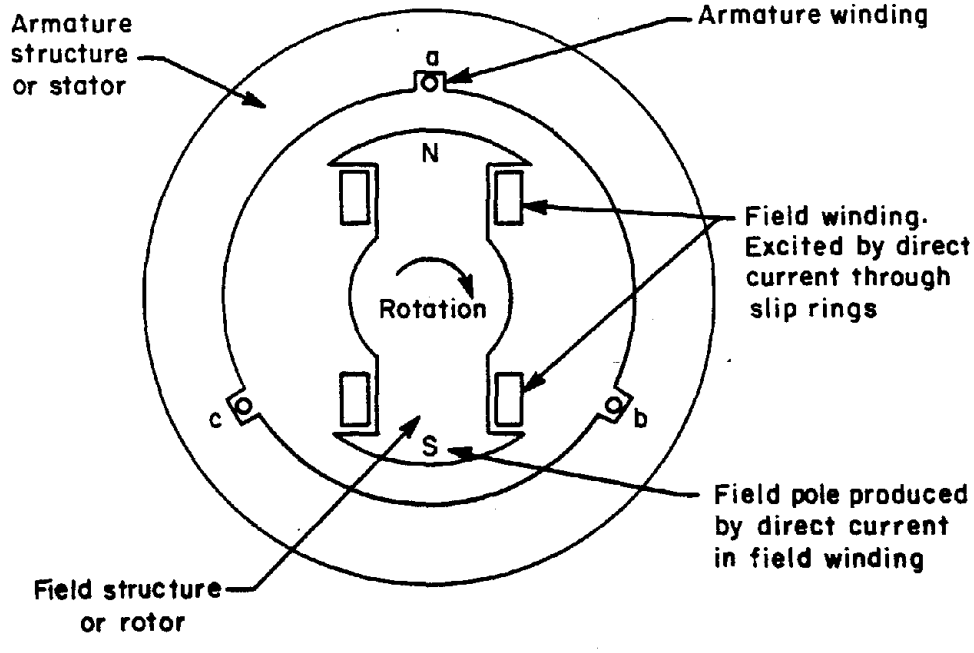


Figure 5.7. An Elementary Two-Pole Three-Phase Generator.

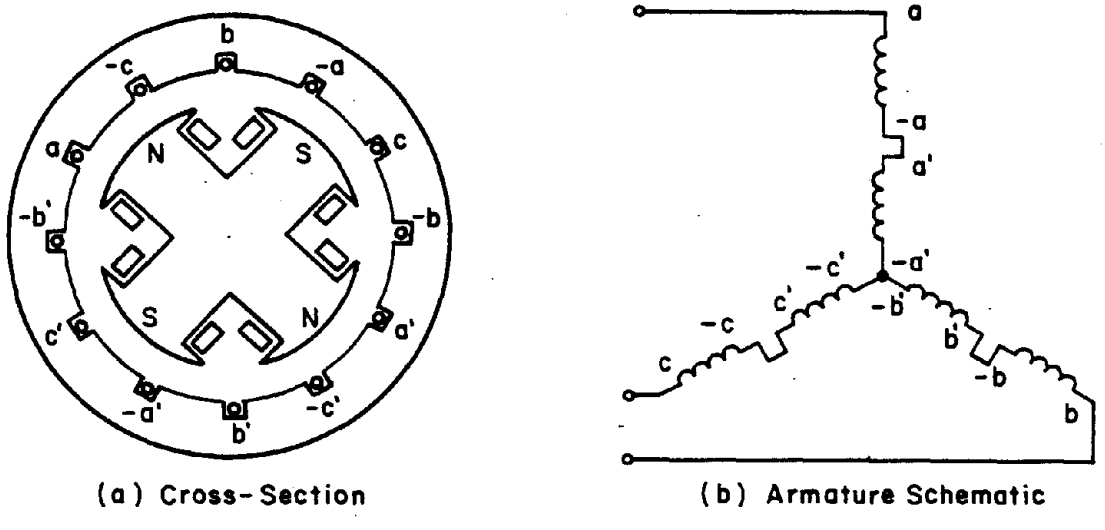


Figure 5.8. An Elementary Four-Pole Three-Phase Generator.

are 120° apart. The rotor, containing the field winding, turns at a constant speed by a mechanical power source connected to the rotor shaft, and the field winding is "excited" by direct current. The magnetic-flux distribution around the air-gap circumference of the machine is designed so it forms a sine wave (2). Therefore, the induced voltage in each armature winding varies sinusoidally with the familiar 120° displacement among the three generated potentials.

For this two-pole generator, the sinusoidal voltage in each phase winding goes through one full cycle per rotor rotation. The waveform frequency (Hz) is identical to the rotor speed (rps). The sinusoid is thus in-time-with or "synchronized" with the mechanical speed. For 60-Hz output, rotor speed is 60 rps or 3600 rpm. Consequently, alternating-current generators are often termed "synchronous generators." (Again, the machine is termed "two-pole," because of the number of available magnetic poles in the field winding.)

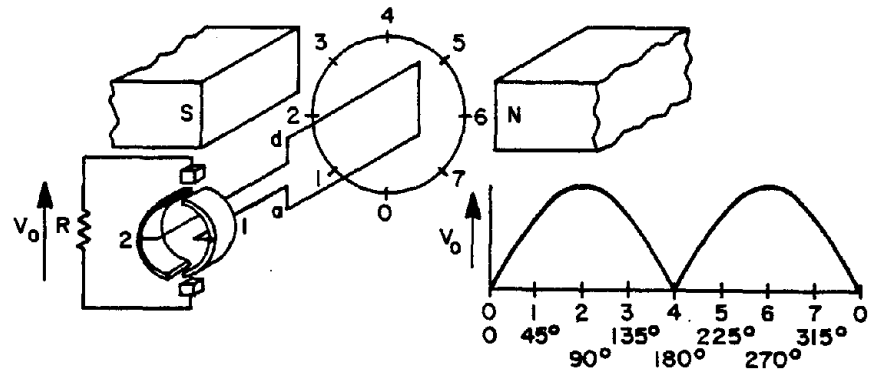
An example of an elementary four-pole generator is shown in Figure 5.8a. Here, the rotor poles alternate a north or south polarity when rotated. Each phase of the armature consists of two windings connected in series, as shown in Figure 5.8b. The induced voltage per phase thus completes two cycles for each rotor revolution.

5.3 Direct-Current Generators

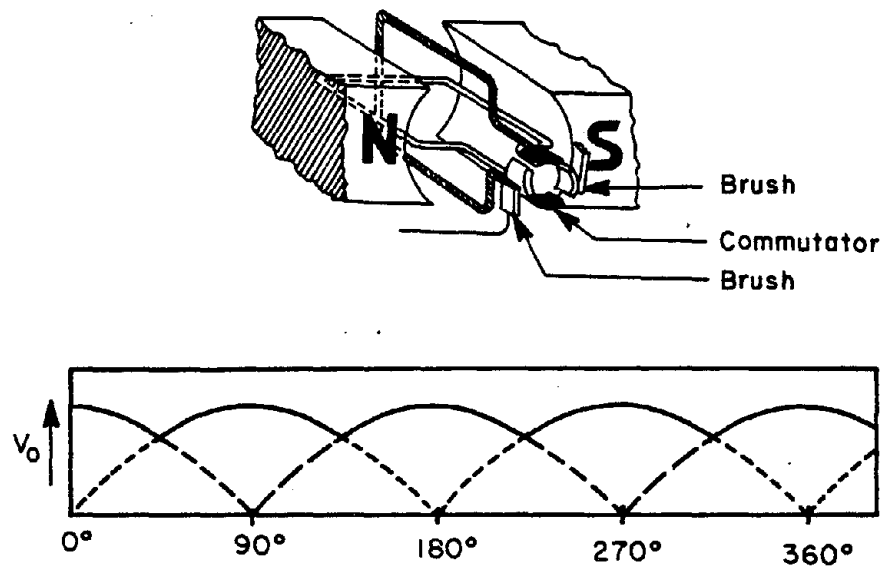
5.3-1 The Commutator

A very elementary two-pole d-c generator is shown in Figure 5.9a. The illustration only differs from Figure 5.2 in that the d-c generator has a "commutator" in place of the slip rings. The commutator is an annular ring which is split into parts (in this case, two), insulated from each other. Each part is termed a commutator "segment." As before, carbon brushes contact the ring surface to allow connection of stationary conductors. During armature rotation, the voltage produced in the loop is still a sinusoid (same as for the a-c generator). The commutator serves to rectify the waveform mechanically; at all times, the positive and negative brushes are connected with the correct armature-winding polarity. In other words, the connection to the loop reverses (or "commutates") every one-half revolution. Thus, the generator output waveforms are the same as full-wave rectification (Figure 3.90c). If rotation direction reverses, so does the brush polarity.

Because of the ripple voltage, the two-pole d-c generator is not realistic. In practical d-c generators, the armature consists of many windings with the commutator having a corresponding number of segments (see Figure 5.9b). In such a case, current from the generator will never drop to zero. When the number of armature windings is increased, the output ripple voltage will decrease, and the average direct voltage will be closer to the peak voltage.



(a) Demonstration of Generation.



(b) Generator with Two Armature Windings.

Figure 5.9. Direct-Current Generation.

5.3-2 Generator Types

Actual d-c generators have the armature winding on the rotor and the field winding in the stator, which is opposite to that of a-c generators. The field must be excited by direct current provided by a source (2). If this source is external, the result is termed a "separately excited generator;" a schematic of such is shown in Figure 5.10. However, because the armature is a d-c source, it can supply current to the field as well as the load. Generators so connected are called "self-excited." However, in order to start generation the stator core of these machines must have residual magnetism.

Self-excited generators have three configurations, depending on the field-winding connection: series, shunt, and compound. These are shown respectively in Figures 5.11, 5.12, and 5.13. Being descriptive modifiers, the terms, "series" and "shunt," relate directly to the winding connections. However, the "compound" generator has two windings, one connected in series and the other shunting the armature.

Each of the foregoing generator connections have a characteristic voltage output versus load current (2). In series generators, because the field, armature, and load currents are the same, output voltage fluctuates widely with load. Thus, this connection is used rarely. Shunt-generator voltage output drops slightly as load current is increased, but the regulation is satisfactory for many purposes. Compound generators are normally connected so the magnetic actions of the shunt and series windings aid each other. The resultant magnetic flux of the field can increase with load current, causing the output voltage to remain nearly constant. The level of output voltage in both the shunt and compound generators can be controlled by the variable resistance in series with the shunt-field winding. The resistance in the separately-excited generator provides the same function, but precise output-voltage control is obtained because the field-winding current is not a function of the load.

5.4 Motor Basics

5.4-1 Construction

Because the construction of a motor is like that for a generator, the essential motor parts generally include:

1. two concentric cylindrical laminated-iron cores, separated by an air gap to carry magnetic flux;
2. two sets of windings, wound or embedded in slots in the iron cores, either or both excited by direct or alternating currents; and
3. the inactive motor elements, including the frame, end bells, bearings, and so forth.

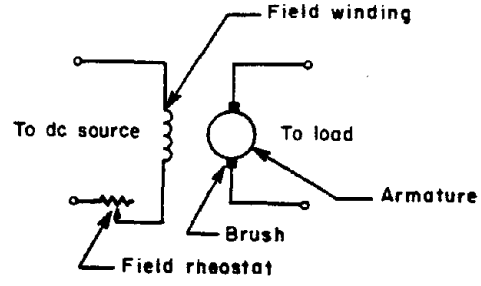


Figure 5.10. Separately Excited Direct-Current Generator.

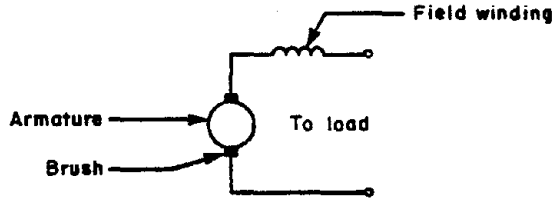


Figure 5.11. Series Direct-Current Generator.

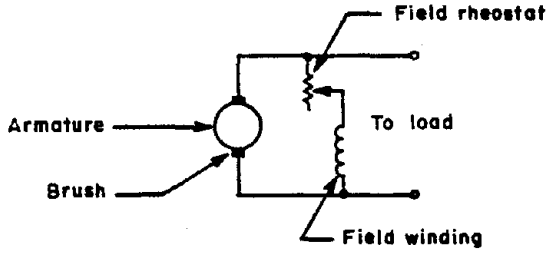


Figure 5.12. Shunt Direct-Current Generator.

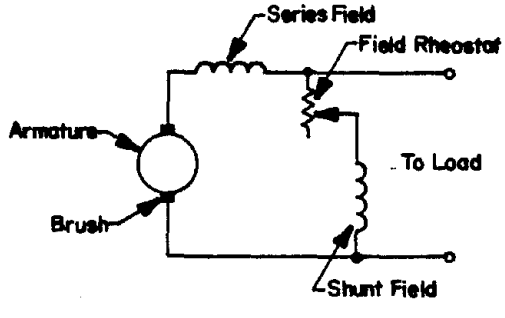


Figure 5.13. Compound Direct-Current Generator.

Combinations of these parts form all the normally-encountered practical motors. In a reverse process to generators, motors employ electrical energy to produce mechanical force. The force of interest in motors is that which tends to produce rotation or torque.

5.4-2 Torque

Motor-torque considerations are based on the fundamental principle that a mechanical force is exerted on a current-carrying conductor in a magnetic field. A graphic example of this situation is shown in Figure 5.14. Here, the magnetic field that surrounds the conductor (due to its current) interlinks with the larger magnetic field, and creates a large concentration of magnetic flux at one side of the conductor. This tends to force the conductor towards the lesser flux concentration, and the result is an instantaneous force, f, at right angles to the magnetic field.

The magnitude of the force depends upon the magnetic-field flux density, the conductor length, and the level of instantaneous current, and can be calculated for a straight conductor by (2):

$$f = Bli \qquad (5.2)$$

in which

f = the force (N)

B = magnetic-field flux density (T)

l = conductor length (m)

i = the instantaneous current (A).

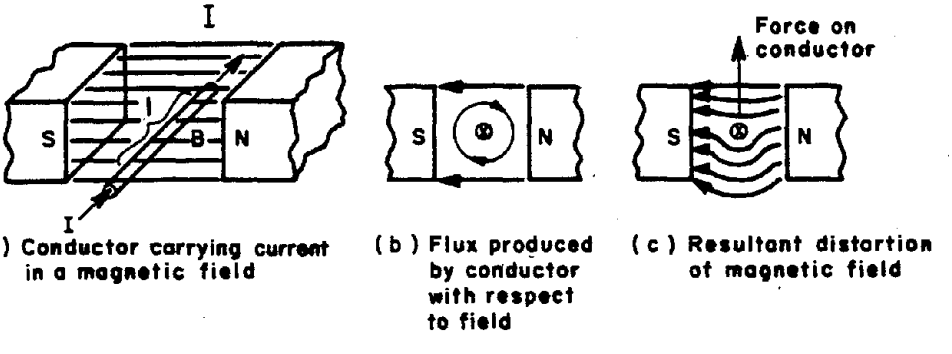


Figure 5.14. A Current-Carrying Conductor in a Magnetic Field.

If the conductor is fixed in radial distance, r, from the center of a rotor shaft, the associated torque, T, is (2):

$$T = Blri \qquad (5.3)$$

where,

T = the torque (N-m)

r = the radial distance or moment arm (m).

For a winding, the total torque is the summation of the torques for the individual conductors or coil sides. For electromechanical machines, this mechanical quantity is termed "electromagnetic torque" and, when combined with rotation, the resultant power quantities follow the rules of mechanics.

Another way of visualizing the development of motor torque is the interaction of two magnetic fields. A mechanical force is exerted on magnetic material, be it a permanent magnet or magnetism created by electric-current flow. The force tends to align the material with the closest part of a magnetic field so that the north pole of one machine member is directly in line with the south pole of the other member. The force, if acting at a moment arm about a rotor shaft, produces torque.

Even though equation 5.3 is expressed in newton-meters (adhering to SI units), quantities normally used are pound-feet, ounce-inches, and gram-centimeters. However, a preferred method of relating motor mechanics is reference to a percent of full-load torque.

5.4-3 Speed-Torque Relationships

"Speed-torque curves" are the characteristic curves of a motor; a general example for an induction motor is provided in Figure 5.15 for discussion (3). A use for these curves is to find the most suitable drive for a given machine, as the machine load can also be described by a speed-torque curve (see load torque in figure). Thus, the comparison of the load and motor curves will show if the motor has the necessary characteristics to drive the load and, further, what the operating point will be. (This point is the intersection of the two curves.) In addition, there are many other parts of the motor characteristic which suggest its suitability for a specific application. Some of these are listed below, and each is labeled in Figure 5.15.

1. "Locked-rotor torque." The minimum torque developed by a motor at the instant of power application (sometimes called "breakaway" or "starting" torque).
2. "Accelerating torque." The torque developed during the period from zero to full-rated speed with rated power applied. Often, the term is used for the net

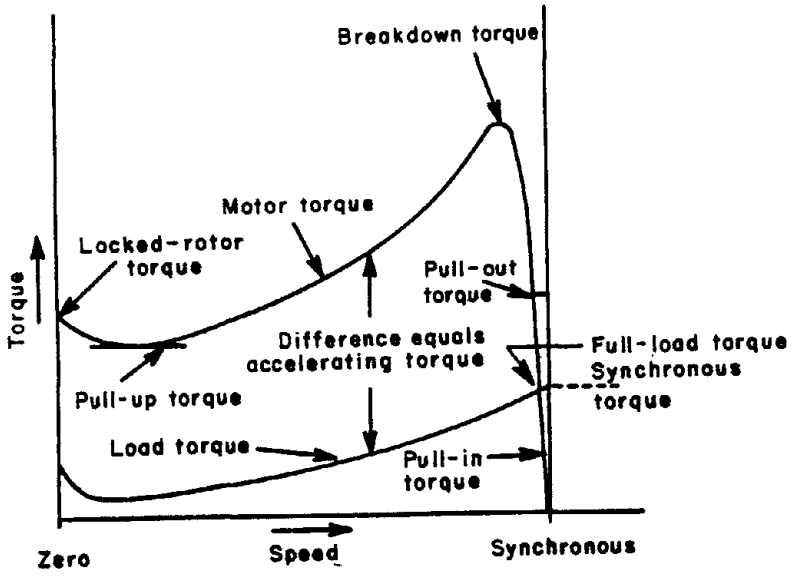


Figure 5.15. A General Speed-Torque Motor Characteristic.

torque between the motor and the load. It is apparent in the figure that this is a non-linear value with speed.

3. "Breakdown torque." The maximum torque possible from the motor with rated-power input (also called "maximum" torque).
4. "Pull-up torque." The minimum torque developed during motor acceleration from zero to full-rated speed with rated power applied. The minimum can exist in some motors at full-rated speed.
5. "Full-load torque." The torque necessary to provide rated output at rated speed with rated power applied.
6. "Pull-out torque." The maximum torque produced by a motor without stalling. Normally, this is referred to as the maximum or breakdown torque. During operation, if a torque is applied to a motor above this value, it will stall.

It can be noticed that other motor terms are listed in Figure 5.15. These are tied to specific motor types or operations which are yet to be discussed.

5.4-4 Standardization

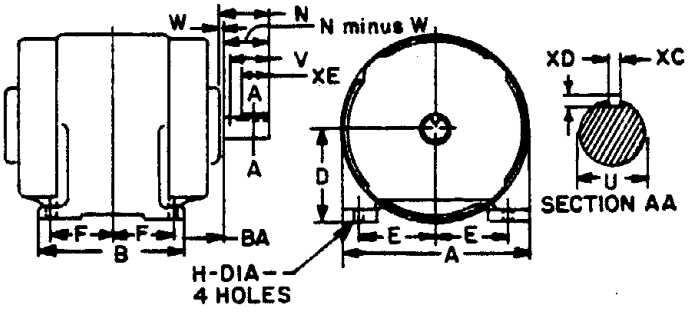
The National Electrical Manufacturers Association (NEMA) sets standards for the manufacture of electric motors (3). These are used throughout the mining industry. There are, however, some exceptions where motors are designed to match a unique task or

load (such designs are commonly termed "job shop"). NEMA standards generally cover seven areas: speed-torque characteristics, frame size, enclosure, horsepower rating, voltage, temperature rise, and application. With motors made to a particular NEMA standard, machines from different manufacturers should be directly interchangeable (but there may be some variation between manufacturers).

Frame Size. Most motors, 250 hp and under, are rated according to a frame number (3). This specifies the essential mounting dimensions, for instance, the three frame numbers provided in Figure 5.16. The same frame number series covers all motor types (a-c or d-c), and a dozen or more different motors might have the same frame.

Enclosure. Including the frame, there are two general classifications for motor enclosures: "open" and "totally enclosed." Open motors simply have openings, usually in the end plates, to allow air cooling of the windings. Totally-enclosed motors prevent air from entering the enclosure, but these motors are not always sufficiently closed to be air-tight. In this general class are the explosion-proof motors (see Chapter 14), dust-ignition-proof motors, dust-tight motors, and waterproof motors. Cooling for these can be by air conduction on the outer frame, internal forced-air through a pipe, or a liquid-cooled (water or oil) outer jacket surrounding the frame.

Horsepower. Horsepowers are also standardized, such as 1/2, 3/4, 1, 1-1/2, 2, 3, 5, 7-1/2, 10, 15, 20, 25, 30, 40, 50, 60, 75, 100, 125, 150, 200, and 250 at speeds for two to 16 poles with 60-Hz operation (3). Above 250 hp, the standard powers are



FRAME NO.	A	B	D	E	F	BA	H	NW	U	V min	XC	XD	XE
145T	7	6	3-1/2	2-3/4	2-1/2	2-1/4	11/32	2-1/4	7/8	2	3/16	3/16	1-3/8
184T	9	7-1/2	4-1/2	3-3/4	2-3/4	2-3/4	13/32	2-3/4	1-3/8	2-1/2	1/4	1/4	1-3/4
213T	10-1/2	7-1/2	5-1/4	4-1/4	2-3/4	3-1/2	13/32	3-3/8	1-3/8	3-1/8	5/16	5/16	2-3/8

Dimensions in inches

Figure 5.16. Examples of Three Frame-Number Dimensions.

related to motor type. When a horsepower is given, it is often tied with a "service factor" to allow for usual fluctuations in supply voltage or slight overloading. Service factor indicates the permissible overload and is a multiplier applied to the normal horsepower rating. The value can range from 1.0 to 1.4, depending on the size and type of motor. For instance, a 1.15 service factor would indicate that a motor can carry 15% more than rated load continuously without overheating (i.e., exceeding the rated temperature rise) as long as frequency, ambient temperature, line voltage, and so on are at rated.

An interesting situation occurs with frame sizes primarily intended for motors of less than one horsepower, or of "fractional horsepower." A "fractional-horsepower motor" is considered to be any motor built in a fractional-horsepower frame regardless of the actual horsepower rating, even those in excess of one horsepower. Most of these motors, however, are only available for single-phase a-c.

Voltage. NEMA voltage designations are specified for most motors, be they three-phase, single-phase, or d-c (3). A listing of the voltage ratings (also called the motor terminal voltage) common to mining is available in Table 5.1. A maximum voltage variation of $\pm$ 10% from rated is permitted. For a-c motors, the allowable system-frequency fluctuation is $\pm$ 5%.

Temperature Rise. The allowable temperature rise from an ambient temperature is dependent upon the class of insulation used in the motor (3). The electrical-insulation system is one of the most important components of a motor, as its degradation seriously affects the reliability and service life of the motor. Insulation systems are divided into four classes, A, B, F, and H, depending upon their thermal endurance. Ratings for industrial motors are typically based on a 40°C ambient temperature (some are based at 25°C, see Section 5.7). Table 5.2 provides the allowable rise for each insulation class; also included are the common insulating materials and maximum "hot-spot" temperatures, the highest temperature allowable at any part of the motor. Motors built to a specific class and operated so the recommended temperatures are not exceeded may be expected to have a serviceable life of 20 years with minimal maintenance. Physical abuse, such as mentioned in 5.7, and the electrical stresses discussed in Chapter 10, however, can seriously shorten the motor life, regardless of insulation class and operation. Class-A insulated motors are rare in almost all applications, except for very small horsepowers. Class F and H insulations are most often used in motors for mining applications (4). It is interesting to note that the maximum surface temperature of any permissible mining motor cannot exceed 150°C (see Chapter 14).

The allowable temperature rise must be decreased, if the maximum ambient temperature is greater than specified, by the difference in temperature above ambient. (The rise may be increased by a like amount when the maximum ambient temperature is

Table 5.1. Motor Voltage Ratings Common to Mining.

	Nominal System Voltage, V	Motor Rated Voltage, V
1. Three-Phase Low-Voltage:[1]		
	208Y	208
	230	220
	460†	440†
	480*	440*
	575†	550†
	600*	550*
2. Three-Phase Medium-Voltage:		
	1,040*	950*
3. Three-Phase High-Voltage:		
	2,400	2,300
	4,160	4,000
	7,200	6,600
	12,470	12,470
	13,200	13,200
	13,800	13,200
4. Direct-Current:		
	300	250
	600	550
5. Single-Phase:		
	120	115
	240	230

[1] System voltage designations follow Title 30, Code of Regulations, Parts 18, 75, and 77.

† More suitable for stationary equipment applications.

* Intended use is mobile mining equipment.

Table 5.2. Motor Insulation Classes.

	Insulation Class			
	A	B	F	H
1. Application:				
a. Open motors:	50°C	70°C	90°C	110°C
b. Totally enclosed motors:	55	75	95	115
c. Max. hot-spot Temp.:	105	130	155	180
2. Common insulating materials (each class has similar materials and compatible bonding agents to those shown):				
	cotton	mica	mica	mica
	paper	glass fiber	glass fiber	glass fiber
	cellulose	asbestos	asbestos	asbestos
	enamel-coated wire			silicone elastomers
	organic			silicone resins

below. Maximum is the highest temperature the motor is normally exposed to.) These specifications are applicable for operation under typical barometric pressure, as long as the altitude does not exceed 1000 m (3300 ft). Above 1000 m (3300 ft), the allowable temperature rise must be reduced 1.0% for each 100 m (330 ft) above 1000 m.

Other Standards. Additional classification standards will be discussed in the following sections, for example, applications as to load-speed and load-torque requirements. These are tied to the torque-speed characteristics, which are related to the motor type.

5.4-5 Motor Types

The classification of a motor type is dependent upon how either or both the stator and rotor windings are excited. This results in three general motor classes: induction, synchronous, and direct current. The first two are a-c machines and for many situations these are more rugged, require less maintenance, and are less expensive than d-c motors of equal horsepower and speed ratings. The most widely used a-c type is the "squirrel-cage induction motor." It has no slip-rings, commutator, or brushes to wear out and uses the simplest kind of starting equipment. Generally, a-c motors can be used effectively for the majority of motor applications; the exception is when very high starting torques are required. Accordingly, the most popular electromechanical machines in mining are three-phase squirrel-cage induction and series-wound d-c motors. The next three chapter sections cover the major motor classes, as well as conventional starting techniques. After a description of mining applications, Section 5.8 will briefly discuss common single-phase motors.

5.5 Three-Phase Alternating-Current Motors

Relating to the presentation in Chapters 3 and 4, it would seem that three-phase motors would be more complex than their single-phase and d-c counterparts and therefore more difficult to understand. However, although some parts of three-phase-motor construction are more complex, their operation is simpler. As was just stated, induction and synchronous machines are the two major a-c motor types. Synchronous motors correspond to three-phase generators. In typical large machines, direct-current is applied to field winding located in the rotor, while three-phase a-c (instead of being generated) is supplied to armature windings placed in the stator. Induction motors also receive a-c power at the stator windings, but a-c is delivered to the rotor winding indirectly by induction in the same manner as a transformer.

5.5-1 Squirrel-Cage Induction Motors

The Induction Motor. In order to comprehend the operation of induction motors as well as important terminology, it is perhaps

best to start with a simple demonstration. Although the following will not use familiar motor components, the actual motor type does have direct application in mine power systems, induction-disk relays.

Consider Figure 5.17 which depicts an aluminum disk and a horseshoe magnet (5). Both are mounted about the same axis and free to rotate. If the magnet is rotated, the disk cuts the magnetic lines of force, a voltage is induced, and eddy currents will then flow. Under the magnet south pole, the eddy currents set up north magnetic poles, conversely for the north pole of the magnet. Because the pole attracts, the disk rotates, following the magnet. The disk can never reach the magnet speed, as there would be no relative motion between the two (i.e., no induction would exist). The mandatory difference in speed for induction motors is called "slip."

In conventional induction motors, the action of the disk occurs in a rotor winding, and the "rotating-magnetic field" is supplied by the stator winding. For induction-disk relays, the aluminum disk remains, but the induction force is supplied by a-c driven stator (see Chapter 8 and also "Watthour Meters" in Chapter 4).

Elementary Three-Phase Motor. Figure 5.18 illustrates an elementary two-pole, three-phase squirrel-cage induction motor (6). The stator consists of three salient poles spaced 120° apart; the stator windings around each pole are connected in wye and energized by a three-phase system. The rotor has three main elements: a shaft (not shown), core, and winding.

As with generators, the rotor core is made of iron laminations pressed onto the shaft. The winding, or "squirrel-cage winding," is constructed by imbedding heavy copper or aluminum

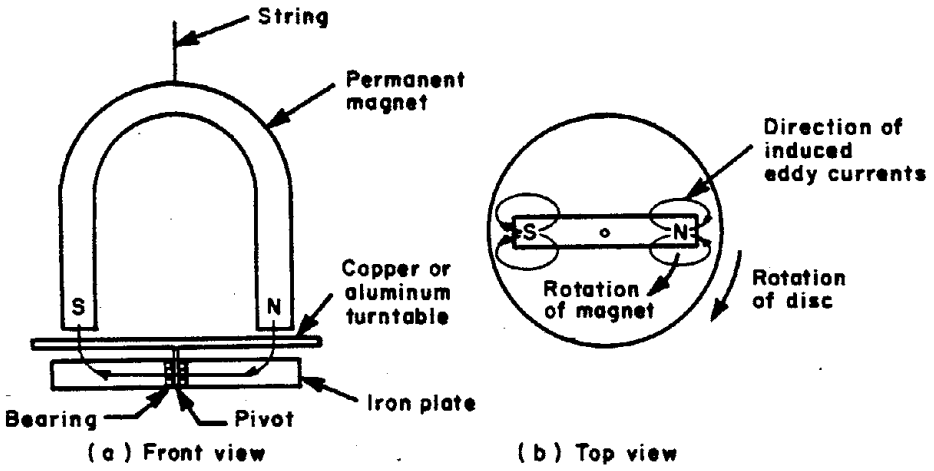


Figure 5.17. Demonstration of Induction-Motor Operation.

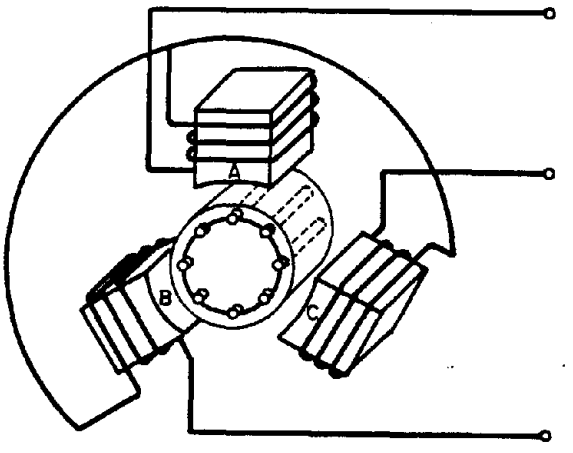


Figure 5.18. An Elementary Three-Phase Induction Motor.

bars in the core slots. The bars are connected to each other by copper or aluminum rings on both core ends to complete the closed circuit. In other words, there are no external connections either by slip rings or a commutator to this rotor winding. Figure 5.19 shows the winding construction; the squirrel-cage terminology comes from the appearance.

When the stator windings are powered by a three-phase system, currents through the coils reach their respective maximums at different intervals in time. Since the three currents are displaced by 120°, the magnetic field generated by each coil is also displaced from the other two by 120° (see Figure 5.20a). Each winding magnetic field alternates from north to south, thus they have the action of two poles. Figure 5.20b shows the instantaneous direction of a stator flux as it passes through the rotor at different time intervals. At zero degrees, for instance, phase A is at maximum north, while phases B and C are weak south poles. At 60°, phase C becomes strongly polarized in the south direction, and phases B and A are weak norths. The large arrows, shown in the figure, represent the instantaneous direction of the resultant two-pole magnetic field. Consequently, for this example, the magnetic field is rotating counterclockwise.

In a transformer, voltages are induced in the secondary circuit by the primary. The stator of an induction motor acts in the same manner as the primary, with the rotor winding acting as the secondary winding. The stator rotating magnetic field cuts the rotor conductors and motor action is developed. The relative motion, or slip, between the rotating flux and the rotor generates voltages within the rotor conductors.

According to Lenz's law, the voltage induced in each rotor bar will be in a direction opposing the relative motion of the

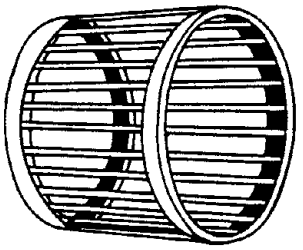


Figure 5.19. The Squirrel-Cage Rotor Winding.

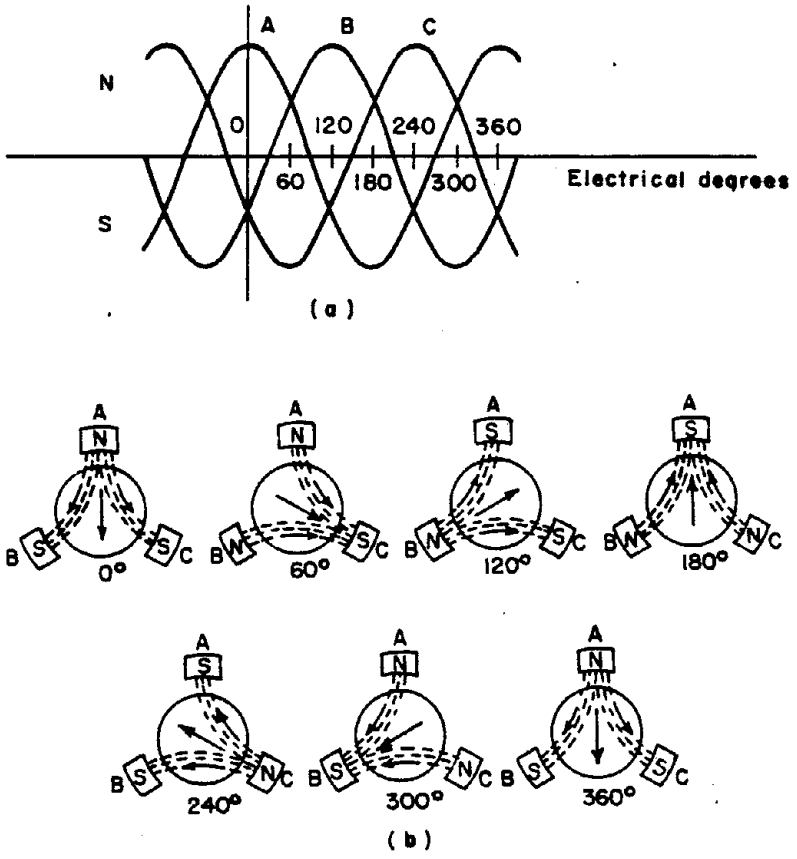


Figure 5.20. Rotating Magnetic Field in an Elementary Three-Phase Two-Pole Induction Motor.

rotating flux and the rotor. The induced-voltage direction in the rotor conductors under the influence of a two-pole rotating magnetic field is shown in Figure 5.21 (positive implies the voltage direction is out of the page). The voltage magnitude in each bar depends upon the stator magnetic-field density at that point. These voltages cause currents to flow through the bars, an end ring, adjacent bars, and then back through the other end ring to the origins, in complete loops. The circulating rotor currents produce magnetic fields about each rotor bar.

The interaction between the stator field and the fields around the rotor conductors results in a mechanical couple and thus motor torque. Hence, the rotor will revolve in the same direction as the stator field. A simple reversal of any two phase conductors to three-phase induction-motor stator windings will reverse the stator phase sequence and thus reverse the motor rotation.

Formulas. The speed at which the stator field rotates is termed the "synchronous speed" of the motor and can be calculated from:

$$n_s = \frac{120f}{p} \tag{5.4}$$

where,

n_s = the synchronous motor speed (rpm)

f = the line frequency (Hz)

p = the number of magnetic poles presented by the stator.

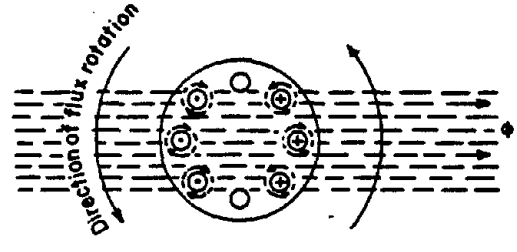


Figure 5.21. Induced Rotor Potential by Rotating Flux.

As slip is required to produce rotor induction, a squirrel-cage motor may approach, but never obtain, synchronous speed. Slip can be expressed mathematically as:

$$s = \frac{n_s - n_r}{n_s} \tag{5.5}$$

in which

s = the motor slip (may be expressed as a per-unit decimal or a percent)

n_r = the actual motor speed (rpm).

Losses will occur in actual motors due to electrical and mechanical inefficiencies. Those prominent in induction motors are:

1. rotor winding, related to I^2R;
2. stator winding, also an I^2R loss;
3. stator core loss, caused by eddy currents and hysteresis in the core iron; and
4. friction and windage (rotational or mechanical) losses.

All these are almost pure active powers; therefore they are often expressed in watts. The losses in both windings of induction motors vary as the square of line current, core loss is nearly constant and, unless motor speed varies considerably, rotational losses are nearly constant (6). Knowledge of machine losses allows the determination of motor heating and efficiency.

The "efficiency" of motor operation is a measure of the motor's ability to convert input power to mechanical power:

$$\text{Efficiency} = \frac{\text{output}}{\text{input}} = \frac{\text{input-total losses}}{\text{input}} \tag{5.6}$$

which may be expressed as a per-unit decimal or a percent. Slip is also related to motor efficiency, being numerically equal to the ratio of winding loss in the rotor to the total rotor power input:

$$s = \frac{\text{rotor winding loss}}{\text{rotor power input}} \tag{5.7a}$$

or

$$s = \frac{\text{rotor winding loss}}{\text{motor power input - stator losses}} . \qquad (5.7b)$$

Stator losses in equation 5.7b include friction and windage. Equations 5.4 through 5.7 can be employed not only to calculate the synchronous and actual motor speeds but also the possible power and torque output, realizing that (5):

$$\text{power output (watts)} = 746 \text{ (horsepower output)} \qquad (5.8a)$$

or

$$P = 746 \text{ (hp)}$$

and

$$hp = \frac{n_r T}{5250}$$

in which

$$T = \frac{K I_r^2 R_r}{s} \qquad (5.8b)$$

where,

hp = horsepower output of the motor
n_r = the actual motor speed (rpm)
T = motor torque (ft-lbs)
K = a torque constant (ft-lbs/V)
I_r = the rotor current (A)
R_r = the rotor resistance (Ω).

Motor Construction. The elementary salient-pole motor of Figure 5.18 is undesirable from the standpoint of the ineffective material and space use, as well as its overall inefficiency. The main disadvantage is coupled to the distinguishable stator poles. To overcome the problem, actual induction motors have lapped stator coils as shown in Figure 5.22(b). Several coils make up a stator winding which can be either delta or wye connected. The flux directions of each coil are illustrated as ϕ_C, ϕ_B, ϕ_A, and each coil contributes to the rotating flux development of the entire stator. The coils, and thus the windings, are arranged to have the same effect as salient poles, but the poles are not physically distinguishable. However, an induction motor is assigned a specific pole number if, at any given instant, the stator windings set up the same number of magnetic-pole fields (again, the elementary motor of Figure 5.18 is a two-pole motor).

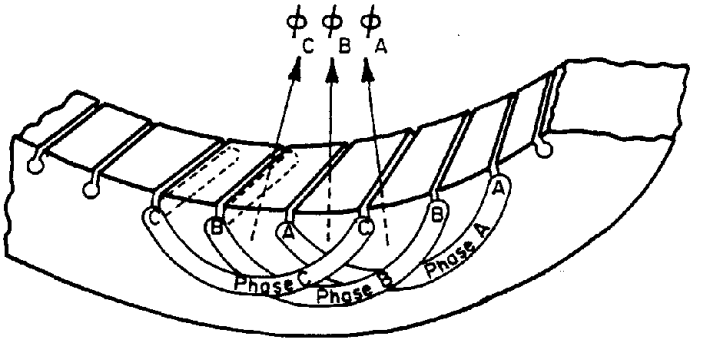


Figure 5.22. Lapped Windings of a Three-Phase Motor Stator.

The rotor core and squirrel-cage conductors are usually not insulated from each other, as the induced current is contained within the conductors because of the significantly lower resistance. The rotor core is pulled magnetically to the stator core across the air gap. If the force is uneven as the rotor turns, the result is vibration, which is detrimental in several ways (for instance, producing structural-insulation failures, premature bearing failures, misalignments with the motor load, and so on). These problems are cancelled if the magnetic effect about the rotor periphery is equal. In addition to lapped stator windings, rotor conductors are most often placed in skewed slots not parallel to the stator slots to also reduce vibration. Thus when a rotor slot passes under a stator slot, the skewed slot passes gradually rather than abruptly. The practice also prevents "dead spots," or positions of near zero or minimum magnetic influence. Another method of eliminating dead spots is to construct the number of rotor plus stator slots to be prime numbers.

Motor Behavior. Figure 5.23 provides an example of the speed, efficiency, power-factor, power-input, and current-load characteristics of a typical three-phase induction motor found in mining applications. Figure 5.24 shows a representative torque-speed characteristic for a similar machine. These curves can be used to describe the electrical and mechanical operation of induction motors under loading.

From the typical torque-speed curve, the torque at locked rotor is approximately 150% of rated. The level increases steadily with rotor acceleration to the maximum or breakdown torque. With applied power input, the rotor continues to accelerate until the slip reduction reduces the rotor current to a point where torque is equal to the load torque.

Consider the motor running with no load. As the motor is loaded, slip increases, causing an increase in induction in the rotor. Hence rotor current rises, resulting in a stronger rotor

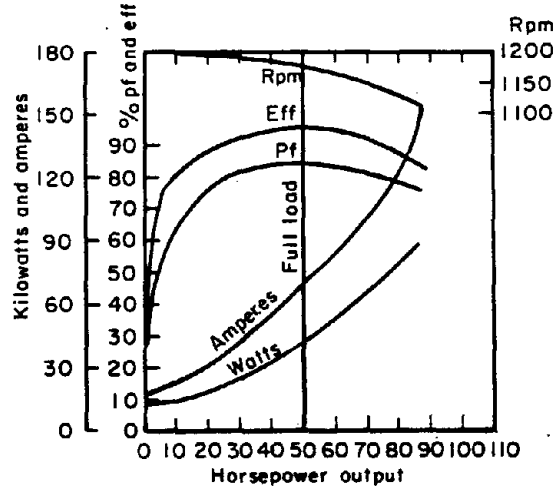


Figure 5.23. Characteristic Curves of a Three-Phase Induction Motor.

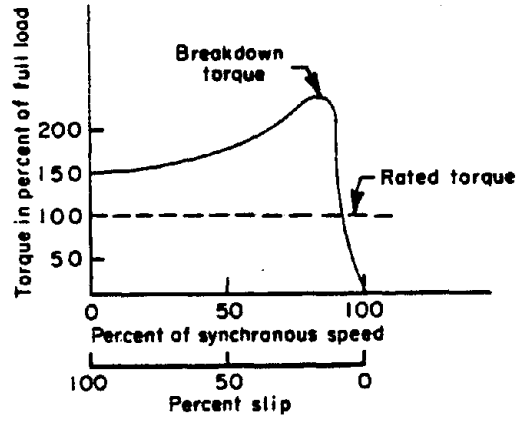


Figure 5.24. Typical Torque-Speed Characteristic for a General-Purpose Induction Motor.

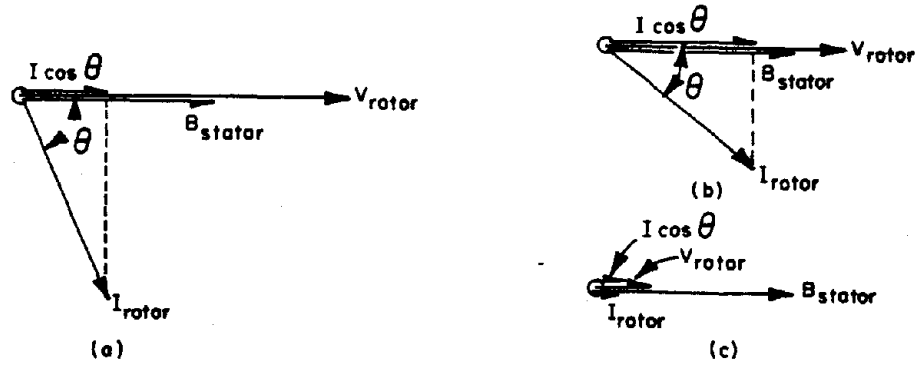


Figure 5.25. Phasor Diagrams of the Rotor and the Stator Flux-Density for an Induction Motor.

magnetic field and motor torque. Torque continues to increase with the increased shaft load until breakdown torque is reached. Then, any further load results in a slip value that decreases torque. If the high load is sustained, the rotor will stop.

Because the induction motor is basically a transformer, its electrical characteristics, as seen by the power source, will be a reflection of that occurring in the stator winding. Figure 5.25 shows phasor diagrams for rotor current and voltage during three operation points; these are referenced to the flux-density phasor of the strator, B_{stator} (6).

The rotor bars are embedded in the steel core so they have a high reactance (2). At locked-rotor conditions (rotor stationary), the stator magnetic field rotates past the motor at synchronous speed, and the induced voltage in the rotor conductors has the same frequency as the stator (or line frequency). The result is a high ratio of rotor reactance to resistance, and stator current lags stator voltage by a large amount (Figure 5.25a). During rotor acceleration, slip decreases, which also decreases the frequency of rotor current and voltage according to the following relationship (5):

$$f_r = sf \tag{5.9}$$

where,

f_r = the frequency of the sinusoidal voltage and current induced in the rotor bars (Hz)

s = the slip expressed as a decimal

f = the frequency of voltage and current in the stator (Hz).

Thus inductive reactance drops, increasing the power factor (Figure 5.25b). Theoretically, if the motor could obtain synchronous speed, the rotor power factor would reach unity (Figure 5.25c). However, as this cannot happen in actual squirrel-cage motors, the maximum power factor is seldom greater than 0.85 (see Figure 5.23) and never greater than 0.95.

Because the output torque increases with slip, motor speed decreases slightly as the load increases from no load to full load. Yet, efficiency and power factor drop rapidly on low-load conditions. Hence, an induction motor should not be operated at low load (much below rated load) for any length of time. It is apparent from Figure 5.23 that efficiency diminishes when motor load increases above a given value. Consequently, an induction motor should not be overloaded for any extended period. Power factor and efficiency curves normally follow roughly the same path; thus power factor can be considered as an estimate of motor-operation efficiency.

Stator-Voltage Effect. The torque developed by a three-phase induction motor varies as the square of the stator supply voltage or:

$$\text{Torque} \propto V^2_{\text{stator}}. \tag{5.10}$$

Therefore, a 10% reduction from rated stator voltage will cause a 19% reduction in available torque output.

Insulation. Insulation in motors normally has five forms: strand, turn, lead, crossover, and ground (3). As the rotor conductors are uninsulated, the concern for induction-motor conductor insulation is for the stator windings (this is the critical concern for all motors in general). The primary insulating system is that between the windings and the stator core or ground, and the secondary insulation is in strands, turns, leads, and crossovers.

Copper magnet wire, and to a much lesser extent aluminum magnet wire, is used to construct the stator windings or coils. Here, strand insulation is most frequently a resinous-coating on the wire. After strands are wound into coils (or the actual windings), turn insulation is applied and may be a resinous coating, resinous-film taping, paper taping, or a fibrous wrapping. These are utilized at applications of 6600 V and less; for higher voltages, additional layers of mica or varnished-cloth tape are at times used. Crossover insulation is employed to protect wires that cross each other. The crossovers are often the weakest point in winding construction; thus they require additional protection. Lead insulation is simply that about the conductors leading to the windings. Lastly, ground (or ground-wall) insulation is the major insulation system of the motor and isolates the windings from the core. This is always subjected to the highest potential difference and requires the most attention.

Design Characteristics. Figure 5.26 illustrates the standard NEMA torque-speed characteristics for squirrel-cage induction motors. The shape of these depends primarily on the ratio of rotor resistance to rotor reactance. For instance, to obtain a greater locked-rotor torque, as well as a greater slip over the usable load range, rotor resistance may be increased by decreasing the conductor cross-sectional area, or inductive reactance may be decreased by placing the bars closer to the rotor surface. On the other hand, an increase of conductor resistance will decrease overall motor torque and the stator current drawn during locked-rotor conditions.

"Single-cage rotors," those previously described, are the most rugged and the most used. "Double-cage rotors" use two conductors, one over the other (see Figure 5.27a) per rotor slot and

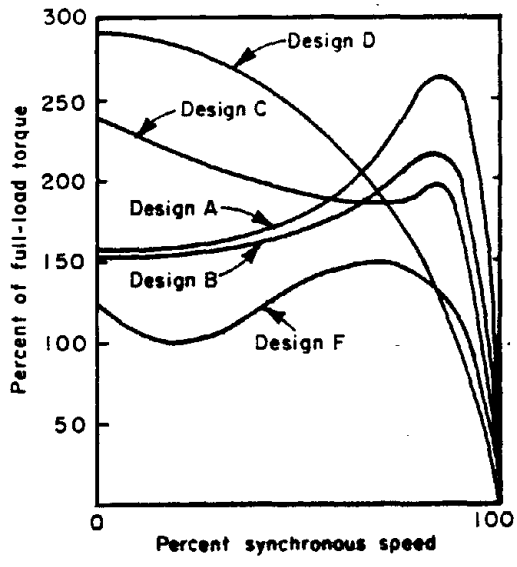


Figure 5.26. Typical Torque-Speed Characteristics for NEMA-Design Three-Phase Squirrel-Cage Motors.

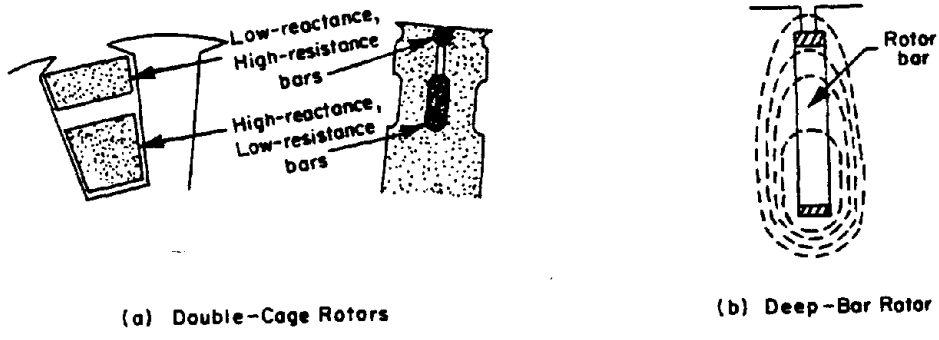


Figure 5.27. Other Rotor-Conductor Designs.

provide higher starting torques with higher load efficiency and lower running slip than the single cages (7). Here, the higher conductor would have high resistance and low reactance, while the lower set would have low resistance and high reactance. Frequently, double-bar rotor conductors are often susceptible to damage on loads with long accelerating times. To overcome the problem, "deep-bar" rotors (Figure 5.27b) can be used. These have a thermal advantage in that the full conductor area is available for heat dissipation, but the design still approximates the performance of the double-bar. Regardless of the design, the torque-speed curves are matched to the squirrel-cage rotor construction, which is fixed for a specific motor.

In addition to rotor-design changes, actual values of breakdown and locked-rotor torque vary with the horsepower, frequency, and speed ratings of the motor.

Although the operating characteristics are a function of rotor impedance, the horsepower rating is mostly dependent upon the power (or kVA) capacity of the stator and rotor windings. As rotor losses are constrained to the rotor cage, rotor thermal capacity is limited. Therefore, motor-designs, which create large rotor currents, such as high-torque high-slip, may have intermittant time ratings (see Section 5.7) or a limited number allowed of successive starts. Unless these constraints are heeded, improper operation will "burn out" the rotor winding.

The different rotor designs have led to a variety of speed-torque characteristics. To distinguish among the various types, NEMA uses a code-letter system that signifies specific rotor constructions (5). Design B serves as the comparison basis for the motor performance of other designs and is often called the "general-purpose" motor. The design has relatively high efficiency even at light loads, and a reasonably high power factor at full load. It has single rotor bars located rather deep in the core but with large-area slots for good heat dissipation. Starting currents range from 4.5 to 5 times the rated (full-load) current. The design B motor has the broadest industrial application field.

Design A has similar characteristics to Design B, except a higher breakdown torque. The rotor conductors are shallower, which decreases rotor reactance but increases the starting current, being 5 to 7 times rated current. Accordingly, Design B motors are often preferred over Design A for large-motor applications. As shown in Figure 5.26, Design-A motors, however, have the best speed regulation, as evidenced by the steep curve portion between synchronous speed and breakdown torque (5).

Design-C motors have a double-cage rotor construction that results in higher locked-rotor torque and lower breakdown torque than the Design B. Starting currents are about 3.5 to 5 times rated current (5). The characteristics are well-suited for

conveyor belt drives and other applications that have sudden large-load increases, but low or normal starting inertia. The motors are not suited for heavy, high-inertia loads because the thermal dissipation is limited and high rotor current tends to concentrate in the upper bars (5). Accordingly, frequent starting of these motors can cause rotor overheating.

Very high locked-rotor and high slip are found with Design-D characteristics. Its principal application field is high-inertia loads. The rotor is of high-resistance design with bars located close to surface (5). Starting currents range from 3 to 8 times rated load current. The motor is suited for heavy-duty starting but again the poor heat dissipation of the rotor design means that starting cannot be frequent.

Design F has lower locked-rotor and breakdown torques than Design B. These motors also use a double-cage rotor with high resistance in both conductors, which reduces both starting and running current (5). The locked-rotor current is the lowest of all motor designs. Thus Design-F motors are applied when starting-current limitations are severe and both starting and maximum-torque requirements are low. The design, however, has poor speed regulation, low overload capacity, and usually low full-load efficiency.

Induction-Motor Starting. From the foregoing it can be seen that if an induction motor is started by directly connecting it to a power system, the momentary starting current can range from 3 to 8 times the full-load current. While this will not damage the motor, the high current can cause a significant disturbance on the power system and in some cases activate overcurrent-protection devices. However, most induction motors in mining applications are started "across the line," especially those within mining machines such as continuous miners. The system usually has enough impedance so protective devices can be set above the in-rush current to prevent nuisance tripping. (This, however, is a major problem and is further discussed in Section 5.7 and Chapter 9.) "Full-voltage" starting can usually be performed on 440-V to 550-V motors up to 1600 hp. NEMA standard magnetic starters for this range are shown in Table 5.3 (2). The "jogging" service listed in the table refers to frequent stop-start or plugging (reversing under load) applications.

As shown in Figure 5.28, the across-the-line starter is simply three contacts driven by a solenoid (also called a "contactor"). Pressing the "start" button energizes the solenoid which closes the M contacts. An auxiliary contact set (M_b) simultaneously closes and bypasses the start switch. Pressing the "stop" button de-energizes the solenoid.

Above 1600 hp (and sometimes lower), full-voltage starting becomes impractical even when the load connected to the motor can withstand the stress. Common methods to start these large

Table 5.3. NEMA Class-A Standard Starters for Three-Phase Induction Motors.

Controller Size	Continuous Current Rating, A	Maximum Horsepower for Normal Service		Maximum Horsepower for Jogging Service	
		220 V	440-550 V	230 V	460-575 V
00	9	1-1/2	2	-	-
0	18	3	5	1-1/2	2
1	27	7-1/2	10	3	5
2	45	15	25	10	15
3	90	30	50	20	30
4	135	50	100	30	60
5	270	100	200	75	150
6	540	200	400	150	300
7	810	300	600	-	-
8	1215	450	900	-	-
9	2250	800	1600	-	-

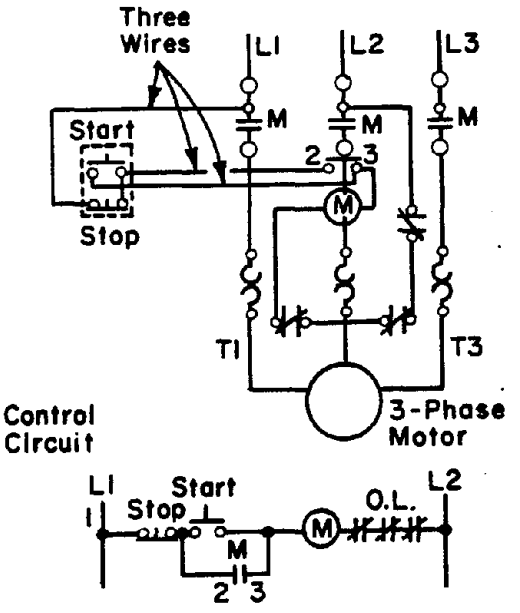


Figure 5.28. An Across-the-Line Magnetic Starter.

induction motors are shown in Figure 5.29. In basic terminology, all these methods can be called "reduced-voltage" starting. In Figure 2.29a, an autotransformer is used to start the motor at reduced voltage (50 to 80% of rated), thus limiting starting current and torque. When almost at full speed, contactors quickly change the motor from the autotransformer to the full-voltage supply. Primary resistor or reactor starting (Figure 5.29b) inserts fixed or variable impedances in series with the motor; these are shorted out after acceleration. For the wye-delta technique (Figure 5.29c), the motor is started as a wye connection, which places about 58% of the rated delta terminal voltage across the windings, limiting line current to 58% and torque to 35%. After acceleration, the motor operation is with a delta connection. Part-winding starting requires that the motor have two identical stator windings (Figure 5.29d). Starting uses only one winding and limits starting current to about 65% of normal torque to 45%. After acceleration, the second winding is switched in.

There are many systems that cannot take the shock of full-voltage starting. One instance is belt-conveyor drives, and the horsepower limit for full-voltage starting here is perhaps as low as 50 hp. The wound-rotor motors described in the next section provide an alternative.

5.5-2 Wound-Rotor Induction Motor

As mentioned earlier, the starting and running characteristics of an induction motor may be adjusted by varying the

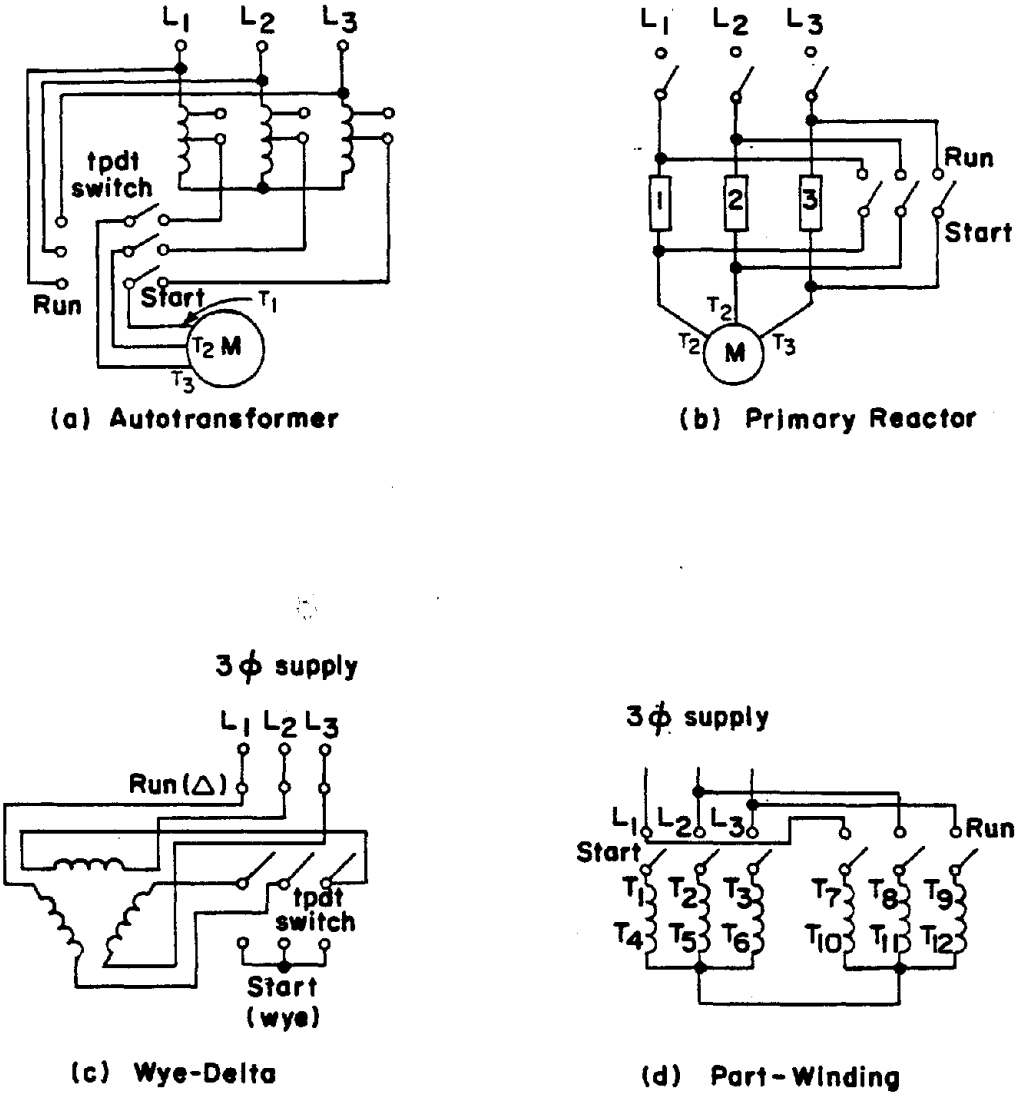


Figure 5.29. Starting Methods for Induction Motors.

resistance-to-reactance ratio of the rotor conductors. Instead of rotor bars and end rings, the wound-rotor motor has insulated windings much like the stator with the same number of poles, and placed in the rotor slots. The windings are usually connected in wye with the ends connected to three slip rings mounted on the rotor shaft. The brush slip-ring circuit is completed through a wye-connected set of variable resistances, as shown in Figure 5.30. Thus the external resistance can be used to vary the speed-torque characteristics (i.e., by changing the rotor R/X ratio). The stator of the motor is the same as for a squirrel-cage machine.

A typical family of wound-rotor-motor characteristics is illustrated in Figure 5.31 (6). As external resistance is increased, the starting current is decreased, and starting torque is increased. For a given shaft load, the reduction in rotor current will result in a speed decrease. Thus when starting a wound-rotor motor, a maximum resistance is inserted in the rotor circuit (R_9 curve). As the rotor accelerates, the resistance is reduced until the desired speed is obtained or, if full-speed is required, the resistance is brought to zero (R_1 curve). Therefore the wound-rotor motor can be considered a variable-speed machine. Thermal considerations do place a lower speed limit and, for self-ventilated motors, continuous rated-torque operation below 70% of rated (full) speed is not recommended (3). This may be reduced to 50% if the motor load is 40% of rated.

Applications for wound-rotor motors include loads that require constant-torque variable-speed drives or where a sequence of slow-speed steps is needed to limit motor current during acceleration, such as for high-inertia or high-torque loads. For the latter reason, these motors have found extensive use in the mining industry to power crushers, grinders, ball and roller mills, belt-conveyor drives, and hoists.

Automatic starting unlike manual control usually uses a definite-time acceleration method, with the controller termed a "step starter." A series of fixed resistances are shorted-out one at a time on a predetermined schedule (8). A simplified schematic of this type of starter is provided in Figure 5.32. When the starting sequence is initiated, all resistors are in series with the rotor winding, then relay contacts 1A, 2A, and 3A are sequentially closed, resulting in four speed-torque characteristics. The last effectively shorts-out the rotor winding. (The actual operation of the relays is discussed in Chapter 8.) As the sequence proceeds regardless of motor speed, the method requires close coordination with motor characteristics (3).

Whether started automatically or manually, the wound-rotor motor continues to find application for the functions previously mentioned. However these motors are quickly being displaced by solid-state-started squirrel-cage induction motors for belt-conveyor drives (see Chapter 12). Reasons for the shift involve maintenance problems and the presence of failures inherent with the brushes, slip rings, and relay contacts.

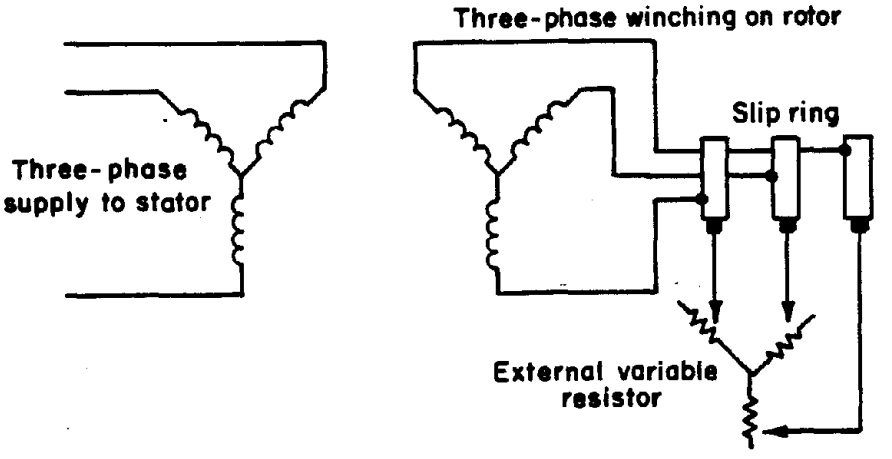


Figure 5.30. Schematic of a Wound-Rotor Induction Motor Showing External Resistance Controller.

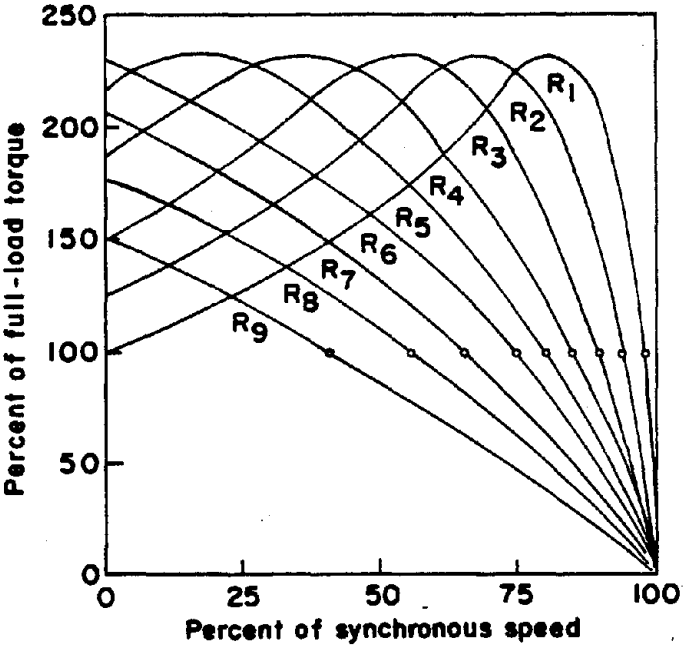


Figure 5.31. Speed-Torque Characteristics for a Wound-Rotor Motor with a Stepped-Resistance Controller.

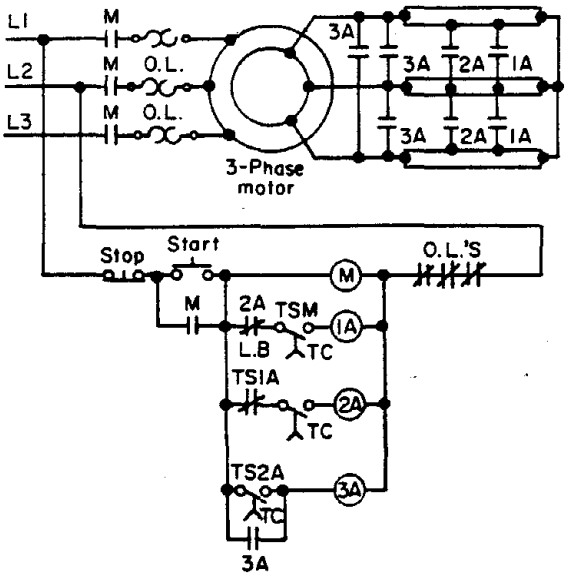


Figure 5.32. A Simplified Step Starter Using Individually-Timed Magnetic Relays.

5.5-3 Three-Phase Synchronous Motors

The three-phase synchronous motor has a stator and rotor and is similar to the induction motor. The stator and stator winding has the same basic construction and purpose, to receive power to drive a load (3). However, the rotor consists of field poles connected in series, parallel, or series-parallel combinations and terminated at slip rings. The field windings are excited by an external d-c source, the "exciter." The number of field-winding poles equals the same number of magnetic poles presented by the stator. A sketch of a typical large synchronous motor is shown in Figure 5.33 (8).

Rotor-field excitation is usually supplied from a small d-c generator which is mounted on the same rotor shaft, as diagrammed in Figure 5.34. Otherwise, d-c supply can be obtained from a three-phase full-wave bridge rectifier, as illustrated in Figure 5.35, or even a separate M-G set.

Pure synchronous motors are not self-starting and are generally accelerated as induction motors. Salient-pole rotors commonly have a squirrel-cage winding (see Figure 5.33) to produce the necessary induction-motor action. "Low-speed cylindrical" rotors closely resemble a wound-rotor induction motor, but with five slip rings (3). As the diagram in Figure 5.36 illustrates, three rings are used for a wound-rotor circuit, the other two for the d-c field (5). These cylindrical-rotor motors can provide high starting torque to accelerate high-inertia loads. The use of

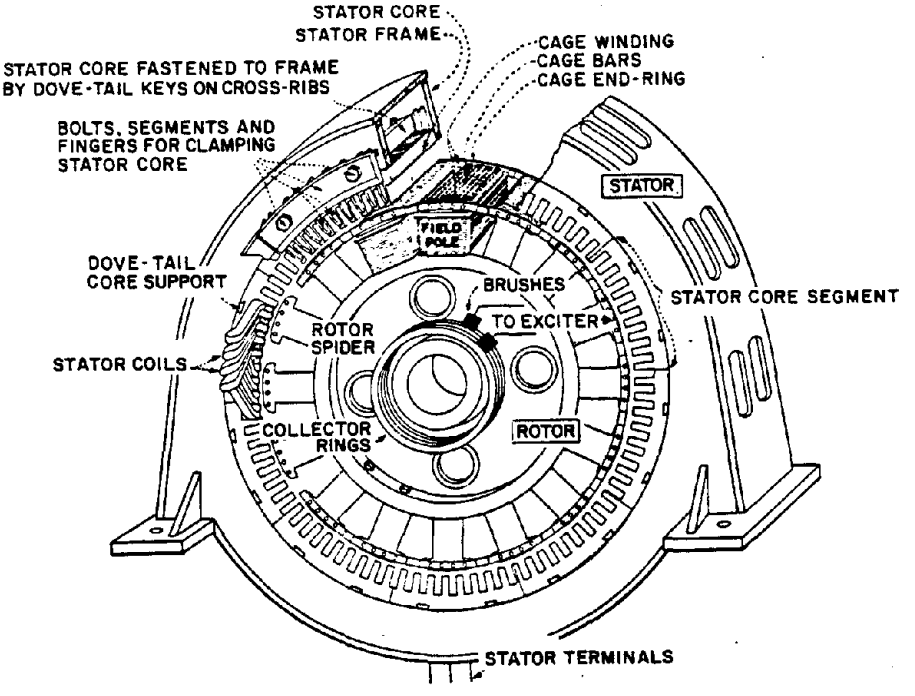


Figure 5.33. A Sketch Relating the Construction of a Salient-Pole Synchronous Motor.

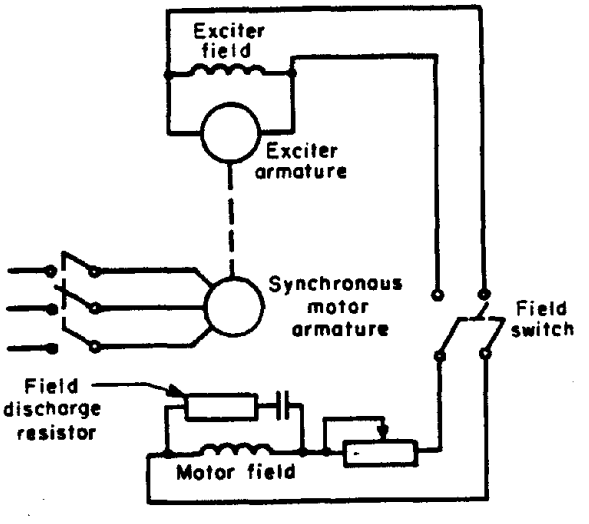


Figure 5.34. Simplified Diagram of a Synchronous Motor Using a Generator for Field Excitation.

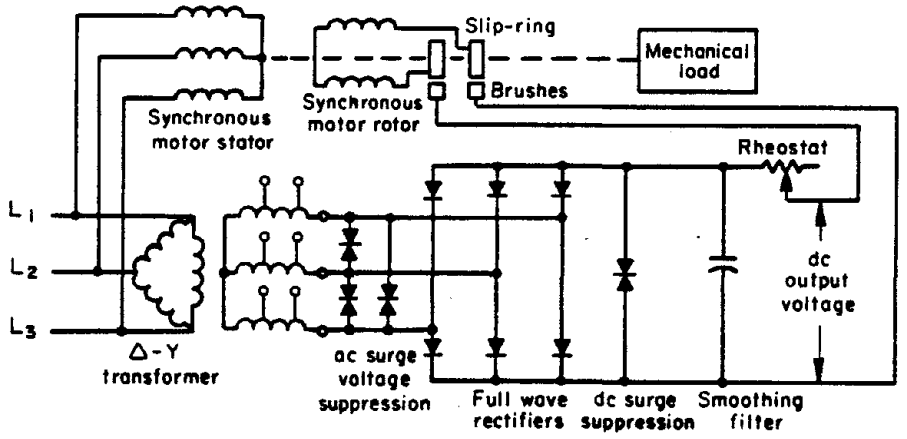


Figure 5.35. External Solid-State Supply Used to Provide Field Excitation.

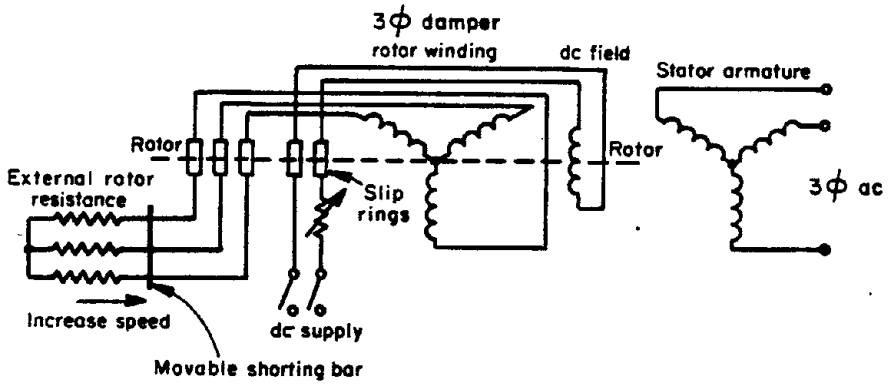


Figure 5.36. Schematic of a Low-Speed Cylindrical-Rotor Synchronous Motor.

squirrel-cage windings, however, is only intended to accelerate the motor rotor, not specifically to develop induction-motor torque to external loads. Some large synchronous motors are accelerated by a small induction motor mounted on the synchronous-motor shaft (8). The induction motor must have fewer stator poles than the synchronous so the required speed may be reached.

Starting. Figure 5.37 can be used to demonstrate the general method of starting a synchronous motor (8). Pressing the "start" button energizes the "CR" relay, which in turn closes the CR contacts. One set electrically locks-in the start sequence (can be terminated by pressing the "stop" button), and the other set energizes the "M" relay. The M contacts close, and three-phase power is applied to the stator winding. This allows the machine to accelerate as an induction motor. For the most simple procedure, the motor could be allowed to accelerate to maximum induction speed (such would be applicable for the motor shown in Figure 5.33). At this speed, the slip between the stator rotating field and the rotor would be very small. A switch could then be manually closed, as in Figures 5.34 and 5.36, to apply d-c to the rotor field winding. A steady rotor magnetic field is thus established and can lock in step with the rotating field of the stator. Therefore, the rotor will turn at synchronous speed (this is where these motors obviously receive their name). However, if the d-c is applied before maximum induction speed, the rotor may not "pull in" to synchronization, and severe vibration can occur (caused by a repulsion action every time a rotating pole passes a stator pole). Accordingly, most synchronous-motor starters do not rely on manual control and, instead automatically excite the rotor field at the appropriate time.

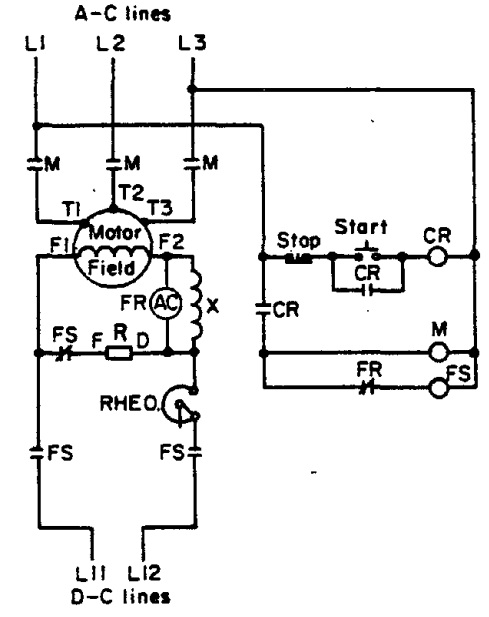


Figure 5.37. Simplified Controller Used to Demonstrate General Starting Method of a Synchronous Motor.

A widely-used approach to automatic starting is "synchronization based on frequency" (8). The technique uses the voltage induced in the field winding during acceleration and before the d-c is applied (9). Again, referring to Figure 5.37, a resistor (R) and inductor (X) are placed across the field winding, with relay "FR" across the inductor. The inductance of the relay coil is selected to be much lower than that of X. Immediately after starting commences, a high-frequency potential is induced in the field winding, and the majority of current flows through the resistor and the relay coil, because the inductance, X, exhibits high reactance. The relay opens the FR contacts faster than the interlock-contact M_b of relay M closes. As the motor accelerates, the frequency of the induced current decreases. When close to synchronous speed, the frequency has decreased to the point where most current flows through the inductor, and the voltage is reduced to the point where the FR relay cannot hold its contacts open. Thus, the contacts close and energize relay FS. The FS contacts then pick up to apply d-c excitation to the field winding and remove the resistor from the circuit.

Motor Torque. Under loading, the synchronous motor behaves much like a nonslip direct magnetic coupling. The rotor does not develop induction-motor torque; it is magnetically locked to the stator rotating field and is pulled around at basically the same speed. The torque developed is dependent on the "hold-in" pole strength. Hence, the lock-in torque may be increased by simply increasing the d-c supplied to the rotor field winding. If a load change occurs, an instantaneous speed change happens but only for a few cycles; after which the rotor again attains synchronism (8). The use of a squirrel-cage rotor winding also helps to dampen-out speed changes and, therefore, is often called a "damper" winding.

A typical speed-torque characteristic for a synchronous motor containing a damper winding is shown in Figure 5.38. Because the synchronous-motor portion cannot start itself, the starting torque results from the damper winding. With external loading not exceeding the "pull-in" torque value, the motor can be started and accelerated to synchronous speed. Now, consider that no significant external load exists and a load equal to the pull-in torque is applied. The rotor will momentarily drop to about 95% of full speed then regain synchronism. With the loading and the momentary drop in speed, the rotor assumes a new position, continuing to rotate at synchronous speed but a few degrees behind the no-load position (α in Figure 5.39)(1). Such can occur for any applied load up to the "synchronous" torque level, above which the restoration of synchronous speed is questionable. If the load requirements exceed the "pull-out" torque, the motor loses synchronism, average torque drops to zero, and the motor stops (8).

Counter EMF. After excitation has been applied to the field winding, the revolving magnetic field of the rotor cuts the stator

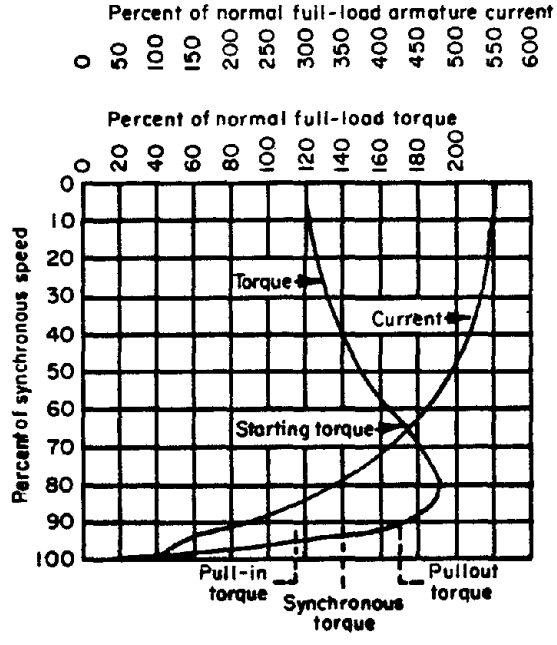


Figure 5.38. A Typical Speed-Torque Characteristic for a Synchronous Motor with a Damper Winding.

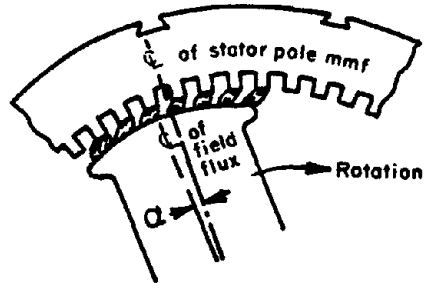


Figure 5.39. Effect of Load on Rotor Position.

conductors and induces a voltage in opposition to the applied voltage. Figure 5.40a shows an equivalent per-phase circuit of a synchronous motor that can be used to show the effect that counter emf (cemf or generated voltage) has on the electrical performance of the machine. From Kirchhoff's voltage law (6):

$$\bar{V}_T = \bar{V}_c + \bar{I}R_e + j\bar{I}X_L = \bar{V}_c + \bar{V}_{XR} \qquad (5.11)$$

where,

$\bar{I}R_e$ = the voltage drop due to effective resistance of the armature (stator) winding (V)

$\bar{I}X_L$ = the voltage drop due to the inductive reactance of the armature winding (V)

$\bar{V}_T$ = the voltage supplied to the motor (V)

$\bar{V}_c$ = the cemf produced by the field winding which has been modified by armature reaction (V).

At first hand, two important phenomena connected with synchronous machines (and in some others as well) are evident in the equation. Under dynamic loading conditions, if the load delivers a torque to the motor shaft, the motor produces or regenerates a cemf that

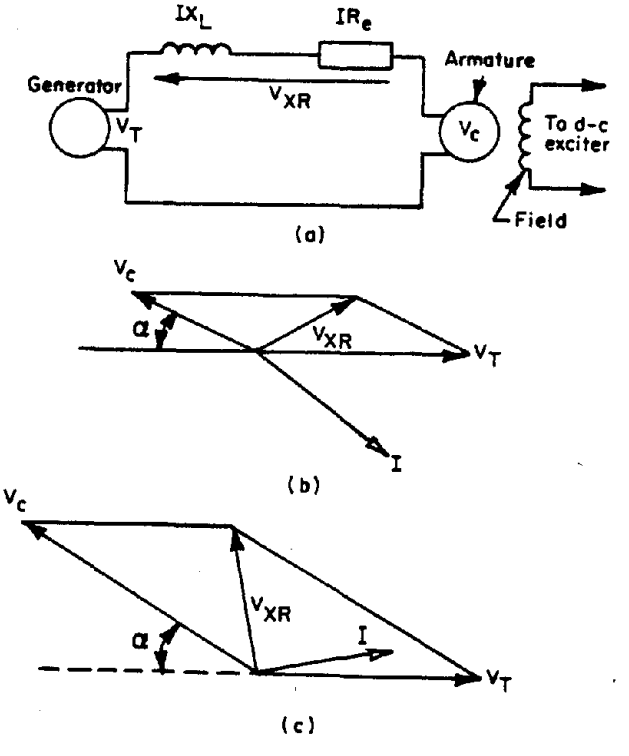


Figure 5.40. Equivalent Per-Phase Circuit of a Synchronous Motor and Phasor Diagrams for (b) Underexcited and (c) Overexcited Field Winding.

is greater than that of the supply, and power can be delivered back into the line. Next, if the supply voltage is removed, the load then acts as a "prime mover," and $\overline{V}_c$ will be generated as long as field excitation exists and until the load dissipates its energy. This last phenomenon is especially important when the supply voltage is lost due to a short circuit, as the synchronous motor can deliver significant current to the malfunction (see Chapter 9 for further information).

Power Factor. Another important effect occurs because of the cemf production. In an ideal synchronous motor under no-load conditions, $\overline{V}_c$ can be equal in magnitude and frequency to $\overline{V}_t$ but 180° out of phase. Hence, with this ideal situation, the motor does not draw current ($\overline{I}$). Obviously, practical motors have losses, for example, windage and friction, and these cause a small shift in angular position, α, between the rotor and the rotating magnetic field. Here, the phasors $\overline{V}_c$ and $\overline{V}_T$ are no longer opposite in position, $\overline{V}_c$ being shifted clockwise by α, as shown in Figure 5.40b. The change causes the motor to draw line current ($\overline{I}$) to maintain the load. Under heavier loading, α increases, and the motor draws more current. (Note: The rotor field actually does no work, and the d-c energy supplied to maintain the field is dissipated as a small I^2R heat loss.)

A change in the rotor field strength, say by adjusting the resistance in Figure 5.34, 5.35, or 5.36, changes the magnitude of $\overline{V}_c$, but not its angular position. The difference between $\overline{V}_T$ and $\overline{V}_c$, or $\overline{V}_{XR}$ in Figure 5.40, determines the angular position of motor current. When $\overline{V}_c$ is adjusted to produce a motor current that lags applied voltage (Figure 5.40b), the motor is said to be "underexcited." However, increasing the d-c field strength with the same shaft load can shift $\overline{V}_{XR}$ such that the reactive component of current will change from a lagging phase angle to leading (Figure 5.40c). In this condition, the rotor field is termed "overexcited," and the motor appears as a capacitive load. The leading power factor is one of the most outstanding features of a synchronous motor, as it can be used for power-factor correction. The ability to operate at unity power factor should be obvious; the field winding is referred to as "normally excited" in this case.

Because the phase angle of operation depends upon both field excitation and motor load (angle α), the characteristics of synchronous motors are often represented graphically in a form called "V" curves. Illustrated in Figure 5.41, they allow selecting a field-excitation current for a load to produce a desired power factor (5). The lines drawn to show equal power factor are termed "compounding" curves (8).

Applications. In the past, synchronous motors had wide use in the mining industry to take advantage of their constant speed and available leading power factors. Applications included ventilation fans, pumps, compressors, grinders, mills, and drive motors

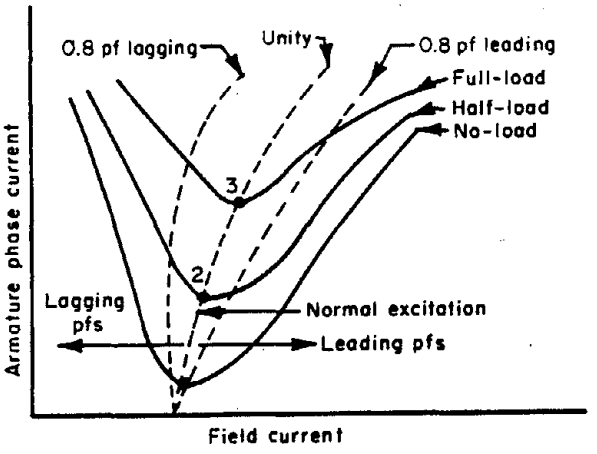


Figure 5.41. "V" Curves for a Synchronous Motor.

on M-G sets to provide power for d-c equipment. Because of their flexibility and ease of utilization, static capacitors have replaced motors for power-factor-improvement reasons in almost all situations, and silicon rectifiers have supplanted M-G sets for power conversion. In this last area, however, a very important use of synchronous motors remains today, as the main drive motor in surface excavators. Here, one or more motors directly drive d-c generators, which in turn power the d-c motors serving the various functions on the machine. Figure 5.42 provides a plan view of a typical mining shovel where one synchronous motor drives three d-c generators and the motor exciter (10). This subject will be continued at the end of the next chapter section.

5.6 Direct-Current Motors

5.6.1 Background

The d-c motor is the most versatile of all electrical machinery. One advantage over all the preceding motors is that its speed may be easily adjusted. Until the 1940's, they accounted for the majority of motors within the mine. At that time, a-c distribution systems started to replace d-c, and d-c motors were replaced with induction machines, mainly because a-c/d-c conversion of reasonably large power quantities was cumbersome. Direct-current motors, however, continued to hold prominence for some specific loads. In recent years, because a-c to d-c conversion is now very easily done, these motors have replaced some of their induction counterparts. The reasons behind the extensive use of some d-c motors in mining will become apparent in the following paragraphs.

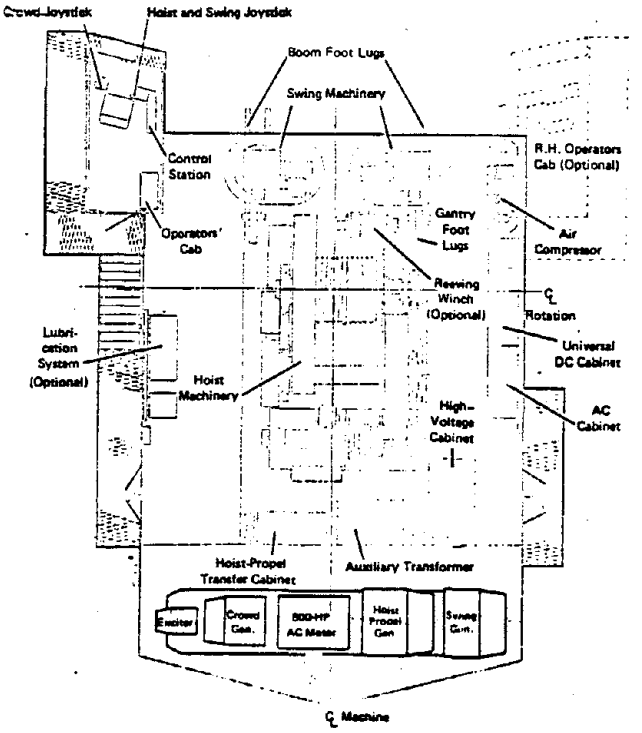


Figure 5.42. A Plan View of a Typical Mining Shovel Showing Motor-Generator Set.

Elementary Motor. Figure 5.43 illustrates an elementary two-pole d-c motor with a one-coil armature. With the armature current flow as shown, the reaction of the armature magnetic field with that of the main field produces forces on conductors A and B, and the torque results in clockwise rotation. The commutator acts as a switch to reverse armature current each time the conductors pass the neutral plane. To reverse armature rotation simply requires reversing the armature-current flow.

The two-pole motor is rather impractical. Torque is maximum when the plane of the armature conductors are parallel to the plane of the field, zero when at right angles (Figure 5.43b). Figure 5.44a shows a four-pole armature, with a four-segment commutator, but still with a two-pole main field. Here, motor torque does not drop to zero, because an armature conductor is always under the magnetic influence of the main field. Actual d-c industrial motors have many commutator segments, armature conductors, and main field poles. The result is nearly constant torque output.

As with the synchronous motor, the d-c motor field does not do useful work. It merely provides the necessary medium for the armature windings to push against when developing rotary motion. In all but the very smallest machines, the field is supplied by d-c through field windings. The energy expended in these windings forms an I^2R heat loss.

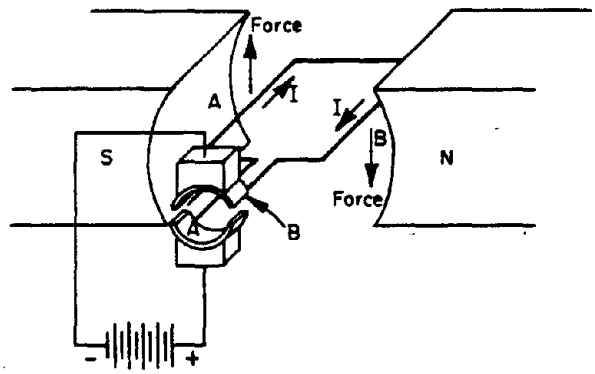


Figure 5.43. An Elementary Two-Pole Direct-Current Motor.

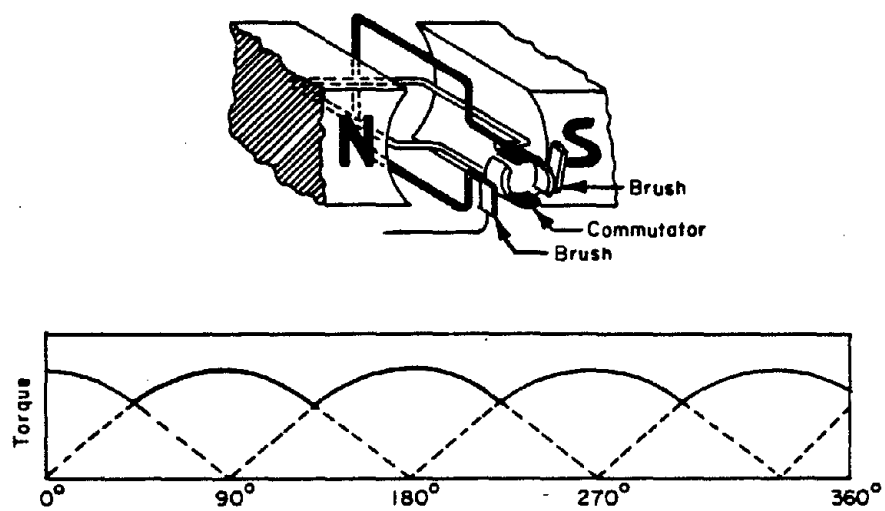


Figure 5.44. An Elementary Four-Pole Direct-Current Motor.

Motor Construction. The essential motor parts are the armature (rotor), the commutator, and the main field frame and windings (stator). The armature is constructed of steel laminations pressed onto the shaft, with slots parallel to the shaft. The armature windings are placed in the slots and connected to the segments of the commutator, which is located at one shaft end. Carbon brushes mounted on (but insulated from) the motor frame or one end bell ride on the commutator segments. The main field windings surround laminated pole pieces that are bolted around the periphery of the motor frame.

"Interpoles" (or "commutating poles") are mounted between the field poles (see Figure 5.45), and the windings are connected in series with the armature (8). Their purpose is to improve commutation by opposing "armature reaction," the distortion of the main magnetic field by the rotating armature field (Figure 5.46). The interpole windings produce a small magnetic field that opposes the main field in the same plane as the brushes. This reduces the magnetic field that is cut by the armature conductors undergoing commutation (current reversal) and thus, reduces brush sparking (2).

The armature reaction can be further neutralized through the use of "compensating" (or "stabilizing") windings (8). These are placed in slots on the end of the main-field poles next to the armature (Figure 5.45) and are again connected in series with the armature. These are especially useful in motors intended for variable-speed or reversing operation. Without the compensation, armature reaction from large loads can neutralize the main field flux (8).

Although interpole and compensating windings serve valuable functions in d-c motor operations, the machines can work without them. As they also can cloud the presentation of motor operation, these windings will not be included in the following discussion.

Torque. The torque developed by any electric motor, of course, is a measure of its ability to pull against a load. In d-c motors, torque is a function of armature current and the magnetic-flux density of the main field or (5):

$$T = K\Phi I_a \qquad (5.12)$$

in which

T = the motor torque (N-m, times 0.738 equals lb-ft)

Φ = the magnetic flux per main field pole linking the conductors (Wb)

I_a = the total armature current (A)

K = a proportionality constant (N-m/Wb-A).

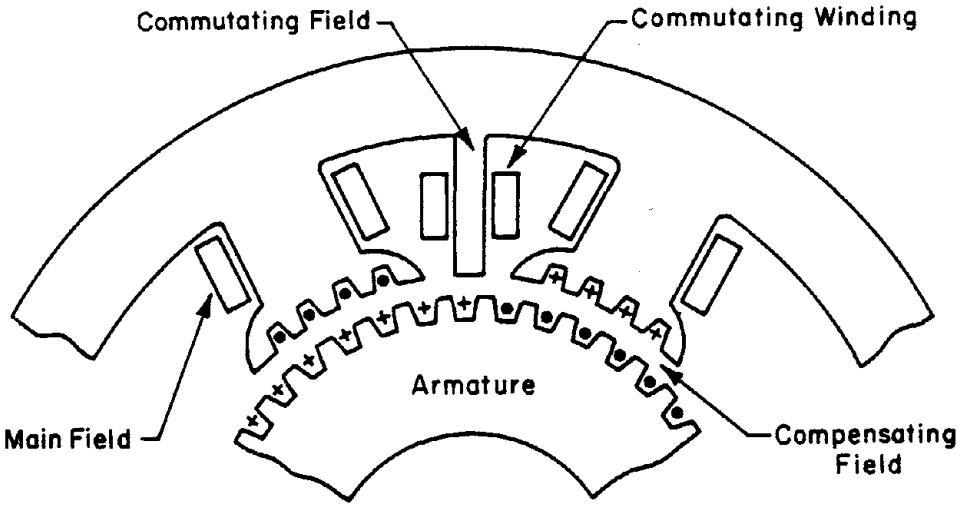


Figure 5.45. Cross-Sectional Sketch of a Direct-Current Motor Showing Interpole and Compensating Windings.

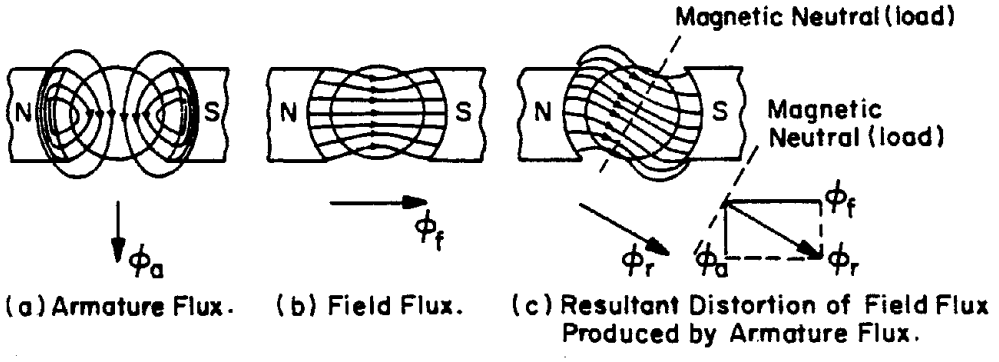


Figure 5.46. Interaction Between Armature and Main Field Flux to Produce Main-Field Distortion.

where,

$$K = \frac{T_{rated}}{(I_{A\ rated})(\Phi_{rated})}$$

T_{rated}, $I_{A\ rated}$, Φ_{rated} = the rated value for torque, armature current, and flux for the motor.

The above equation can be used to find the torque output from a machine if the rated torque and the changes in armature current and the field flux are known.

5.6-2 Motor Connections and Performance

Exactly like d-c generators, d-c motors can be connected as separately excited, shunt, series, and compound. These are again shown in Figure 5.47. The performance of a separately excited motor is similar to the shunt, and its importance in mining applications is primarily with regard to motor control. Thus, this motor will be discussed later. The speed-torque characteristics of shunt, series, and compound motors can drastically change depending on the connection. Typical curves are illustrated in Figure 5.48 (5).

Shunt Motor. The shunt motor has the main field winding connected in parallel with the armature (Figure 5.47b). Because the field winding is connected across the supply, its resistance must be rather high, but the armature windings through the constraint of space have a much smaller resistance. When the motor is energized, armature current, I_a, is only limited by its winding resistance and is thus much higher than field-winding current, I_f. However, as soon as the armature starts rotation, its conductors cut the main-field magnetic flux, and a contour emf is generated in the windings. This cemf opposes the applied armature voltage and begins to limit armature current. The opposition to current flow can be seen by applying Kirchhoff's voltage law to Figure 5.47b:

$$V_T = V_c + I_a R_a \qquad (5.13)$$

where,

V_T = the supply voltage (V)

V_c = the cemf induced in the armature winding (V)

I_a, R_a = armature current (A) and resistance (Ω).

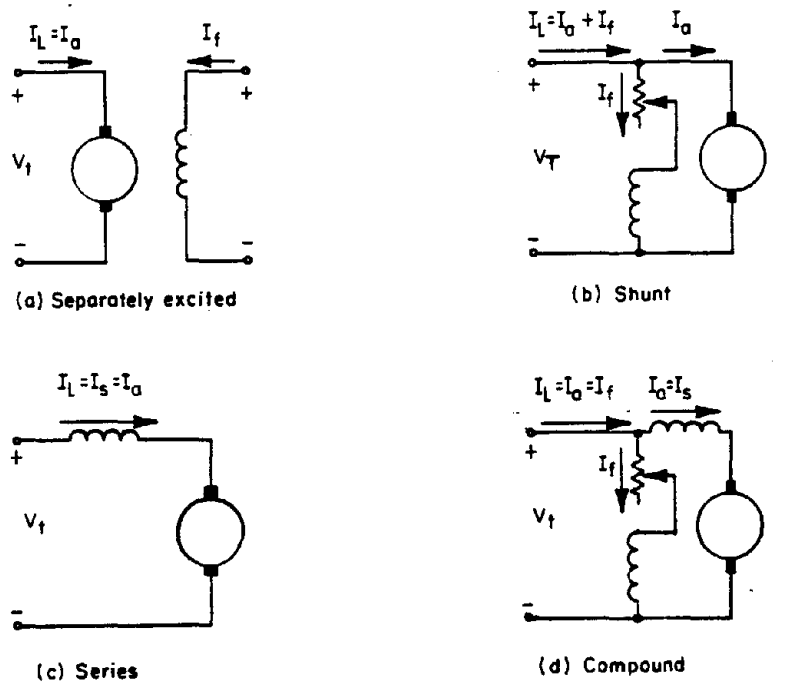


Figure 5.47. The Four Connections for Direct-Current Motors.

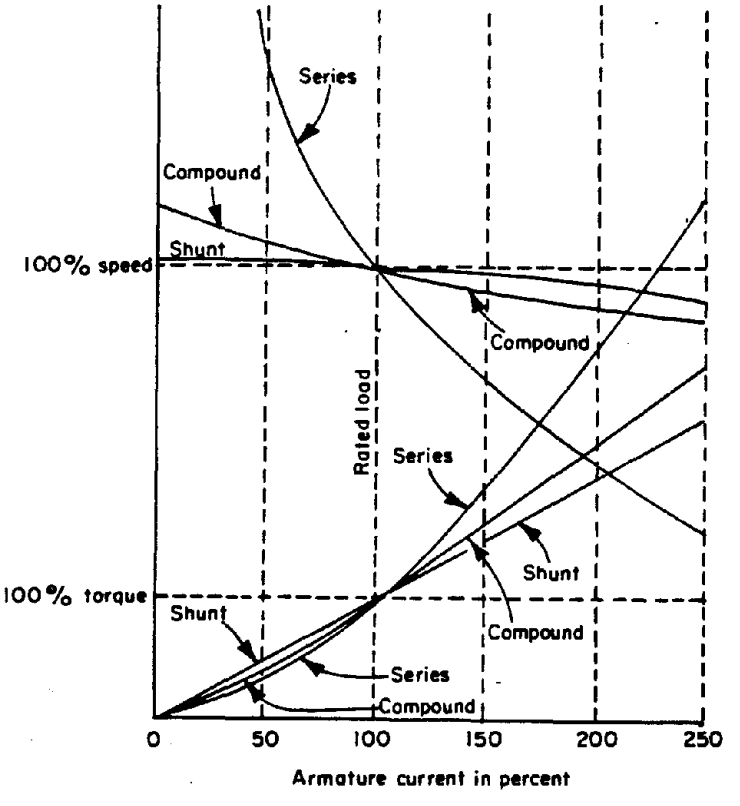


Figure 5.48. Typical Characteristics for Shunt, Series, and Compound Motor of Equal Horsepower and Speed Ratings.

The cemf is proportional to the speed of the armature, or

$$V_c \propto n\Phi \qquad (5.14)$$

in which

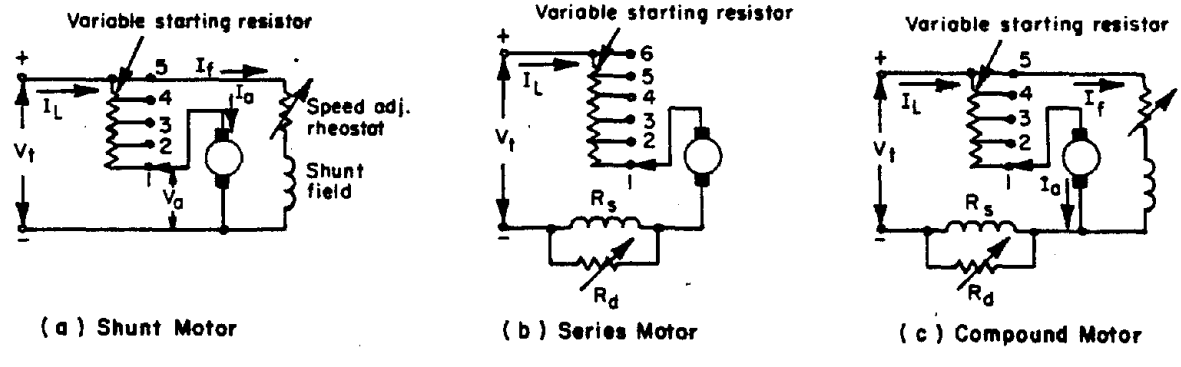
n = the armature speed (rpm)

Φ = magnetic flux per main field pole (Wb).

Thus, as the armature accelerates, the cemf rises, and the armature current drops. Yet according to equation 5.12, motor torque decreases. A final speed is reached when the cemf is almost equal in magnitude to the supply voltage.

If the motor is unloaded, the difference would only allow enough armature current to overcome friction, windage, and core losses. Under motor loading the armature slows down, cemf decreases, and more current enters the armature. However, as shown in Figure 5.48, the speed of the shunt motor remains relatively constant from no-load conditions up to 100% rated and slightly beyond. The speed can be easily adjusted by changing a resistance in series with the field winding. From equation 5.14, weakening the field flux by decreasing field current increases motor speed. Yet for a constant field flux, torque varies linearly with the armature current (i.e., $T \propto I_a$).

If across-the-line starting was attempted with the shunt motor shown in Figure 5.47, the cemf will likely not build-up fast enough to limit armature current to a safe valve. Otherwise, damage to the commutator, brushes, and the armature winding may result. For this reason, a "starting" resistance is used in series with the armature (see Figure 5.49a) for all d-c motors except those of fractional horsepowers.



(a) Shunt Motor (b) Series Motor (c) Compound Motor

Figure 5.49. Simplified Direct-Current-Motor Schematics with Starting Resistance.

The resistance is usually selected to limit armature current from 150 to 250% of rated current depending on the starting torque required. The shunt winding is always connected across full-line voltage when starting so less armature current is needed to develop the rated torque.

Manual controllers are found on many d-c machines in mining. These are available in three general forms: face-plate, multiple-switch, and drum controllers. Schematics for these are shown in Figures 5.50, 5.51, and 5.52.

The "face-plate" starters are often used with stationary d-c motors of small size. The level is advanced (to the right) in steps, momentarily stopping at each position to allow the motor to accelerate, until the resistance is removed. A holding-coil then maintains the lever in the last position. A spring is used to return the lever to the off position during a power failure or if the lever is left in an intermediate position.

One method of "multiple-switch" starting is shown in Figure 5.51, and uses two double-pole single-throw switches. The upper switch is closed first, energizing the shunt field through a 100-Ω resistor. This allows the main-field flux to build up to some extent before the armature is connected to the line. Initial in-rush current is thus reduced and helps prevent brush-arcing and the possibility of commutator flash-over. The lower switch is then closed, energizing the armature through a second resistor, and the motor accelerates. The armature resistor remains connected during running. The two line switches are mechanically interlocked so the upper switch must always be closed first. (A variation of this technique is to use relay contacts (or contactors) to supply main-field excitation, insert the starting resistance, then bypass the resistance.)

"Drum controllers" (Figure 5.52) are frequently used on mine locomotives but are also found on some d-c mining machines. A handle-controlled rotary shaft is connected to the switch segments (dark lines) shown. These segments are of various lengths so contact with the stationary contacts can be made at different intervals. For starting, the M1 and M2 contacts engage first, energizing the shunt field and inserting all resistors in series with the armature. Advancing the controller then removes the resistors one at a time. Although not shown, an additional drum or "reversing" controller is usually available to reverse armature current and thus motor direction.

The use of "fixed-resistance" starting has widespread application in mining. (The starting resistance remains in series with the armature for running.) An instance would be a small d-c motor, such as a pump, in a remote location. The resistance gives poor speed regulation, but the motor can be started unattended.

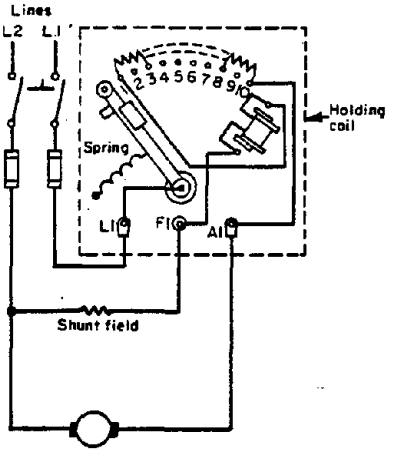


Figure 5.50. A Face-Plate Manual Starter.

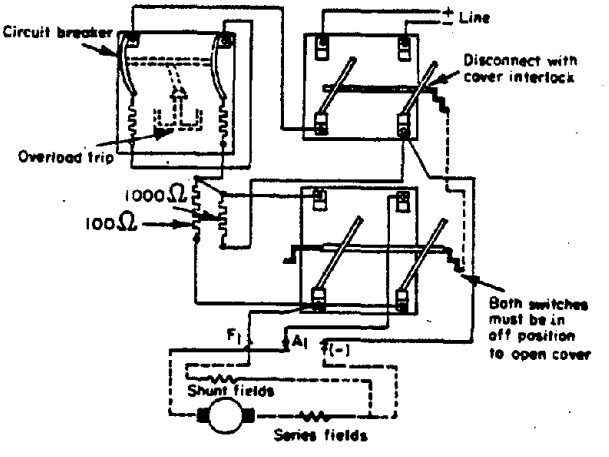


Figure 5.51. Multiple-Switch Starting.

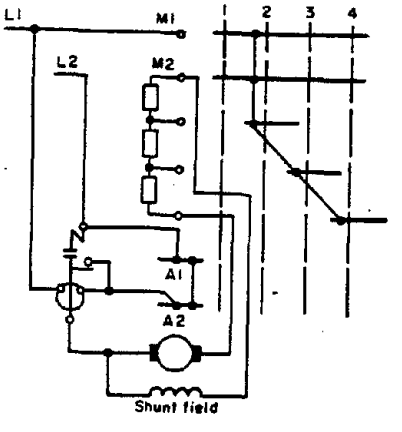


Figure 5.52. A Drum-Type Starter.

Dynamic Braking. If a shunt motor is running under load and the armature circuit is opened, the inertia of that load will drive the machine as a d-c generator. "Dynamic braking" simply connects a resistance across the armature to dissipate the available energy and decelerate the load (see Figure 5.53). The braking action is most effective at high armature speeds, becoming negligible at low speeds. The value of resistance, R, is selected from (8):

$$R = \frac{V_c - I_a R_a}{I} \qquad (5.15)$$

where,

$V_c - I_a R_a$ = the armature voltage at the start of the braking (V)

I = the dynamic braking current, depending upon the desired braking level (A).

The normal value for I is 150% of rated motor current, but may be as high as 300% for quick stopping.

Series Motor. The armature and main-field winding are connected in series and both carry load current in a series motor. The magnetic flux, Φ, now produced in the main-field winding is proportional to the armature current. Thus motor torque varies as the square of armature current ($T \propto I_a^2$). Furthermore, the main-field strength will change with load, causing a speed decrease with increased load.

In starting a series motor, cemf builds up (as before) as the armature speed increases. During the initial acceleration,

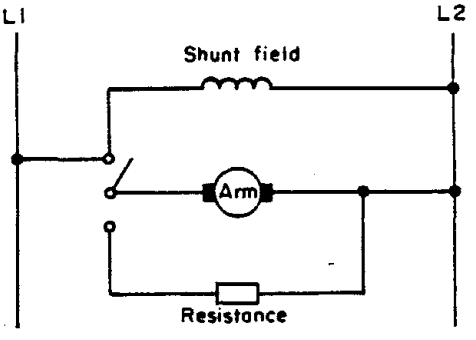


Figure 5.53. A Simplified Diagram of Dynamic Braking Applied to a Shunt Motor.

the cemf is small, armature and field current are high, and the torque is very high. When comparing the curves in Figure 5.48 and the material presented earlier, the starting torque of the series-wound motor is higher than any other motor type. Because of this, it is often said that the series machine has the best traction (or starting) characteristics. Thus, it is the most used motor for traction purposes in mining; examples include locomotives, shuttle cars, and surface diesel-electric trucks. A problem, however, with this motor is that at light loads, motor speeds may become excessively high. Therefore, series motors must be direct-connected to loads which cannot be removed freely; otherwise, the motor may race to destruction.

Starting the series motor is similar to that for shunt machines. The arrangement of the starting resistance is shown in Figure 5.49b. A direct application of contactor-controlled multi-switch starting of a mining-machine traction motor is illustrated in Figure 5.54 (11). After the power-source contacts, M1, close, the motor is accelerated with both resistances in series with the armature. The same control that activated the M1 contacts simultaneously energizes a definite-time relay. This relay after a preset time (about 1.0 s) closes its contacts which energizes the M6 contactor, shunting its starting resistor. The M7 contacts could be used to provide a second step before full-speed is obtained, or could be used to enable two-speed operation of the motor. In the latter case, control circuitry is arranged so the M7 contacts cannot close before the M6 contacts. Figure 5.55 shows a one-step starting arrangement with the addition of forward-reverse control (contacts 1F and 2F close for forward, 1R and 2R for reverse) (11).

Dynamic braking is an identical procedure to that already described, with the exception of excitation for the main field. The simplified circuit in Figure 5.56 is one approach (switches are closed for motoring) (8). Upon dynamic braking the switches place the armature, series field, and braking resistance in a loop circuit. The series-field connections are reversed to maintain current flow in the same direction.

Compound Motors. Compound motors utilize both shunt and series field windings installed on the same poles. The series winding may be "differentially" or "cumulatively" compounded, subtracting or adding from the magnetizing force of the shunt field. Respectively, this causes reduced or increased armature speed with load. Only the cumulative compound motor characteristics are shown in Figure 5.48.

Cumulative compounding gives greater torque than is possible with the simple shunt motor, due to the greater amount of main-field flux available (5). The increased flux, however, causes the speed to drop off more rapidly than for a shunt motor, but not as much as for a series motor. Therefore, the cumulative-compound motor will develop a high torque with any sudden increase in load but, at light loads, it will not run away because the

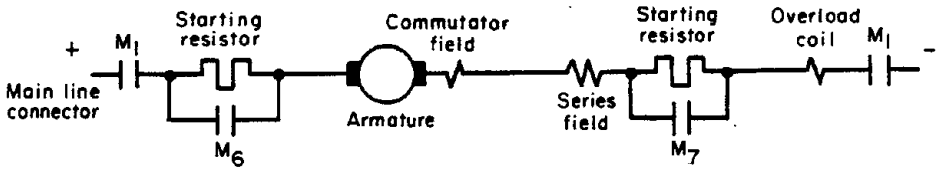


Figure 5.54. Two-Step Resistance Starting of a Series-Wound Motor.

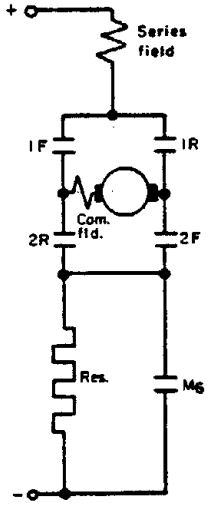


Figure 5.55. Forward-Reverse Switching of a Series-Wound Motor.

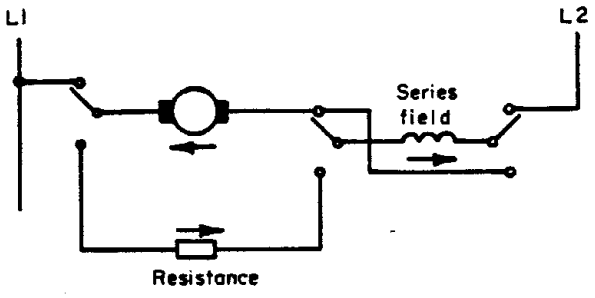


Figure 5.56. Dynamic Braking Applied to a Series-Wound Motor.

shunt field provides a constant field flux. These motors are often applied to loads requiring high starting torque, but fairly constant operating speed under normal conditions. Thus, cumulative compounding combines the characteristics of both series and shunt motors.

The differential-compound motor produces torque which is always lower than the shunt motor (5). The amount of series winding can be adjusted to offset any drop in speed as loading increases, or it may be sufficient to give a slightly higher speed than normal speed at full load. A motor having constant speed from full load to no load is termed "flat-compounded," while that with slightly higher speed than normal is called "over-compounded."

Again, armature current is limited traditionally by resistance when starting. Figure 5.49c shows the process in elementary form, but Figure 5.57a illustrates an actual application for a mining-machine hydraulic-pump motor (11). It can be seen that two circuits are almost identical. Here, however, fixed starting resistor is used for acceleration and, as in Figure 5.54, the resistor is shunted by the M3 contacts after a definite time period (usually 1.0 s). A semi-automatic variation of this scheme is illustrated in Figure 5.57b. ("Semi-automatic" means that under certain conditions, the starter requires some attention.) The accelerating contacts (A) are as before, but the contactor coil is placed across the armature circuit. As cemf increases during acceleration, the voltage across the coil causes contact closure at the proper time.

Dynamic braking employs a resistance to dissipate energy generated in the armature, either involving the series field (like Figure 5.56) or simply the armature itself (Figure 5.53).

Ward-Leonard System. For large-motor applications, the Ward-Leonard system provides one of the finest techniques for

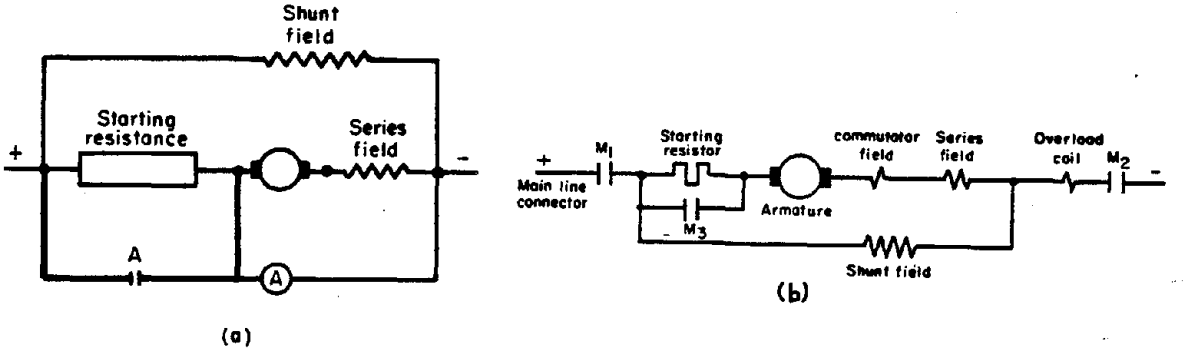


Figure 5.57. One-Step Starting of a Compound-Wound Motor.

controlling motor speed over a wide range and in both rotational directions (2). Two specific examples are mine hoists and surface excavators (12,13). Figure 5.58 illustrates the basic system. The d-c generator is driven at constant speed, typically by a synchronous motor. Some systems employ induction-motor drives, but usually in smaller horsepower applications. The generator and motor field windings are separately excited (see exciter in Figure 5.42); the motor has a constant field current.

Because the main field of the motor is constant, the speed is directly proportional to its armature cemf (V_m). The magnitude of V_m is directly dependent upon the generator output voltage (V_g) less i_aR_a, i_a being the armature current and R_a being the combined resistances of the generator and motor armatures. Therefore, excellent control of all motor speeds, and both accelerations and decelerations, is obtained by adjusting the generator field strength. The generator field-winding resistance is high so the required level of control power is relatively low. Motor reversing is obtained by changing the current direction in the generator field. Braking is performed by reversing or reducing the generator-field current.

5.7 Mine Motors

5.7-1 Face Motors

Many uses for industrial motors in mining have been covered so far in the chapter. This section serves to clarify some additional applications but mostly for underground mining equipment.

Mine-motor functions can usually be divided into two groups: auxiliary and face (4). Auxiliary motors are employed for fans, pumps, conveyors, hoists, compressors, and other vital functions for mines set aside from the actual process of mineral extraction. These operations commonly call for direct application of general

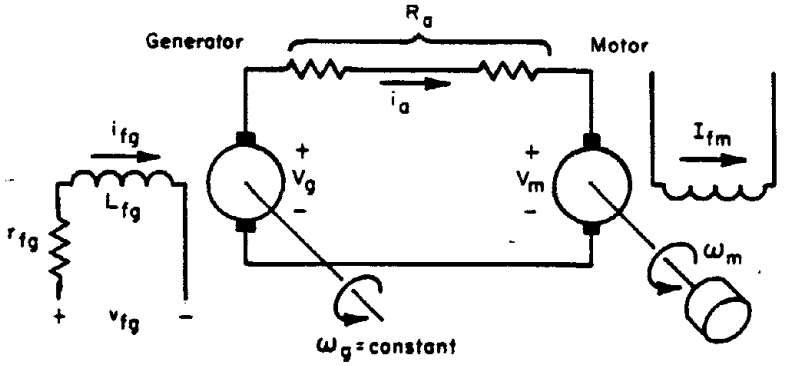


Figure 5.58. A Basic Ward-Leonard System.

purpose industrial motors, and their load is often well-defined and continuous. Thus the motor characteristics covered so far are applicable. Face motors, however, are associated with mining equipment, such as continuous miners, shuttle cars, loaders, roof bolters, locomotives, and so forth. They are mounted in the machine, and their duty usually involves cyclic or random loading as well as the possibility of shock loading. The result is higher electrical and mechanical demands than are placed on equipment in other industrial applications.

The horsepower rating for a motor is based on a maximum winding temperature for a continuous duty or intermittent duty. The temperature-rise parameters have already been covered, but the meaning of a duty cycle has not. "Continuous duty" is quite obvious and refers to a substantially-constant load (torque) over an indefinitely-long period. "Intermittent duty," however, means that loading is at alternate intervals of load and no load (motor running idle); load and off; or load, no load, then off (1). Each portion of the cycle is equal with the time interval specified. In some cases, face-motor intermittent duty is given a definite time interval of 15, 30, or 60 minutes, but it is often just listed as "mine duty" (4,14). Tsivitse (4) states that a very successful horsepower rating for face motors has used both the continuous rating and the 60-min. rating. The continuous duty is matched to the average or rms requirements of the load, and peak-horsepower loading is limited to the 60-minute value. The rms value for horsepower can be defined as:

$$hp_{rms} = \left(\frac{\Sigma (hp_i)^2 \Delta t_i}{\Sigma \Delta t_i}\right)^{1/2} \qquad (5.16)$$

where hp_i is the mean horsepower during the time segment Δt_i and $\Sigma \Delta t_i$ is the total time interval.

Alternating-current motors in mining machines are normally four or six pole with synchronous speeds of 1800 and 1200 rpm, whereas d-c motors often have comparable base speeds of 1750 and 1175 rpm (4,14). These are high enough to provide adequate horsepower, but low enough to have reasonable reliability. Series-wound motors for traction are built to withstand rotation up to 6000 rpm, as such might occur during maintenance.

Table 5.4 contains a listing of common applications for different motor designs for the various functions found in mining equipment (4,15). Some additional information, however, is warranted. Locked torque of traction motors is set so the wheel or crawler-tractor treads will lose traction before the motor stalls. Alternating-current motors that are mechanically paralleled, such as for continuous-miner cutting, are often sequence started, the delay to limit starting currents. Further, the high-slip characteristics mentioned in the table are also for load sharing as well

Table 5.4. Common Methods for Mining Equipment.

Function	a-c[1]	d-c
Traction (direct coupled)	Design D	Series Wound
Hydraulic Pump	Design B or A	Compound or Stabilized Series[3]
Conveyor	Design C	Compound
Loading Arm	Note 2	Heavily Compounded[4]
Cutting	Note 2	Heavily Compounded[4]

[1] NEMA Designs for induction machines.

[2] Similar to NEMA Design A but sometimes with higher locked-rotor and breakdown torque and higher slip per torque value.

[3] Speed regulation from no load to full load from 10 to 15%.

[4] Speed regulation from no load to full load from 30 to 35%.

as to limit the rate of torque rise during shock loading. Direct-current motors which are similarly used often have matched speed-torque characteristics. Otherwise, the motors are compounded with a differential field that is in series with the armature of the other motor.

Because mining equipment operates at the tail end of the distribution system, voltage drop becomes an important factor in the selection and utilization of motors. This is more critical for a-c equipment than it is for d-c, and the next section will discuss some ramifications for two types of machines.

5.7-2 Actual Equipment Operation

Continuous Miners. Of all electrical equipment used in U.S. underground coal mines, the continuous miner is the most concentrated single load. It is the heart of present underground-coal-mining systems both from production and electrical standpoints. A recent study investigated 26 different a-c continuous miners with utilization voltages of 440, 550 and 950 V, and total rated motor powers from 100 to 535 hp (16). These machines were operating in the Appalachian Coal Field. Production ranged from 50 to 770 raw tons/shift.

The following statements are related to a-c continuous miners designed for high-production coal mining. Although defined in Chapter 4, the term "load factor" used in the discussion needs additional explanation. Machine load factor can be defined as the ratio of actual power consumption to rated motor power. Alternating-current continuous miners use squirrel-cage induction motors, and for these the rated power is set by the manufacturer for either one motor or a combination. As mentioned earlier, motors are often rated by NEMA guidelines but sometimes can be designed on a job-shop basis. Still, torque and power are the only common ratings available to judge motor utilization. Because horsepower is directly proportional to the product of motor speed and torque, the power rating can be employed to determine three-phase motor performance. The load factor can be used not only to investigate effective operation of a particular machine but to compare different equipment of a specific type, no matter what the rated power.

At low-load conditions, motor efficiency and power factor drop off rapidly. Furthermore, the motor functions on the steep portion of the power-factor curve which means a small load variation will cause a relatively large motor-current fluctuation. This can produce detrimental current peaks and stresses in trailing and feeder cables, particularly in marginal-size conductors. Poor power-factor operation additionally means either correction capacitors or utility-company penalties. Average load factors were found for each machine in the study. Mainly because cutting power consumption is the most demanding, the study focused on the cutting-and-loading cycle.

The average cutting load factors ranged from 0.26 to 1.17, averaging 0.52 for the measured machines. Employing all hydraulic, mechanical, and electrical machine components, a 0.60 load factor might be considered satisfactory. Therefore, the implication is that the majority of these miners were being used inefficiently. Because of the numerous factors involved, making conclusions about machine efficiency and utilization by just the load factors alone could be misleading. However, an important finding here is that 0.52 is much less than the assumed design level of 0.85 that is popularly used by the industry.

Generally, low to moderately powered machines had higher load factors, some being considered totally adequate. During field measurements, close attention was paid to the machine operator's performance. In almost every case, the operator was pushing his machine as much as possible during cutting (actually, sumping) because traction approached full slip. From adequate employment, some of these machines can be termed overpowered, for example, a high-powered machine cutting very friable coal. Furthermore, when a high-horsepowered machine (say, 500 hp or more) is used on a low-voltage system, demand for large current can create large trailing-cable voltage drops and a machine-voltage condition that not only hampers operation but reduces the safety levels of the system on which it operates (for example, substantially reduced motor-torque capabilities, poor power factor, and so on).

On almost a one-to-one comparison, good machine voltage conditions (as close as $\pm$ 10% as practical) resulted in good motor load factors. To obtain the favorable operation requires not only "good voltage" but a strong utilization system. This is a help in purchasing new machines, and it is strongly recommended that mine operators consider 950 Vac for their continuous miners. The higher face voltages substantially reduce trailing-cable current. For low-voltage systems, 4/0 trailing cables are recommended, with the length not exceeding 500 ft, even though a smaller conductor size could be used. In any event, the nominal system voltage should be set at no less than 10% above the rated voltage of the machine. The recommendation for a strong utilization system also applies to distribution. When distribution voltage regulation is bad, normally poor machine load factors occur. The situation is most evident on 4160-V distribution systems which have been extended beyond their limits. More information on these subjects is presented in Chapters 7 and 11.

Traction Locomotives. A specific case study that was associated with the preceding work involved measurements on main-line traction locomotives. The importance of the findings extends to all series-wound motor traction applications.

The company involved was experiencing numerous motor-armature failures on their locomotives (47 in one year). Two avenues were undertaken to determine the problem: inspection of the failed

motors and electrical measurements on an operating machine. Examination of the motors found that the commutators were heavily pitted and charred, a direct indication of overloading. Subsequent electrical measurements substantiated the suspicion. The locomotive encountered severe continuous stress every time it encountered a particular curve located on a steep upgrade. With this information, the mining company reduced the locomotive's trailing load, and the motor failure diminished.

The direction to problem solution was very low motor voltages. Differing for a-c motors, d-c series-wound motors are not "hurt" by low voltage, although their control circuitry might not function properly. Popular knowledge incorrectly believes that all motors overheat under these conditions. Because the trolley system was under good maintenance, had adequate capacity, and properly spaced rectifiers, low voltage indicated high current.

There is another method that will directly indicate if the motors within a vehicle are being overstressed while performing a specific duty cycle. Every manufacturer supplies characteristic curves for their mining equipment, and an example is shown in Figure 5.59 for a small locomotive using series-wound motors. The figure relates the characteristics per motor (two motors being used on this machine). The process is simply to find the current needed by the job and, using the characteristic curves, compare the needed value with the maximum allowed per motor.

The classical method employs rms current, as well as the following assumptions.

1. The vehicle operates under constant velocity while performing a specific function.
2. The motors heat during acceleration and cool for deceleration.
3. The ampere rating for the motors stabilizes after eight-hours operation.

The input to the method requires complete knowledge of the entire duty cycle (in mining, the repetitive process that places individual demands on the machine). For instance, the track profile for a locomotive under loaded then unloaded conditions can be divided into segments of equal demand, such as the grade for a specific haulage distance. For each portion of that duty, the torque or tractive-effort demand must then be found. In lieu of other sources, reference 17 does contain calculation methods to obtain this input information.

With the above data, the characteristic curves are used to find the current demand at the actual time at that current for each portion of the duty cycle. For instance, consider that the locomotive of Figure 5.59 is operating on 600 ft of + 0.5% grade and has a tractive-effort per motor of 1020 lbs. From the tractive-effort curve, the current demand is 81 A, and the

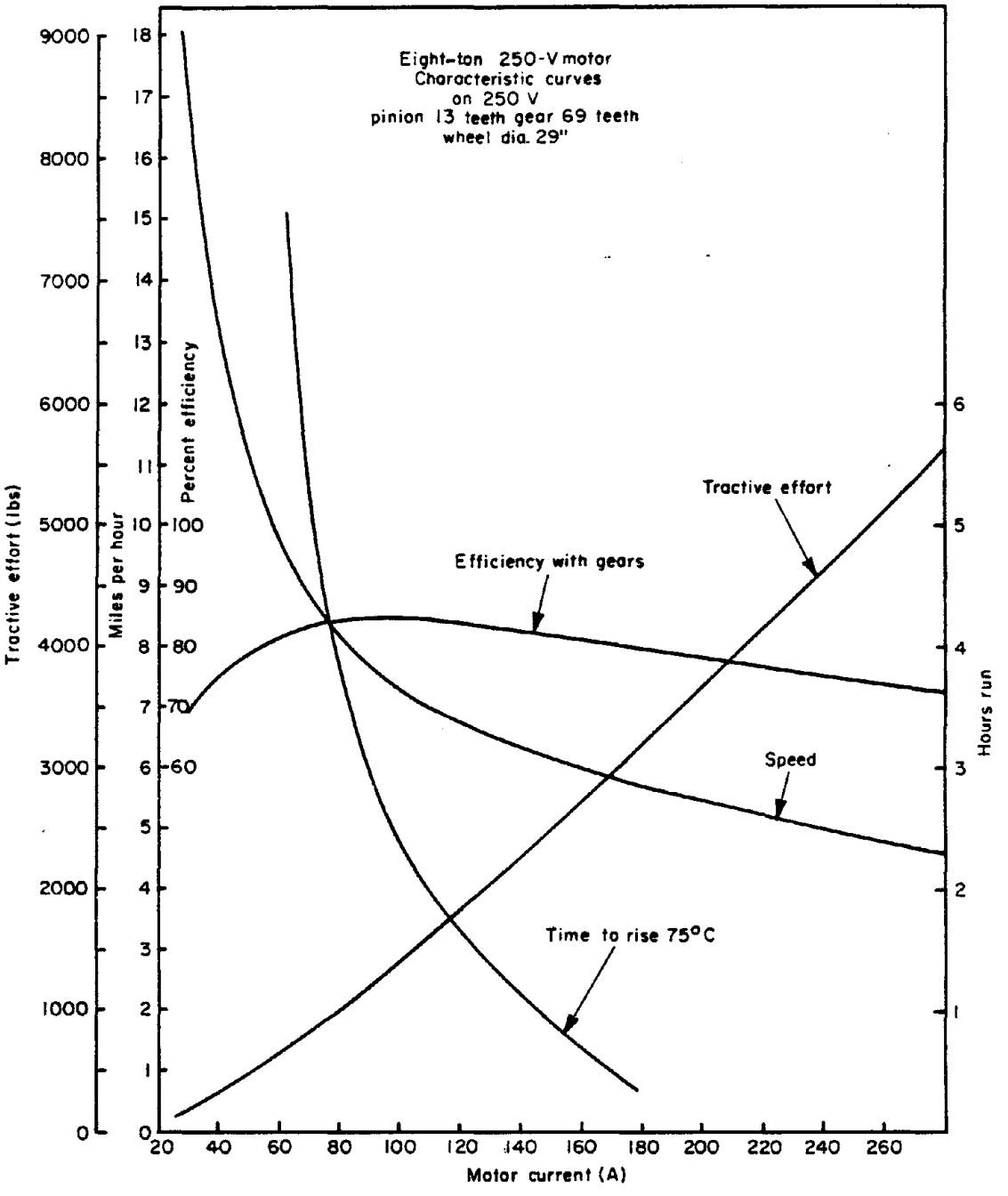


Figure 5.59. Typical Characteristic Curves for Each Motor in a Traction Locomotive.

machine speed is about 8.1 mph, using the speed curve. Thus, the locomotive would take 0.84 minutes drawing 81 A to move the 600 ft. The technique is continued until all times and currents are known for each duty-cycle portion.

A problem occurs in the above procedure when the speed obtained from the curves is greater than that allowed. For example, assume that the next portion of the track profile is 2400 ft at a -0.5% grade, and the tractive effort for each motor has been found to be 340 lbs. Referring to Figure 5.59, current is 42 A, and speed is 12.5 mph. However, say that the maximum allowable speed is 10 mph. In this case, the locomotive would be commonly operated on-off, on-off, and so on, to maintain but not exceed 10 mph throughout the haulage portion. The time the motors are on and off can be precisely calculated by:

1. finding the time required to travel the distance at maximum allowed speed (i.e., for 2400 ft at 10 mph yields 2.73 min)
2. determining the time it would take at the curve speed (2400 ft at 12.5 mph gives 2.18 min), and
3. subtracting the results of item 1 from 2 (0.55 min).

Item 2 provides the time the motors are on (42 A to 2.18 min), while Item 3 gives the off time (zero current for 0.55 min).

With all currents and times known, including those times at zero current, the following equation provides the rms current demanded by the duty cycle:

$$I_{rms} = \left(\frac{\Sigma I_i^2 t_i}{\Sigma t_i}\right)^{1/2} \qquad (5.17)$$

where,

I_i = the current demand for each duty-cycle portion (A)

t_i = the time involved for the respective current demand (min)

I_{rms} = the effective current demand for the duty cycle (A).

For additional functions that haulage locomotives perform, the following (jeep) factors are assumed.

1. Switching operations have zero current demand but one-quarter (1/4) of the actual time is applied in the above summation.
2. If the locomotive is used to load and unload its cars, the maximum tractive effort is employed for the loading

process, the minimum for unloading. One-half the actual time involved for each is used for the effective time (t_i).

3. Delays are taken as zero current and zero time. Normal delays are assumed to not allow effective motor cooling.

Mine motors are presently standardized at a 90°C allowable temperature rise based on a 25°C ambient temperature (4). Older motors, however, may have a 75°C temperature-rise limit but are still based on the 25°C ambient. (Figure 5.59 is an instance.) The base temperature closely fits the typical conditions found in underground operations.

As mentioned earlier in the chapter, the allowable temperature rise holds up to elevations of 3300 ft (1000 m); above which, the allowed is reduced one percent for every 330 ft (100 m), or

$$\% \text{ Reduction} = \frac{\text{ELEV.} - 3300}{330} \qquad (5.18)$$

In addition, for maximum ambient temperatures exceeding 25°C, the allowable rise must also be reduced by the difference above the base temperature. For example, a motor with 75°C temperature-rise insulation, operating at 6600 ft in 30°C ambient temperature, has only a 62.5°C allowable temperature rise.

Consequently, if the locomotive is operating at 3300 ft or less in a maximum ambient of 25°C or less, the characteristic curves can be used directly to find if the duty-cycle demands exceed that allowed. In other words, the rms current found by equation 5.17 can be compared with the time-to-rise temperature curve. If the resulting time is greater than the actual time involved, the locomotive will work under the duty cycle. For example, if I_{rms} is 80 A, 7.5 hours of operation is allowed (Figure 5.59).

However, if the allowable temperature rise must be reduced, the manufacturer's curves can no longer be used directly, and must be corrected. Fortunately, the time-rise curve is very nearly parabolic. Thus any allowable temperature-rise curve can be closely approximated by a straight line through two points plotted on log-log paper, with the two axes representing motor current and operation hours. Yet this process can be time consuming. Using the parabolic relationship, the following formula also gives the allowable effective (rms) current for the total operation time when curve correction is necessary.

$$\ln(I) = \frac{[\ln(H_T) - W][\ln(I_1) - \ln(I_2)]}{Z - W} + \ln(I_2) \qquad (5.19)$$

where,

$$W = \ln \left\{ \frac{[(I_2^2 H_2)^{1/2} (T_p/T_c)]^2}{I_2^2} \right\}$$

$$Z = \ln \left\{ \frac{[(I_1^2 H_1)^{1/2} (T_p/T_c)]^2}{I_1^2} \right\}$$

H_T = total operation time for the motor (hours)

T_c = the rated allowable temperature rise (°C)

T_p = the corrected allowable temperature rise (due to elevation or ambient temperature) (°C)

H_1, I_1 = a point taken off the manufacturer's time-to-rise temperature curve (hours, A)

H_2, I_2 = a second point taken from curve (hours, A)

I = allowed rms current for the total operation time H_T (A).

If I from equation 5.19 is less than I_{rms} from equation 5.17, the motor is overstressed for that duty cycle. Even though the foregoing was applied to d-c motors in traction locomotive, the same concepts can be adapted to any mine-motor application.

5.8 Single-Phase Motors

Although the vast majority of motors in mining are three-phase and d-c, single-phase motors do find widespread use for auxiliary functions aside from the mining process. As a general statement, single-phase induction motors have one running speed and require a separate means to start rotation. This means has the form of a separate stator (or "starting") winding, and motors are classified by the starting method. The most-used techniques are split phase and capacitor start, and these will be discussed briefly in this section.

5.8-1 Rotating Stator Field

When a single-phase a-c voltage is applied to one stator winding, the current flow produces a magnetic field with a resultant direction that alternates on a line, for instance, line OP in Figure 5.60. If a squirrel-cage rotor winding is in the stator field, a voltage will be induced in the rotor conductors, but the current produced will create a magnetic field that coincides with the stator field (Figure 5.61). As no magnetic interaction occurs, no torque is developed, and the rotor remains stationary (1).

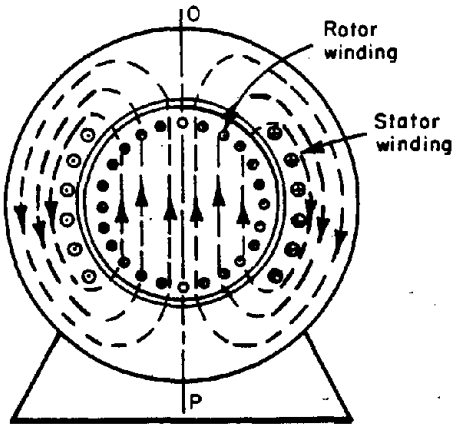


Figure 5.60. The Stator Field of a Two-Pole Single-Phase Induction Motor.

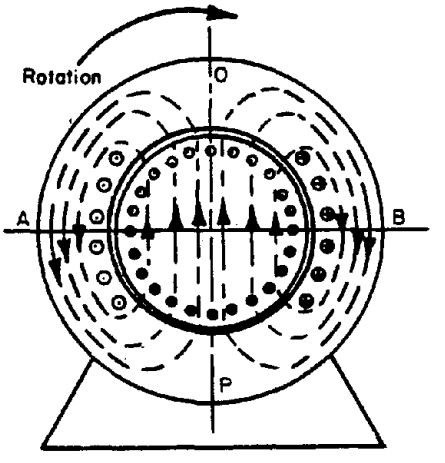


Figure 5.61. The Rotor Field of a Stationary Two-Pole Single-Phase Induction Motor.

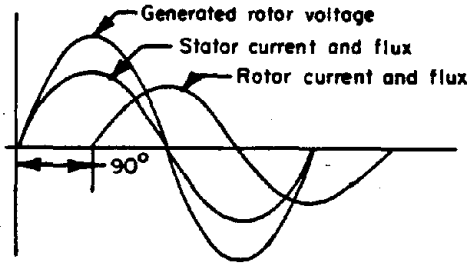


Figure 5.62. Phase Relationships Between Stator and a Turning Rotor.

If the rotor is moved by some means, the rotor conductors cut the stator magnetic field, and the induced voltages are in phase with the current through the stator winding. However, the rotor-winding impedance appears as almost pure inductance, and rotor current will lag the induced voltage by almost 90° (Figure 5.62). Thus, the rotor magnetic field is now 90° from the stator field and is termed a "cross-magnetizing" field (1). The rotor and stator fields combine to produce a resultant field that rotates at synchronous speed. The cross-field strength is proportional to the rotor speed, and is about equal to the stator-field strength at synchronous speed. However, the same operational principles that have been given for three-phase induction motors also hold for single phase; slip must always exist between the rotating field and the rotor. Because of the cross field, the slower rotor speed causes the rotating field to pulsate. Accordingly, vibration and noise are inherent with single-phase induction motors.

5.8-2 Split-Phase Starting

Split-phase motors have two stator windings connected in parallel, as shown for a two-pole motor in Figure 5.63. The impedance of each winding is such that the currents through both are out of phase. One winding, the "auxiliary" or "starting" winding, is usually constructed of small gauge wire and has high resistance and low reactance. The other, the "running" or "main" winding, has a heavier-gauge conductor so the winding is of low resistance and high inductance. When energized, the phase angle between the currents through the two windings is only about 30°, but this is enough to produce a rotating magnetic field. The rotating field pulsates and starting torque is small.

Once started, however, the rotor cross field is produced. Thus the starting winding is no longer needed and is disconnected

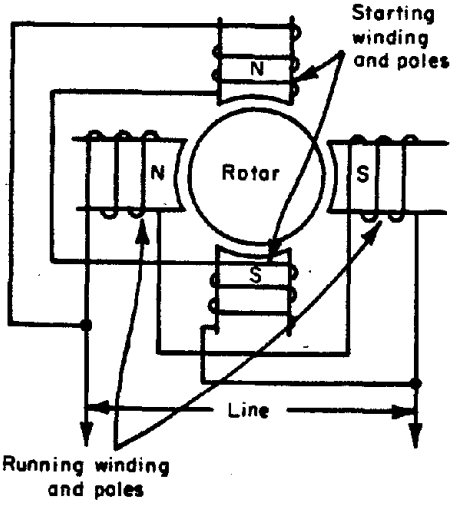


Figure 5.63. Starting and Running Stator Windings.

usually when the rotor speed reaches 70 to 80% of synchronous (1). A centrifugal switch mounted on the rotor shaft is almost always used (see Figure 5.64).

The starting direction determines the final rotating direction. Unlike three-phase motors, single-phase induction motors must be stopped, and the starting-winding connections reversed, then re-energized to produce a rotating field in the opposite direction.

5.8-3 Capacitor-Start Motors

The capacitor-start motor also has two stator windings. The main winding is arranged for direct connection to the power source, but the auxiliary winding is connected in series with a capacitor. With this arrangement, the currents through the two windings can be as high as 90° out of phase. Starting torque can thus approach 100% of rated (1). Typically, the starting winding is again disconnected at 70 to 80% of synchronous speed. A centrifugal switch or a relay sensing current through the main stator winding may be used (see Figure 5.65). Other than the

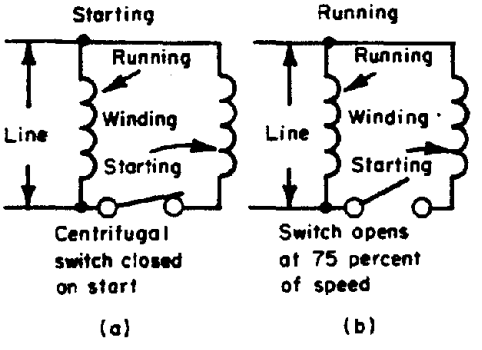


Figure 5.64. Centrifugal Switch to Remove Starting Winding.

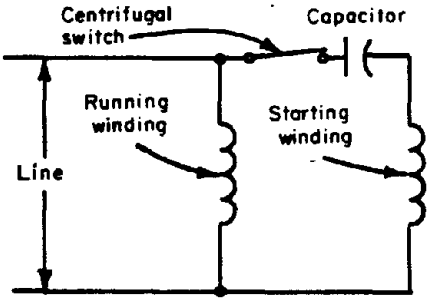


Figure 5.65. Capacitor-Start Motor.

high starting torque, the operation of capacitor-start motors is basically the same as split-phase. However, popular split-phase motors have an upper power limit of 1/3 hp, whereas capacitor-start machines can be obtained up to 10 hp.

5.9 Summary

This chapter has had the purpose of introducing the operation and characteristics of motors that are commonly used in the mining industry. Although elementary in nature, the contents of the chapter should not be discounted. The electrical power systems in and about mines have the purpose of adequately serving motors. If the characteristics of these loads are not precisely known, it is doubtful that a safe and effective mine power system can be achieved.

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Chapter 6

GROUNDING

6.1 Grounding-System Purposes

A vital part of any mine power distribution system is the connection to earth or ground. This portion is referred to as the mine's "grounding system," and consists of grounded or grounding conductors extending from ground beds to equipment. A "grounded conductor" means that a power conductor is tied to the grounding system. On the other hand, a "grounding conductor" is separate from the power conductors, used only to ground exposed metallic parts of the power system. A "ground bed," also termed a "ground mesh," "grounding electrode," as well as other names, is a complex of conductors placed in the earth to provide a low-resistance connection to "infinite" earth. The grounding system serves to protect personnel and machinery from the hazards associated with electrical equipment that is operating improperly. The protection afforded can be divided into four main functions, the purposes behind grounding the system.

First, the grounding system must limit potential gradients between conducting materials in a given area (1). During a ground fault, for instance, a phase conductor comes into contact with a machine frame, current flows through the equipment, which tends to become elevated above ground by an amount equal to the voltage on the conductor. If a person touches the machine, while being simultaneously connected to ground in some manner, the body can become elevated in potential, possibly to a lethal extent. Thus, the grounding system should provide a low-resistance path for the fault current to return to the source. The maximum potential to which a person could be exposed, when touching a machine frame, is equal to the voltage drop along the grounding conductors. An illustrative example of the exposed potential, in a surface mining situation is shown in Figure 6.1 (1). The ground conductors, therefore, should have low resistance so they can carry the maximum expected fault current without excessive voltage drop.

Second, the grounding system should limit the energy available at the fault location. Heavy arcing or sparking can ignite nearby combustible material. The air itself can become ionized, making it capable of carrying tremendous amounts of current. A high-energy fault can vaporize breakers, switchgear, and phase conductors, and protective enclosures may be blown apart with explosive force (2). By controlling the maximum allowable fault current, the danger of fire is significantly reduced and equipment damage is held to a minimum.

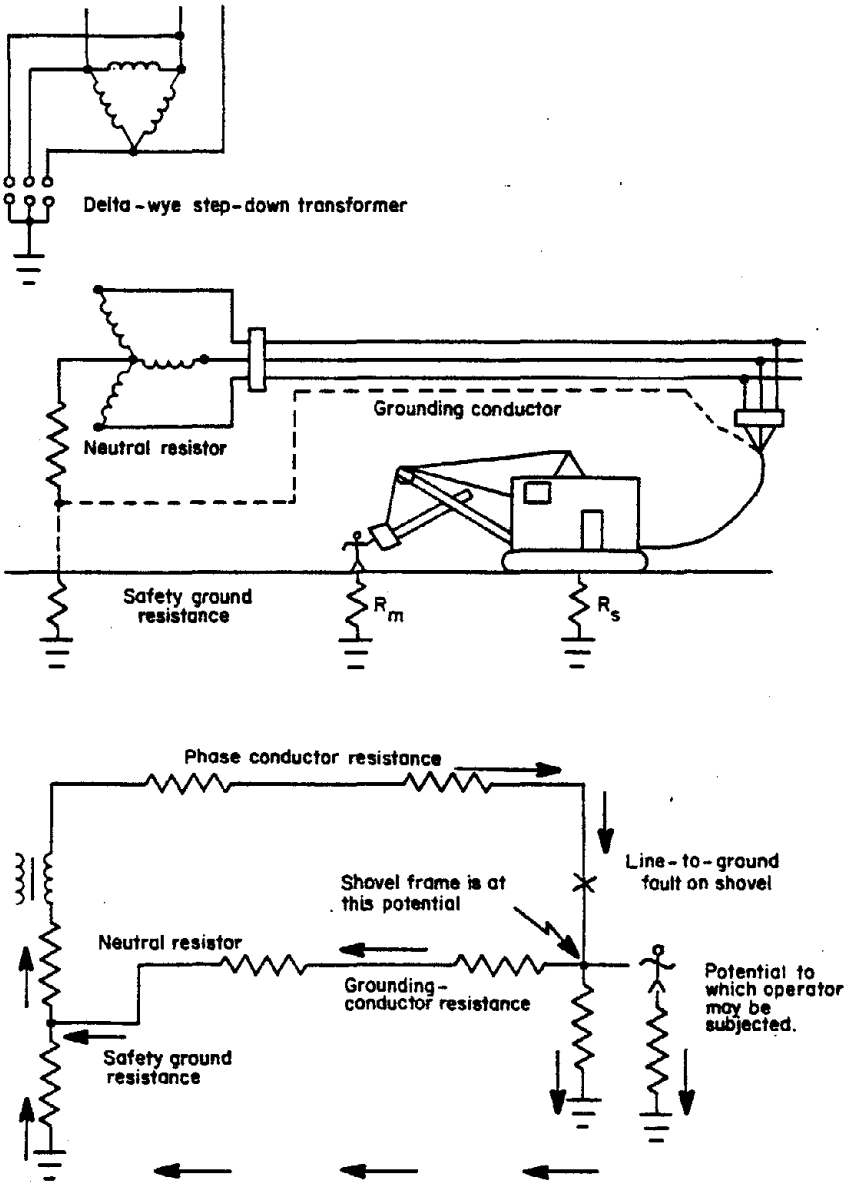


Figure 6.1. Illustration of Electric Shock Hazard.

Third, the control of overvoltages is essential. This condition may occur by accidental contact with a higher voltage system, or could result from transient (short-lived) phenomena due to, for example, lightning strokes, intermittent ground faults, autotransformer connections, or switching surges (3). The maximum ratings for cable insulation, transformer windings, relay contactors, and so forth may be temporarily exceeded in these cases. This does not usually result in an immediate breakdown of equipment, but component parts of the electrical system are successively over-stressed and weakened by repeated exposure (see Chapter 10). This leads to premature failures, reduced component life, and mysterious "nuisance trips" which can occur without apparent reason. By providing a path between the transformer neutral and ground, most of the sources of transient overvoltages can be reduced or possibly eliminated.

Last of all, a grounding system should isolate offending sections by selective relaying of ground faults (4). The sensitivity and time delays of the protective circuitry should be adjusted so a fault in a certain area will cause the local breaker to sense the malfunction and quickly remove power from only the affected section. If the relative tripping levels and speeds are not established correctly, nearby breakers may not trip when they should, and a small problem could develop into a large calamity. Consequently, power to half the mine may go out due to poor relay coordination, and much time could be lost in the effort to trace and locate the trouble spot. Thus, the relaying system must be arranged so sufficient fault current, even at the lowest level of the power-distribution chain, can flow to enable the protective circuitry to sense it and take remedial action.

Chapters 8 and 9 will cover the protective circuitry used to provide the section-isolation function, while Chapter 10 will describe the devices employed with the grounding system for transient overvoltage control. As an introduction, this chapter will mainly look at the first three purposes and present the common methods of system grounding, the effect of electric shock on human beings, mine-ground-system characteristics, and ground-bed construction. Extensive information about grounding is contained in practically all subsequent chapters.

6.2 Grounding-System Methods

Over the past few decades, several different grounding philosophies have held sway in the electrical industry, each with its own advantages and disadvantages (5). These methods of grounding are discussed below. (Note: Reactance-grounded systems are not presented in the following paragraphs, as they are not normally used in industrial power systems.)

Ungrounded Neutral. The "ungrounded" system was probably the first to be used because of its simplicity. There are no intentional ground connections in the system whatsoever. However, a perfect ungrounded system cannot exist since any current-carrying conductor may be coupled to ground through numerous paths including the distributed capacitance of its wiring, or through motor windings (6). This phenomenon is shown in Figure 6.2 (5). The first line-to-ground fault on such a system will have very little effect (7). There is no way for the fault current to find a complete circuit back to the source so its magnitude will be very small or nil. Very low fault current means no flash hazard and no equipment damage. Circuit operation continues normally, with no interruption of power, an important consideration in industries where downtime is critical (8). The first fault is often hard to locate, because its effects are negligible. Often no repair effort is made until a second fault occurs, with its concomitant hazards of arcing, heavy current flow, and equipment damage. Since the entire system is "floating," there is no control of transient overvoltages. Except for the problem of accidental contact with a higher-voltage system, all the other overvoltage sources (mentioned previously) are enhanced due to distributed capacitance to ground (5).

Solidly-Grounded Neutral. An alternative is the solidly grounded neutral (5). The first ground fault produces a substantial neutral current flow which may be quickly sensed by protective circuitry, thereby shutting down the bad section. Overvoltages are controlled since the system, as illustrated in Figure 6.3, now has its neutral solidly referenced to ground (5). The hazards of this system, however, are due to the magnitude of the fault current. Detection equipment must be sensitive enough to detect low-level fault currents and fast enough to disconnect bad circuits before heavy faults can disrupt system integrity. Large fault currents, typically several thousand amperes, can explode protective enclosures, destroy equipment, and start fires, which is an excellent reason for not using this technique in explosive atmospheres.

Low-Resistance-Grounded Neutral. The low-resistance-grounded neutral system is established by inserting a resistor between the system neutral and ground. The resistance is such that ground-fault currents are limited from 50 to 600 A, but commonly about 400 A (5). Transients are controlled due to the ground connection, and ample fault current is available for actuating protective relays. The flash hazard is not as serious as in the solidly-grounded neutral system, but a current flow of 400 A can still do considerable damage. To limit damage, the least sensitive ground relay should respond to 10% of maximum ground-fault current. A schematic diagram of this method is shown in Figure 6.4 (5).

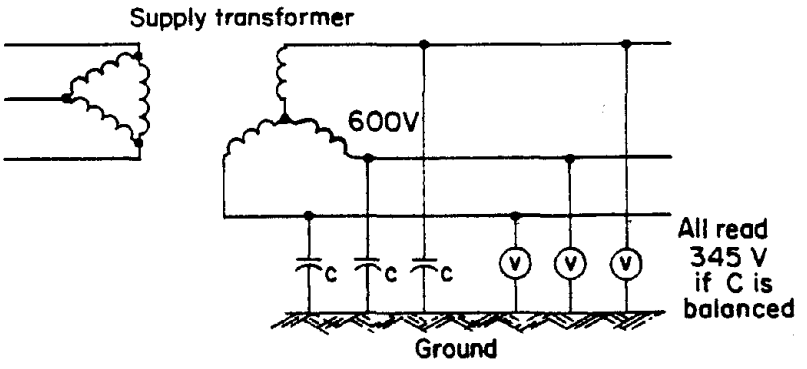


Figure 6.2. Capacitance Coupling in an Ungrounded System.

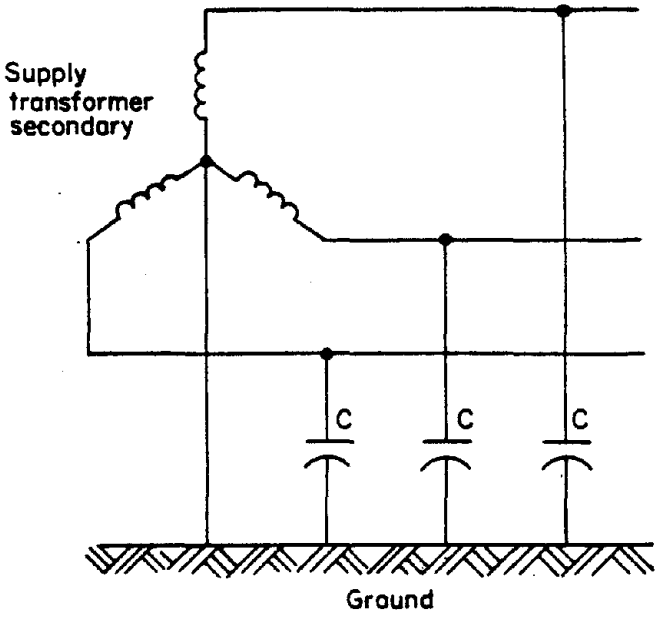


Figure 6.3. A Solidly Grounded System.

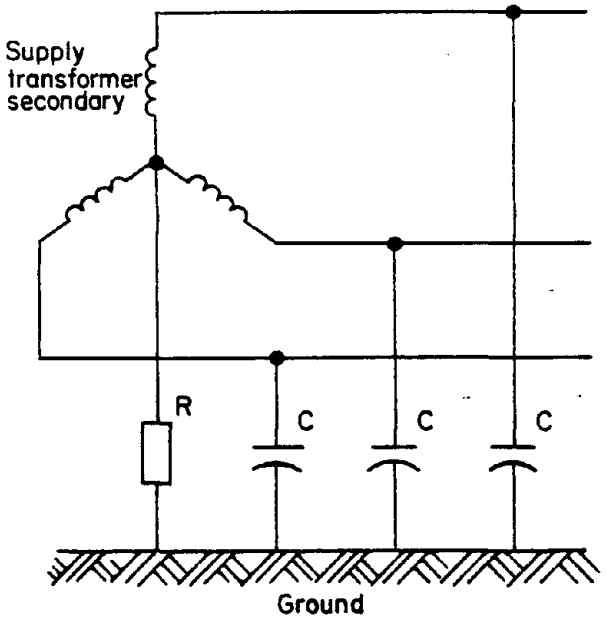


Figure 6.4. A Resistance-Grounded System.

High-Resistance-Grounded Neutral. Perhaps the best technique, and that which is required by law in coal mining applications on portable or mobile equipment, is the high-resistance-grounded system, often referred to as the "safety-ground system." The neutral-grounding resistor is sized according to the system voltage level, in general to limit ground-fault current at 50 A or less. Where the line-to-neutral potential is 1000 V or less, the grounding resistor must limit fault current to 25 A or less; above 1000 V, the voltage drop in the grounding circuit external to the resistor must be 100 V or less under fault conditions.[1] With the system, sensitive relaying must detect faults on the order of a few amperes to provide fault isolation and facilitate quick location of the trouble spot (8). The level of fault current is also low enough to practically eliminate arcing and flashover dangers. The ground connection also serves to limit the amplitude of overvoltages. However, loads cannot be connected phase-to-neutral, as the grounding conductor must not carry any load current.

6.3 Electric Shock

For a safe grounding system to be efficiently and economically designed, voltage and current levels that are harmful to human beings must be determined. With the trend to larger and more powerful mining machinery, distribution voltage and current levels

[1] Title 30, Code of Federal Regulations, Parts 75 and 77.

have risen proportionally. Constant vigilance is required when using electricity if the hazard of electrocution is to be avoided. Even if a shock is nonlethal, involuntary movement caused by the shock may lead to serious injury or death. As an example, a man standing upon a ladder may come into contact with a live wire and fall from his perch (9).

Physiologically speaking, the muscles of the body are controlled by electrical impulses transmitted from the brain via the nervous system. These pulses occur at a rate of about 100 per second, and may be of positive or negative polarity. From this, it can be seen that the human "internal power supply" operates at about 50 Hz, which is exactly the frequency of the electric power-generated in Europe, and is only 10 Hz removed from the United States' power generation frequency of 60 Hz (10). This is an unfortunate coincidence, for tests have shown that the most dangerous frequencies to which a person can be exposed are the "power frequencies" in the range of 50 to 60 Hz (9). Figure 6.5 demonstrates the effect of various frequencies upon the human body (11).

How sensitive are human beings to the flow of electricity? Tests have indicated that, for an average male holding No. 7 AWG copper wire electrodes in his hands, 60 Hz a-c is first perceived at a level of about one milliampere (9). By intermittently touching or tapping an electric conductor, currents of only one-third milliampere can be felt. In the case of d-c, the threshold of perception for the average male is 5.2 mA. Sensitivity levels for women, in the cases mentioned above, can be found by multiplying the male values by a factor of two-thirds (12). It is generally agreed that the magnitude and duration of the current are the important shock parameters, rather than the potential difference or voltage (9). See Table 6.1 (13).

As current magnitude was increased above the level of perception, many test subjects reported a tingling sensation, the intensity of which increased as the current rose. Generally, muscles in the vicinity of the current path started to contract involuntarily, until finally a point was reached where the subject being tested could no longer release his grip on the conductor (14). The maximum current magnitude, which a person can withstand and still be able to release from the live conductor through the use of muscles stimulated directly by that current, is called the "let-go current" (11,14). Tests performed on hundreds of volunteers have shown that the maximum let-go current for a healthy adult male is 9.0 mA a-c and 62-mA d-c. The corresponding values for women are 6.0-mA a-c and 41-mA d-c. These safe limit values apply to 99.5% of the sample population (15). The value of a specific individual's let-go current is virtually constant, even with repeated exposures to that current level. In addition, these multiple exposures can be tolerated with no ill effects (11).

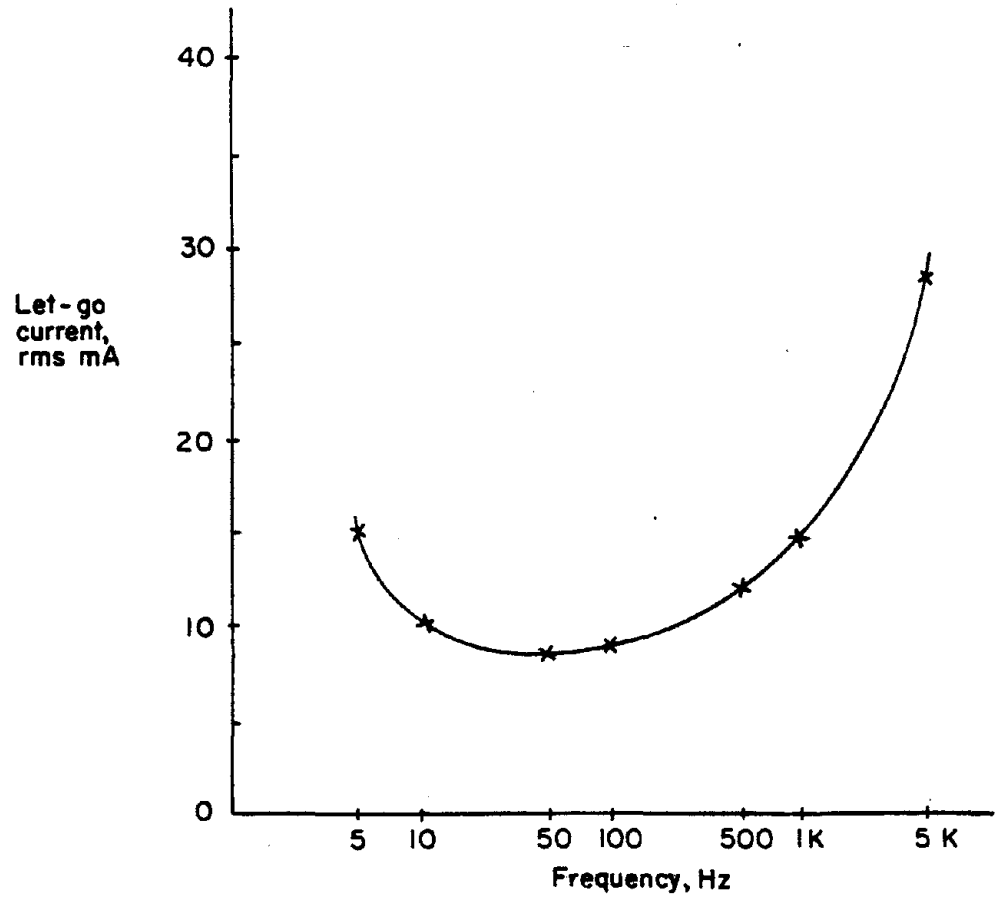


Figure 6.5. Effect of Frequency on Let-Go Current for Men.

Table 6.1. Current Range and Effect on 150-lb Man.

Current	Physiological Phenomena	Effect on Human
<1 mA	None	Imperceptible
1 mA	Perception threshold	
1-3 mA		Mild sensation
3-10 mA		Painful sensation
10 mA	Paralysis threshold of arms	Cannot release hand grip; if no grip, victim may be thrown clear; may progress to higher current and be fatal.
30 mA	Respiratory paralysis	Stoppage of breathing; frequently fatal.
75 mA	Fibrillation threshold	Heart action discoordinated; probably fatal.
4 A	Heart paralysis threshold (no fibrillation)	Heart stops on current passage, normally restarts when current interrupted.
>5 A	Tissue burning	Not fatal unless vital organs are burned.

It has been stated that human tissue possesses a negative-resistance characteristic. In other words, an increase in current magnitude or contact duration leads to a decrease in the value of skin resistance (16). In any case, if a person has grasped a live conductor, realizes that he cannot let go, fear-induced perspiration will cause a lowering of the body's resistance, and more current will flow. For a-c, when the current level across the chest reaches more than 18 to 22 mA, the chest muscles tighten involuntarily and breathing ceases. Although circulation of blood by the heart is unimpaired, death by asphyxiation can occur within minutes (17).

If an individual's initial contact with a live wire causes a current flow ranging from about 50 to 500 mA, ventricular fibrillation may result (10). Under normal conditions, the heart beats with a strong, coordinated rhythm. However, a current, passing through the heart when the ventricles (the heart's two large pumping chambers) are just starting to relax after a contraction, can cause the various fibers of the heart muscle to beat weakly and haphazardly, in a disjointed and uncoordinated manner (17). In this condition, known as venticular fibrillation, the heart is almost totally incapacitated and blood circulation decreases practically to nothing. Within two minutes, the brain begins to die due to oxygen deficiency. Once initiated, ventricular fibrillation almost never stops spontaneously. Treatment by trained medical personnel must be secured if the victim is to survive.

Obviously, people cannot be used as test subjects in ventricular-fibrillation experiments due to the high risk involved. Numerous tests have been carried out on several species of animals and the results extrapolated, based upon body weight, to cover human beings (18). It was found that fibrillating current is proportional to body weight and inversely proportional to the square root of the shock duration. Using 50 kg (110 pounds) as a typical body weight, it has been proposed that the value of current which can be safely endured at 99.5% of normal adults without causing ventricular fibrillation is (11):

$$I = \frac{116}{\sqrt{t}} \Bigg|_{8.3\ \text{ms}}^{5\ \text{s}} \qquad (6.1)$$

where,

I = rms alternating current (mA)

t = shock duration (s).

As noted, this equation is valid for values of time between 8.3 ms and 5.0 s (18).

It may be seen from the above equation that for a one-second contact time, the ventricular fibrillation threshold current is about 116 mA. Since a normal person has a pulse rate between 60 and 80 beats per minute, the critical phase of the heartbeat (when a person is vulnerable to ventricular fibrillation) occurs about once each second. Therefore, during a shock lasting for one second or more, the heart must pass through this critical phase (10). As a result, it is thought that ventricular fibrillation is the leading cause of death by electric shock.

Higher currents, on the order of a few amperes, will "freeze" both the chest and heart muscles, thereby preventing the onset of ventricular fibrillation. Generally, the heart will restart upon the cessation of current flow (10). These current magnitudes are less dangerous statistically than the lower values where fibrillation is prevalent. Further increases in current level, to five amperes and above, may produce serious burns, leading to shock and possible death, while current levels which elevate body temperature substantially, produce immediate death (11).

In an electric-shock situation, the victim's electrical resistance plays an important role in determining how much current will flow, as indicated by Ohm's law:

$$I = \frac{V}{R}. \qquad (6.2)$$

For a human being, at least three components of resistance have been isolated: contact resistance, skin resistance, and internal resistance (17). Contact resistance, as illustrated by Table 6.2, depends upon the degree of skin moistness and the area of contact with the live conductor (13). Values of 40,000 to 50,000 Ω/cm^2 are given for dry skin and 1000 Ω/cm^2 for wet skin (12). Skin resistance depends upon the physical condition of the tissues. A person who does rough, heavy, outdoor work may have a skin resistance of 10,000 Ω, while a value of 1000 Ω is typical of a sedentary office worker (17). Internal resistance is the resistance of the body's interior and is generally accepted to be about 500 Ω between major extremities (19).

Voltage magnitude has some effect upon the body's reaction to electric shock, although current is by far the most important parameter, as stated previously. Potentials greater than about 240 V simply puncture the skin, thereby negating the effects of skin resistance (9). There is also some evidence that overall body resistance varies inversely with the applied voltage, although this is subject to disagreement. The relationship is given by (17):

$$R \propto E^{-n}$$

Table 6.2. Typical Resistance for Various Contact Situations.

Skin Surface Only (void when cut, blistered or abraded)		Resistance
Dry	Wet	Ω
		1 M
Finger touch		500 k
		200 k
		100 k
Hand on wire		50 k
Finger-thumb grasp	Finger touch	20 k
Hand holding pliers		
Palm touch	Hand on wire	10 k
	Finger-thumb grasp	5 k
Hand Holding 1.5" pipe	Hand holding pliers	2 k
	Palm touch	1 k
Two Hands Holding 1.5" pipe	Hand on 1.5" pipe	500
	Hand, immersed	200
	Foot, immersed	100

where:

R = resistance, (Ω)

E = potential, (V)

n = 1.5 to 1.9.

Above about 2400 V, tissue damage due to burning becomes the major cause of electric-shock injury (13).

Thus, it can be seen that the body's response to electricity is extremely complex, and currents on the order of a few milliamperes can be fatal if long continued.

6.4 Characteristics of Mine Grounding Systems

The preceding discussion has outlined why a grounded neutral is necessary. The concept of protecting mine electrical equipment and personnel against the consequences of ground faults by suitable grounding has existed since electricity was first introduced into coal mines. As early as 1916, the U.S. Bureau of Mines recommended equipment frame grounding as a means of preventing electrical shock to miners working on or around electrical equipment (20). For the coal mining industry, a suitable grounding system has always been a difficult problem, more complex and difficult than in other industries.

6.4-1 Ground Beds

For mine usage, the electrical-distribution cables and overhead-transmission circuits carry one or more grounding conductors, as well as the phase conductors, into the mine. Each piece of a-c equipment has its frame solidly connected via these grounding conductors to a safety ground bed commonly located in the main surface-substation area, consisting of buried horizontal conductors or driven rods, or a combination of both. The neutral of the substation-transformer secondary is also connected to the safety ground bed through the neutral grounding resistor, as shown in Figure 6.6 (21). It should be noted that many important components are missing from this diagram, and Chapter 11 will cover substation circuitry in detail.

The substation actually requires two ground beds maintained some distance apart. Lightning discharges and other transformer primary surging conditions are directed to the system or station ground. The system and safety grounds must be kept separate so current flow intended for one will not enter the other. It is essential for the safe operation of the mine power system that the resistance of the beds be maintained at 5.0 Ω or less

(4,22,23). A ground bed with this resistance range is often termed a "low-resistance ground bed."

To demonstrate a reason for a low-resistance bed, consider a situation where lightning strikes the substation, and 10,000 A is discharged through the surge arresters into the system ground bed. If the ground bed is of 5.0-Ω resistance, a potential of 50,000 V is developed, and the grounding grid, comprising the ground bed, becomes elevated to 50 kV above infinite earth. Depending upon the physical (areal) extent of the grid, a man walking through the area underlain by the grid could bridge a lethal potential gradient with his feet (24). Metallic objects within the potential gradient field can also be elevated to dangerous potentials and become lethal to the touch. Typical step and touch potentials are illustrated in Figures 6.7 and 6.8 (24).

These "touch and step" potential hazards are applicable to both the system and safety-ground beds. However, the dangers of a high-resistance safety-ground bed are not to be found in the bed's vicinity, but at the mining equipment. The most insidious feature of the safety-ground system is that the equipment connected to it is maintained not at earth potential, but at the safety-ground-bed potential. Unless the bed has low resistance, any safety-ground-bed current flow can render every piece of mine equipment potentially lethal. Incidents creating the flow include faults to earth, coupling from lightning strokes to the system ground, lightning strokes to safety-grounded machinery, and stray currents from d-c haulage systems. Three such cases are illustrated in Figures 6.9, 6.10, and 6.11 (21,25). Consequently, with high-resistance ground beds, an elevated frame potential is a problem not just on the machine where it occurs, but everywhere (26).

6.4-2 Underground Mining

Arrangement. Early practice in underground coal mining was to drive a metal rod into the mine floor and use that as a ground. In almost every case this arrangement proved to be totally unacceptable, with test measurements indicating 25-Ω or more resistance (21,27). In addition, with the exception of pumps, the contact resistance of mining machinery with the mine floor also proved to be too high for adequate grounding. Rail-haulage track systems, even though often poorly bonded, showed much lower resistance to ground than most metallic rods driven specifically for that purpose. As a solution Griffith and Gleim (27) in 1943 stated that ". . . consideration should be given to a grounding circuit carried to the outside of the mine." Present coal-mine practice does just that.

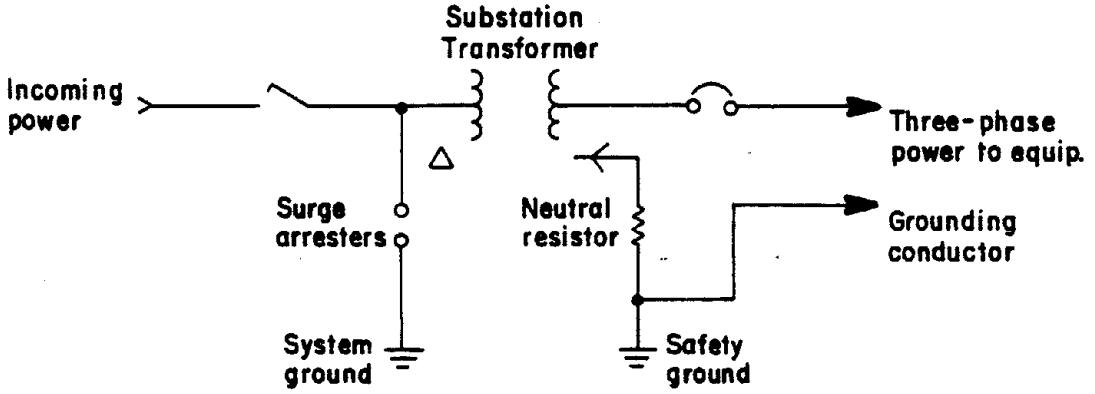


Figure 6.6. A Simplified Substation One-Line Diagram.

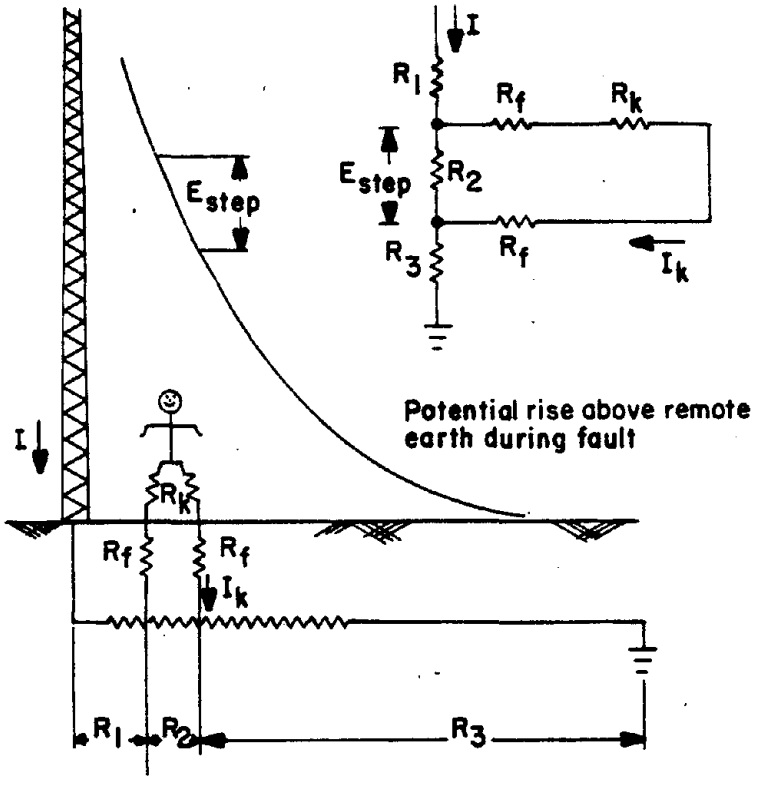


Figure 6.7. Step Potentials Near a Grounded Structure.

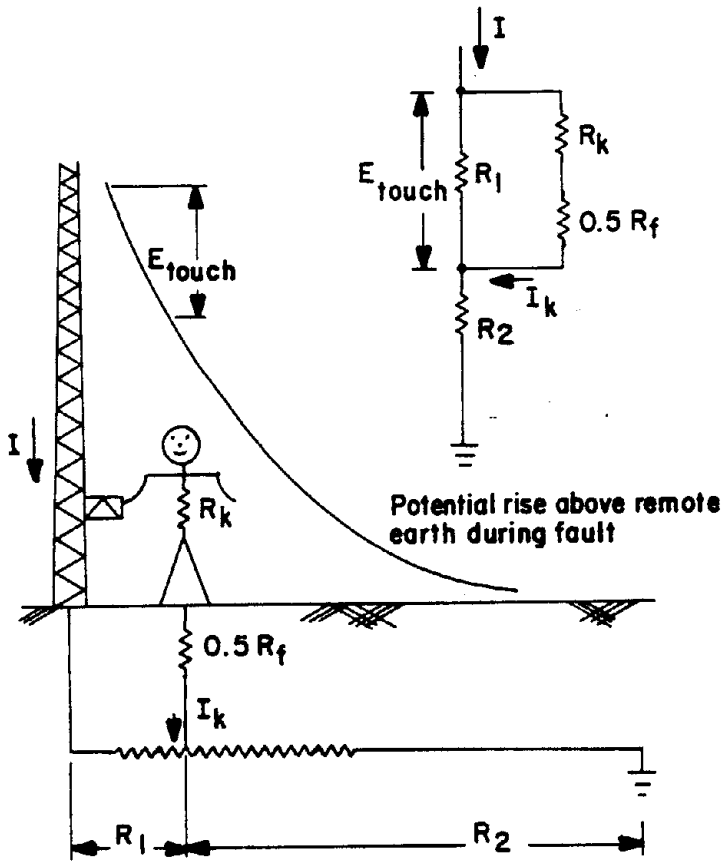


Figure 6.8. Touch Potentials Near a Grounded Structure.

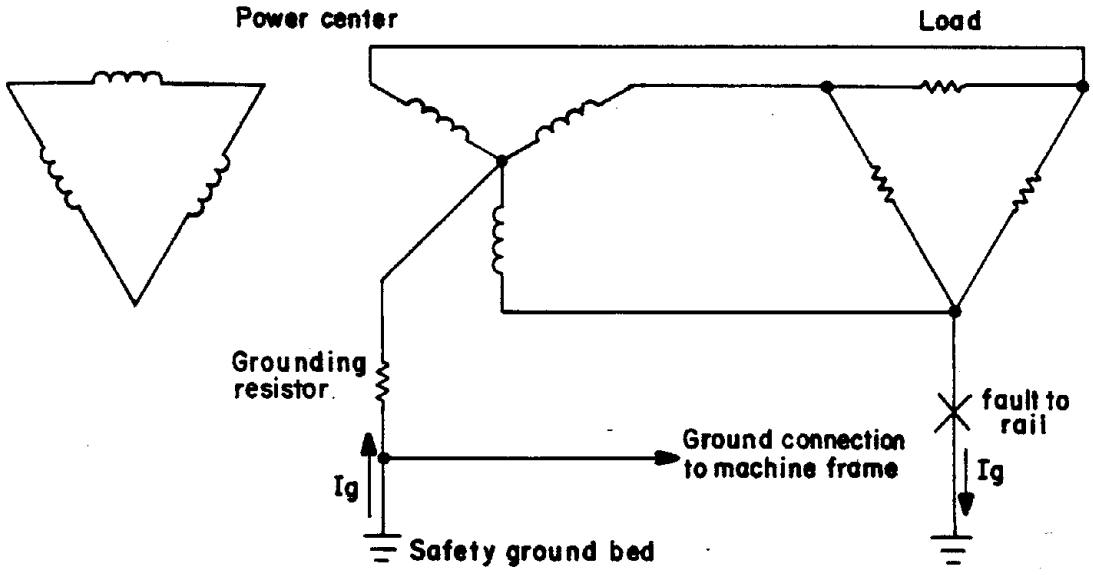


Figure 6.9. Phase-to-Earth Fault Resulting in Current Flow Through the Safety Ground Bed.

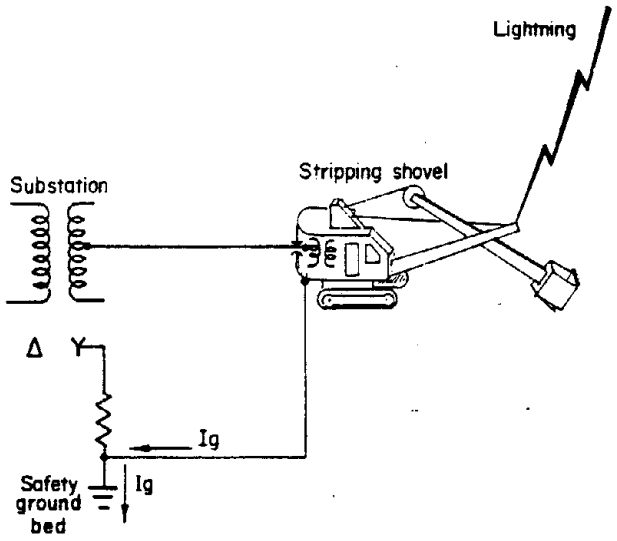


Figure 6.10. Lightning Stroke to Equipment Causing Current Flow Through Safety Ground Bed.

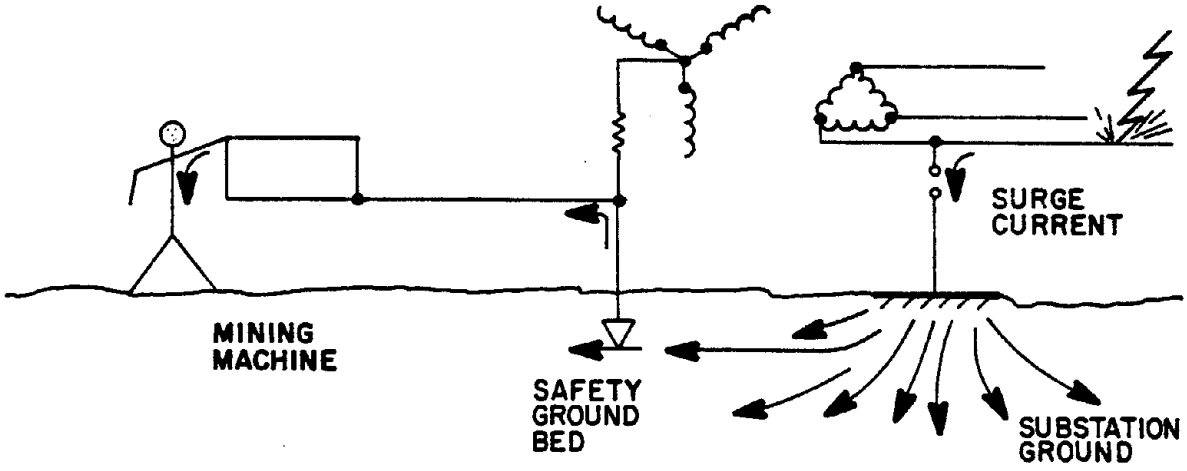


Figure 6.11. Coupling from Lightning Strokes to the System Ground Bed.

A simple form of today's underground coal-mine bi-power (or mixed a-c/d-c) systems is illustrated in Figure 6.12. Three-phase a-c power enters the mine after transformation to supply the various three-phase a-c loads. Some of the a-c power is converted to d-c at rectifier stations to power the locomotive system and, occasionally, d-c face equipment. More often, the d-c face machinery is powered from mine-section located rectifiers. Basically, except for trolley systems, all d-c as well as the a-c equipment frames are connected together via grounding conductors carried in feeder and trailing cables to a common junction which is tied to the surface safety ground bed. In order for the system to be effective, grounding conductors must be maintained continuous. Ground-check monitors ensure this.

Trolley locomotives generally utilize the overhead trolley wires as the positive conductor and the tracks for the negative. Neither of these is tied to the rectifier-station frame ground. However, because the track is on the mine floor, the negative in this case is grounded (for the trolley system only). The d-c system, which supplies power to face equipment, normally employs trailing cables that have neither the negative nor positive conductor grounded. Thus this subsystem is usually ungrounded, unless the supply is obtained from the trolley system (note in some diode-grounded systems, the negative conductor may be grounded).

At each transformation step within the distribution, such as in a load center, an additional neutral point must be established on the transformer secondary. The neutral is tied through a grounding resistor to the equipment frame and, thus, via the grounding conductors to the safety ground bed (an exception is in the next section).

Even with all these grounding points, the a-c ground system must be isolated from the d-c power system. Otherwise, d-c may appear in the a-c ground system, thus elevating it above true ground potential. If an a-c ground current is present, it will be "offset" by the d-c level. The principal concern is associated with trolley installations, and isolation is achieved by having no common points between the a-c and d-c systems. Various techniques have been tried to maintain separation or to eliminate d-c offsets while grounding d-c face-equipment frames.

Face-Equipment Grounding. When a working section utilizes an a-c continuous miner energized from a section load center and d-c shuttle cars powered from the trolley system, the ground potentials of the d-c and a-c equipment frames are not necessarily equal due to the voltage drop in the track. Jacot (28) suggested that this problem could be solved by isolating the low-voltage

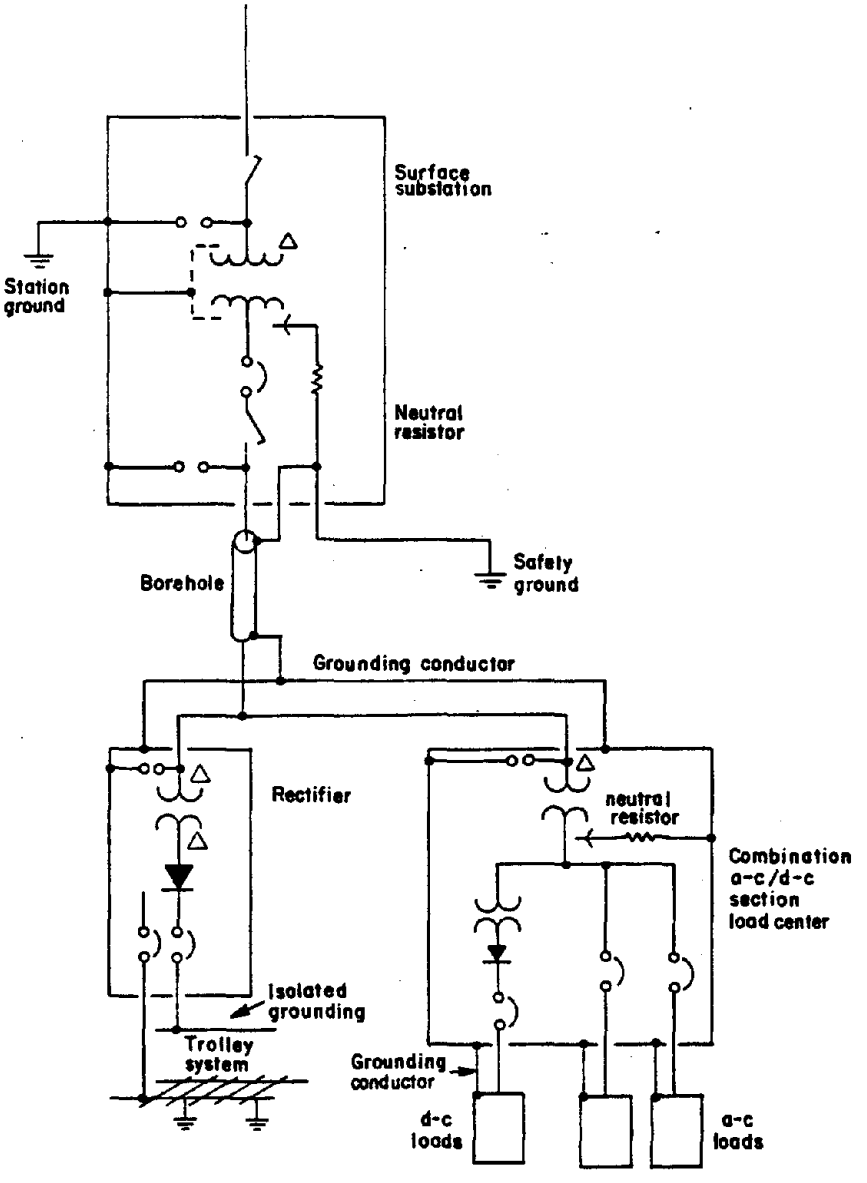


Figure 6.12. A Mine Electrical Power System.

a-c neutral point from the load-center frame and also the high-voltage grounding system, and connecting it via an insulated cable to the track as shown in Figure 6.13. The low-voltage neutral point remains connected to the a-c face equipment frames. The technique should make the low-voltage a-c and d-c equipment frame potentials the same, thus eliminating d-c offset problems. Difficulties can still arise with this method. If any track rail bonds are bad between the a-c and d-c low-voltage ground points, the d-c frames potentials might be elevated in respect to the a-c frames. Further, the load center must be constantly maintained a safe distance away from the tracks to preserve isolation between the track and high-voltage grounding systems.

Another method is shown in Figure 6.14. Here, a section load center supplies power to a-c face equipment and also, through a rectifier, to d-c machinery (usually shuttle cars). The rectifier is isolated within the section load center, but the d-c output is grounded through a center-tapped current-limiting resistor. All d-c equipment frames are then grounded by trailing-cable grounding conductors, which in turn are connected to the center tap of the grounding resistor. The latter point is connected to the high-voltage grounding system. Trasky (21) considered this a very safe d-c ground protective system because it could permit the use of protective circuitry to trip the rectifier breaker in case of a d-c subsystem ground fault (see Chapter 8). However, the use of the center-tapped resistor has been critized (29). On such a system, any failure in maintaining ground conductivity or accidently connecting a wrong conductor when splicing cables may lead to a hazard. Nevertheless, an important advantage of the method is that the d-c and a-c frame potentials can be the same.

In July, 1963, the U.S. Bureau of Mines accepted the employment of silicon diodes as a means of d-c face equipment frame grounding. When a diode is used, the center-tapped resistor is removed because the frame is grounded through the diode to the negative conductor as illustrated in Figure 6.15. The diode circuit also includes a ground protective device which will interrupt the power if a positive-power-conductor-to-equipment-frame current flows (again, see Chapter 8). According to Jones (30), diode grounding should ensure good ground continuity since the same wire acts as both a d-c negative conductor and ground wire. However, a grounding diode protects the d-c subsystem against ground faults within the equipment frame only. Ground leakage or faults within trailing cables can still present hazards.

Track Grounding. As previously mentioned for trolley systems, the rectifier-station frame is grounded by the a-c system but, to maintain isolation, there is no internal connection between the rectifier output (or the trolley distribution system) and its

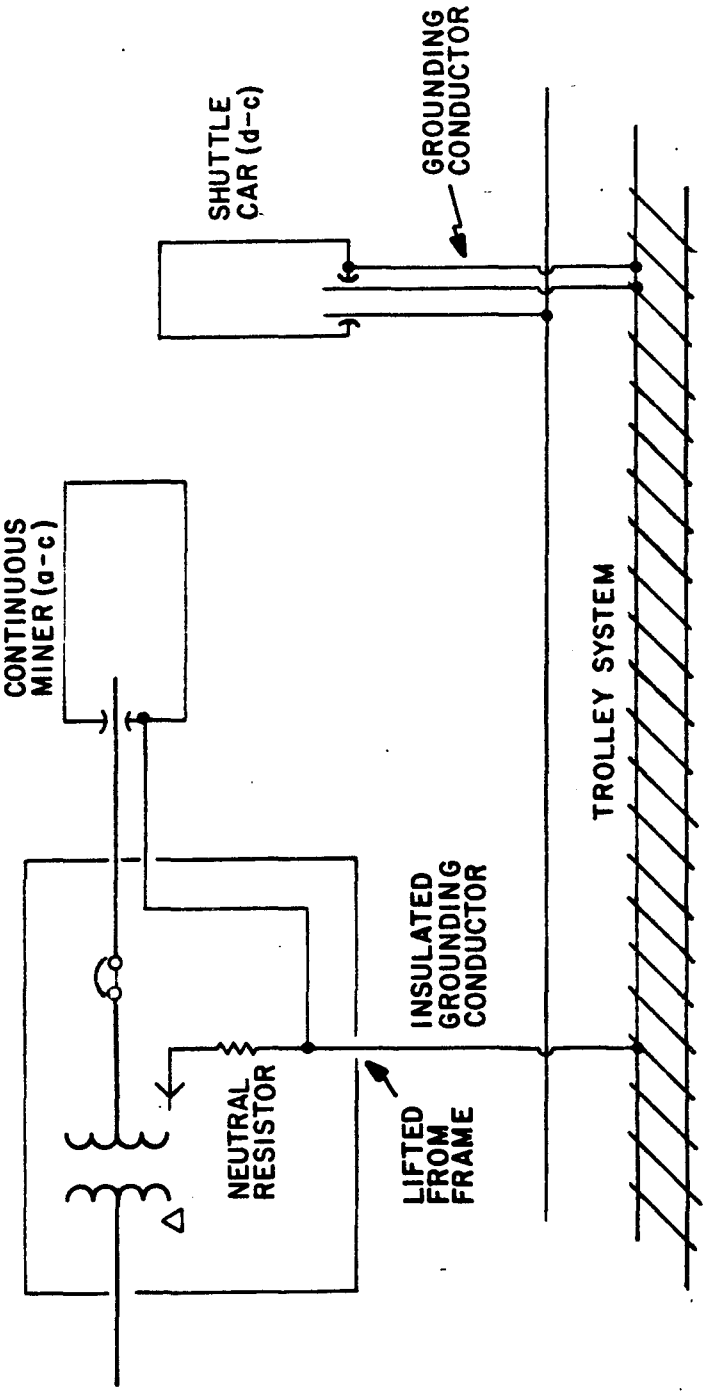


Figure 6.13. Mixed Mine Electrical Power System, D-C Load Energized from the Trolley System.

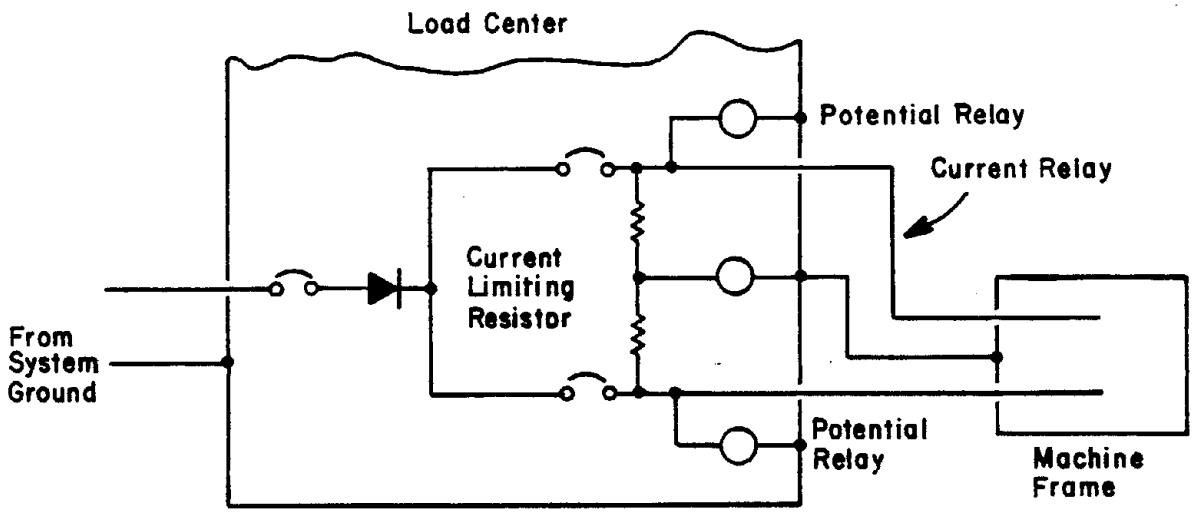


Figure 6.14. System Grounding with Current-Limiting Resistor.

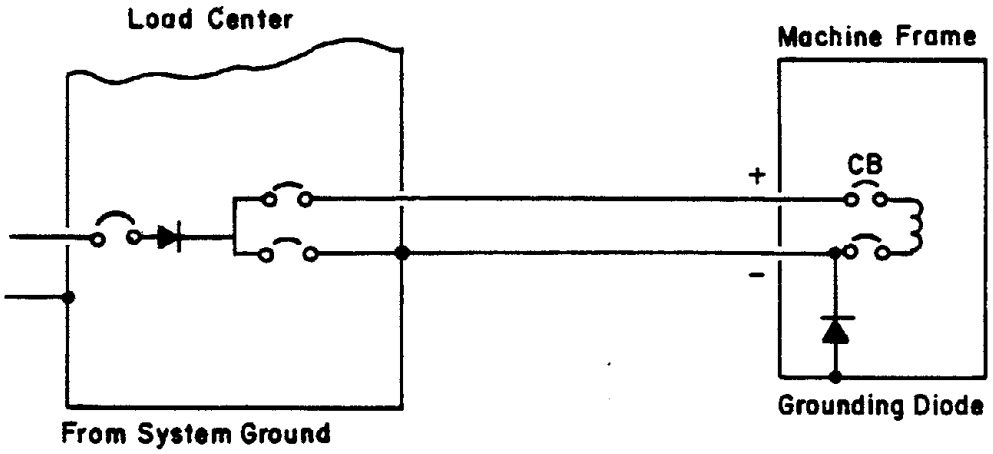


Figure 6.15. Diode Grounding of a Machine Frame.

frame. Nevertheless, if the rectifier is sitting on the mine floor, there is a possible common point from the track (d-c) to the rectifier chassis (a-c).

Normally, or at least ideally, the common point through the earth is a much higher resistance than the rail itself so that all rectifier current returns in the rail. When the rail resistance increases due to poor bonding or cross-bonding, some current may flow through the earth to or from the rectifier frame, depending on the rail potential. Thus, d-c is again introduced in the a-c ground system. Trolley-wire insulator leakage to the roof or rib may cause the same effect, although it appears less common. This effective separation situation can be a d-c offset problem for any mining machine and electrical system whenever the mine-floor resistance and equipment-frame-contact resistances sum is too low and permits d-c current flow (through the earth). To help minimize any problems, rectifiers should be located no closer than 25 ft from the track. In severe cases, the rectifier frame can be insulated from the mine floor.

The preceding indicated that the primary sources of d-c offset currents are haulage-conversion units. Regardless of the source, once stray d-c currents occur, they can be on all the a-c grounds within the mine. This problem is further complicated since these currents may also travel through water pipes and hoses (i.e., anything conductive).

Direct-Current Offset Problems. The two most undesirable effects of d-c on the a-c ground system are nuisance tripping and intermachine arcing. Nuisance tripping will occur whenever the offset a-c waveform is greater than the relay trip value, affecting primarily ground-overcurrent relays and ground-check monitors. Intermachine arcing occurs when two machine frame potentials are not the same. While they are touching, a current flow is possible but, when they separate, arcing may occur. In theory, both machines should be at ground potential since their chassis are connected to grounding conductors. However, one ground connection may not be at ground potential due to induced a-c currents or stray d-c currents. With these currents in different cables, different machine potentials may be developed. These problems are further discussed in Chapter 15.

6.4-3 Surface Mining

The grounding system for a surface coal mine is similar to that for underground mining. One or more substations with resistance-grounded secondaries are employed to transform the incoming utility-voltage to the lower potential used by the mining machines. At this level, pit distribution is carried

on overhead lines or cables to supply switchhouses located near the particular piece of equipment. From the switchhouse a trailing cable completes the power circuit to the machine. At times, a switchhouse is connected via cable to a portable substation, supplying lower voltage power to production, auxiliary, or lighting equipment.

Substation grounding includes both a system and a safety ground bed, each of which is physically removed and electrically isolated from the other. Grounding conductors extend from the safety ground bed to frames of all equipment. The neutrals of the portable-substation transformer secondary are resistance grounded to the equipment frame.

In contrast with underground coal mines where the entire secondary distribution system is underground, both the primary and secondary lines in a surface mine are out in the open where they are exposed to lightning. In fact, equipment such as draglines and shovels are subject to direct strokes (see Figure 6.10).

For the best possible protection from lightning, it is essential that the grounding system have as low a surge impedance as possible. The key factor here is to provide many short direct paths to earth. The specifics of lightning protection for all mines are presented in Chapter 10.

6.5 Ground-Bed Construction

6.5-1 General

Since the mine site is determined by the location of the rock or mineral to be extracted, the conditions required for the installation of an adequate ground bed are not always easily met. If annual rainfall is low or soil resistivity is high, an extensive array of buried metallic conductors may be necessary to assure a low-resistance connection to earth. Measurement of soil parameters can be made before the construction of a grounding grid is begun, and the configuration of a metallic network, which will yield the desired values of earth resistance and potential gradient, thereby ascertained. After construction, the resistance of the selected ground-bed configuration must be checked. Proper design at the time the ground bed is installed will save much time and expense in later years.

6.5-2 Ground Resistance

Ground Beds. Present-day ground beds can be divided into two general categories: meshes and rodbeds. A mesh is a horizontal network of wires arranged in a grid pattern and

embedded a short distance below the earth's surface. A rodbed is an inter-connected network of vertical rods driven into the earth.

Any grounding system exhibits some finite resistance with respect to infinite earth, even though it is completely immersed in the soil. When a fault occurs, current flows through the metallic electrodes, across the soil/metal interface, and into the ground. The greater the surface area of metal in intimate contact with the soil, the lower the resistance. Most of the actual resistance exhibited by each ground conductor occurs within six to ten feet of the electrode, as illustrated in Figure 6.16 (31). If the surrounding soil is viewed as a succession of concentric shells, it is easily seen that those shells adjacent to the electrode have a much smaller cross-sectional area, and hence a higher resistance than more distant shells.

The main factors, which determine grounding-grid resistance are the physical dimensions of the system and the innate characteristics of the soil, primarily its resistivity (32). Figure 6.17 shows how the total resistance of a driven rod varies as it penetrates soil horizons of different resistivity (31).

The electric field around a current-carrying wire is analogous to the electrostatic field surrounding a charged conductor of similar shape. By calculating the capacitance of an electrode immersed in the soil, its resistance can then be determined. For a conductor buried deeply in the earth (33),

$$R = \frac{\rho}{4\pi C} \tag{6.4}$$

where,

R = resistance (Ω)

ρ = soil resistivity (Ωm)

C = capacitance (F).

If the conductor is relatively near the earth's surface, as is usually the case, then the effects of the conductor's image, which is located on an equal distance above the surface, must be included in the formula, yielding (33):

$$R = \frac{\rho}{2\pi C} . \tag{6.5}$$

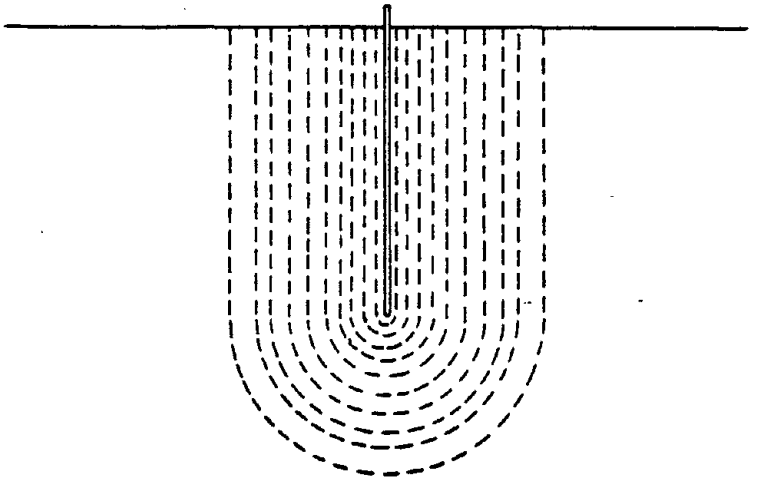


Figure 6.16. Resistance of Earth Surrounding an Electrode.

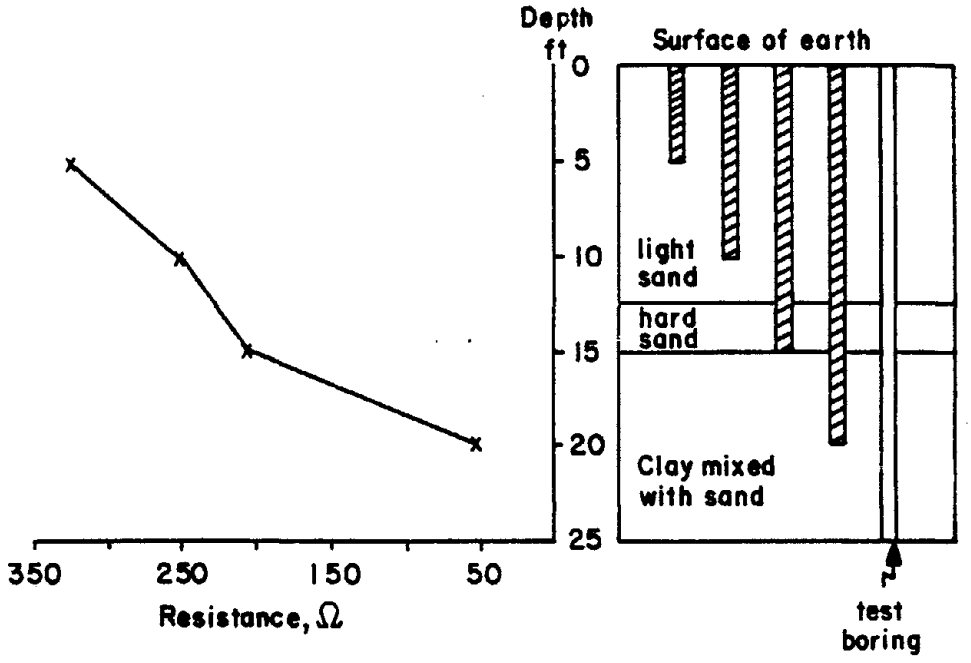


Figure 6.17. Decrease in Earth Resistance as Electrode Penetrates Deeper Soil Horizons.

For multi-electrode systems, the capacitance of each conductor, that is its mutual capacitance with respect to all other conductors, must be calculated. By maximizing the capacitance, the resistance can be minimized, which is the desired goal.

The two predominant methods for determining the capacitance of earth-electrode systems are Howe's average potential method and Maxwell's method of sub-areas, each of which has a constant charge density and potential (33). Howe's technique is similar in that he assumes a uniform charge density on each electrode and then calculates the average surface potential. The capacitance can be found from (34):

$$C = \frac{Q}{V} \tag{6.6}$$

where,

C = capacitance (F)

Q = charge (C)

V = potential (V).

Formulas for Specific Electrode Configurations. One of the most common ground systems, as previously stated, is the rodbed. For a single vertical rod (34):

$$R = \frac{\rho}{2\pi\ell}\left(\ln\frac{4\ell}{a} - 1\right) \tag{6.7}$$

where,

ρ = soil resistivity (Ωm or Ωft)

ℓ = length of rod (m or ft)

a = radius of rod (m or ft).

Figure 6.18 shows how the resistance and conductance of a typical driven rod vary as the rod length is increased (35). As can be seen, the resistance curve is starting to flatten out, which would seem to indicate that lengths in excess of 15 ft are relatively useless. However, the conductance curve is almost linear. Figure 6.19, which is an extended version of the previous graph, shows very clearly that even at depths of 100 ft, the conductance increases in direct proportion to the length (35). If the soil can be easily penetrated, deeper rods are always better. The simple nomogram shown in Figure 6.20 may be used to determine the resistance of a driven rod if calculations are not preferred (36). Figure 6.21 shows the effect of soil resistivity on the resistance of a driven rod, as well as the benefits gained

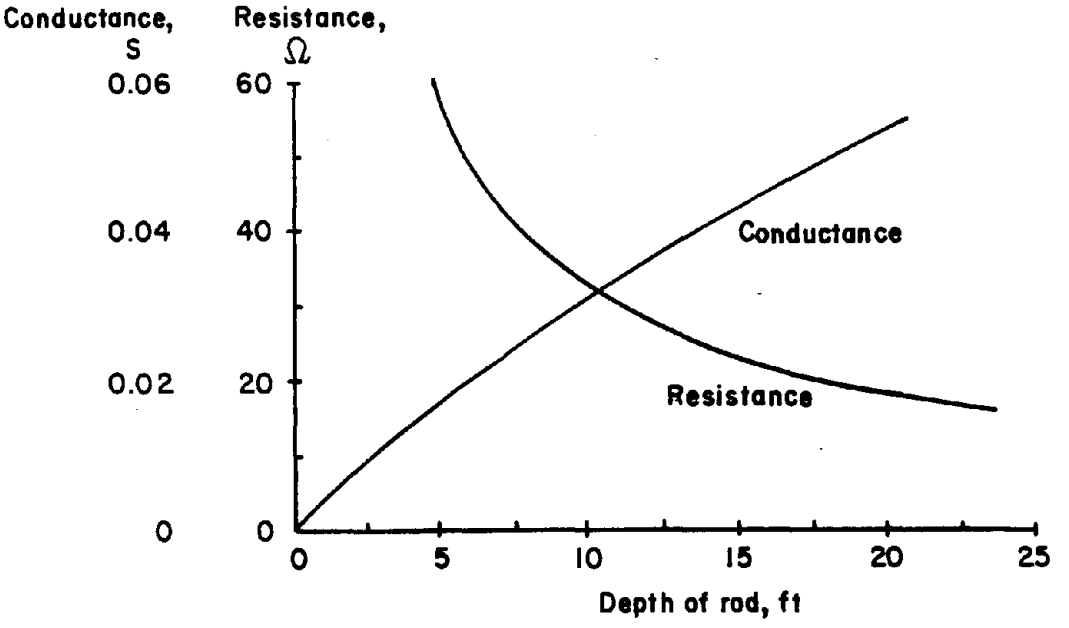


Figure 6.18. Calculated Values of Resistance and Conductance 3/5-inch Rod Driven to a Depth of 25 feet.

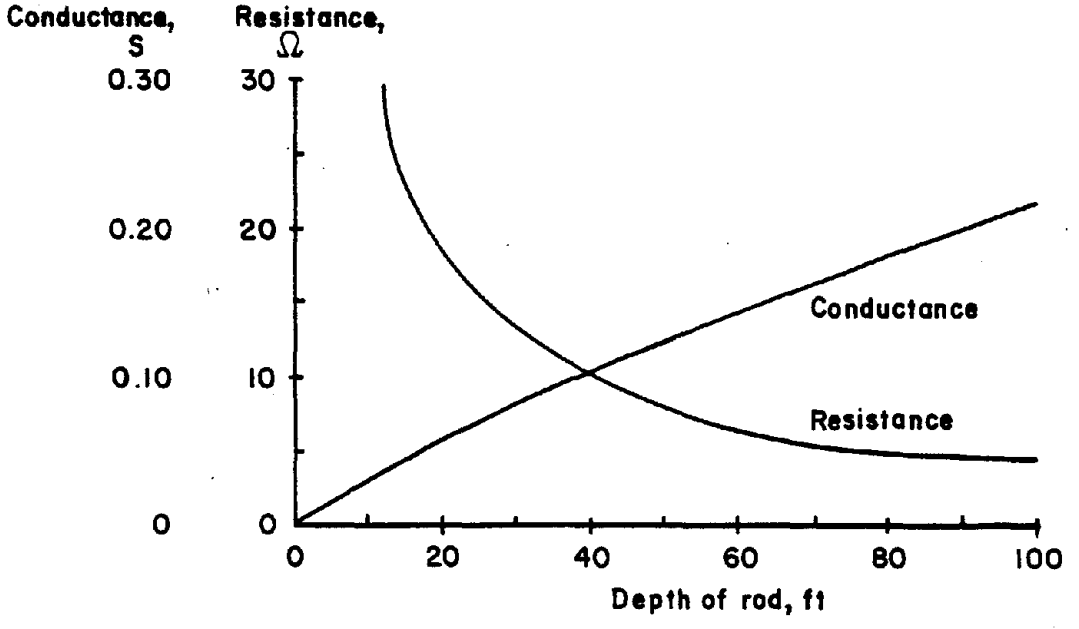


Figure 6.19. Calculated Values of Resistance and Conductance, 3/4-inch Rod Driven to a Depth of 100 feet.

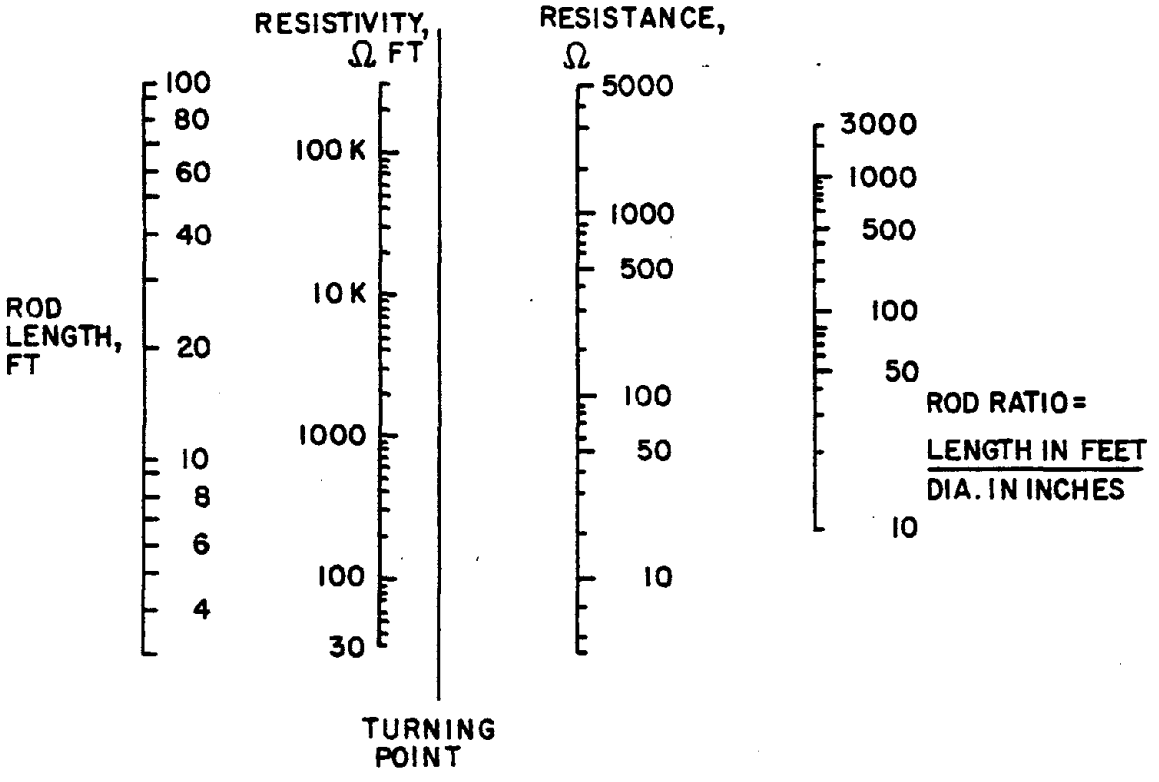


Figure 6.20. Nomogram to Give Resistance of Driven Rod.

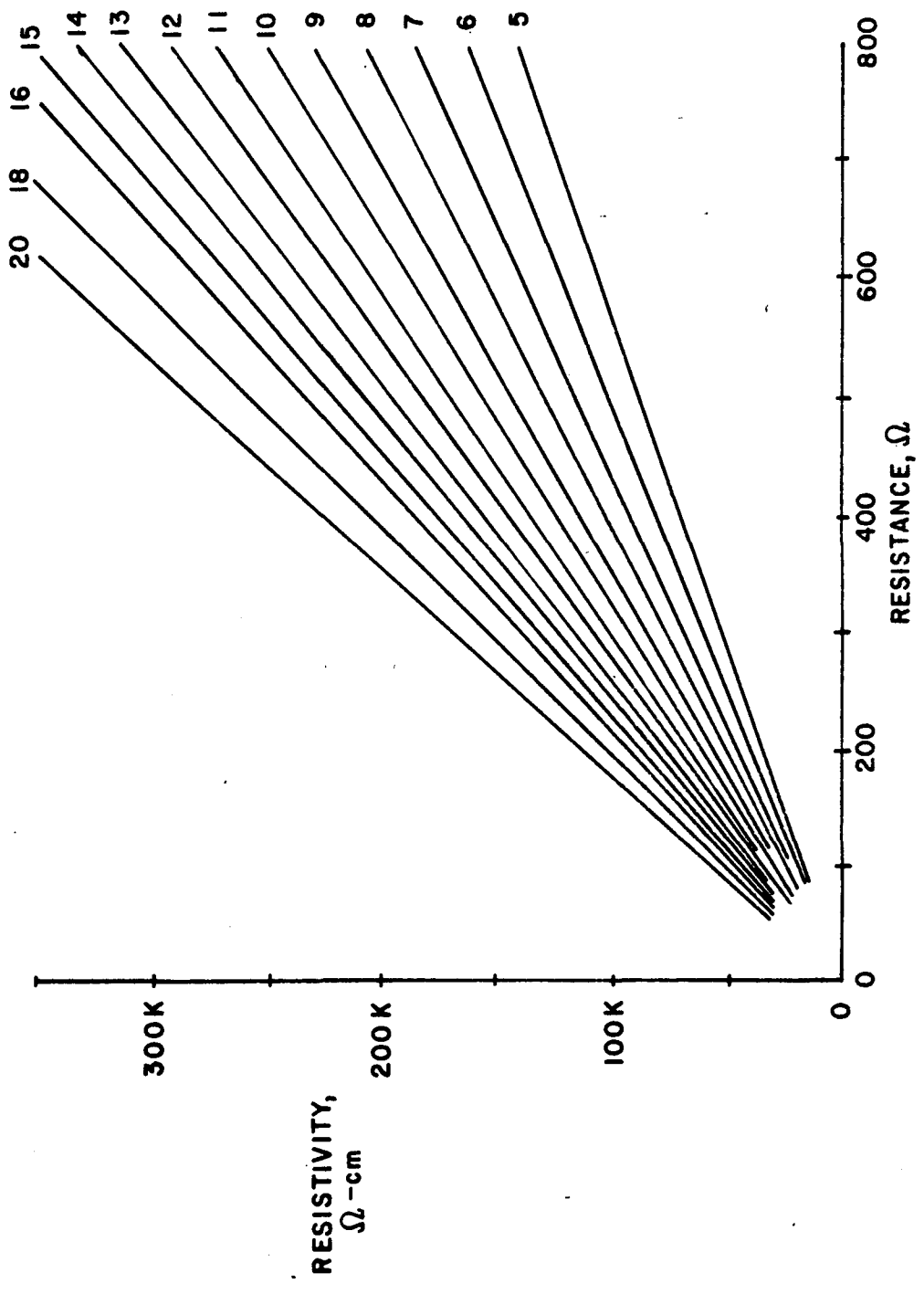


Figure 6.21. Resistance of One Ground Rod, 3/4-inch Diameter; Numbers on Curves are Lengths in Feet.

by using longer rods (34). It can be reasoned that several shorter ground rods are easier to drive than one long rod of the same total length. However, when using multiple rods, mutual-resistance effects tend to negate some effectiveness so the resistance of the group is greater than would be expected, unless very large spacings are used between electrodes (35). Figure 6.22 shows this effect for rods spaced at a distance equal to their length, while Figure 6.23 shows the advantages which accrue as spacing is increased from 5.0 to 100 ft (37).

For systems composed of multiple rods, one of the following two formulas will be applicable. If the rod spacing-to-length ratio is large (spacing >> length), then (38):

$$R = \frac{\rho}{n2\pi\ell} \left(\ln \frac{2\ell}{a}\right) \tag{6.8}$$

where,

n = number of rods

and the other variables have been previously defined. If the rod spacing-to-length ratio is small (length >> spacing)(38):

$$R = \frac{\rho}{2\pi\ell} \left(\ln \frac{2\ell}{A}\right) \tag{6.9}$$

where,

$$A = (a\, S_{12}S_{23}S_{34} \ldots)^{1/n}$$

S_{12} = spacing between electrodes 1 and 2, and so forth.

For grounding meshes (horizontal grids), a formula for determining their resistance is given by (39):

$$R = \frac{\rho}{\pi\ell}\left(\ln\left(\frac{2L}{(2az)^{0.5}}\right)+k_1\left(\frac{L}{(B)^{0.5}}\right)-k_2\right) \tag{6.10}$$

where,

L = total length of buried conductor

z = burial depth

B = area enclosed inside mesh perimeter.

The constants, k_1 and k_2, depend upon the burial depth and the length-to-width ratio of the mesh and may be determined from the graphs shown in Figures 6.24 and 6.25 (39). However, for

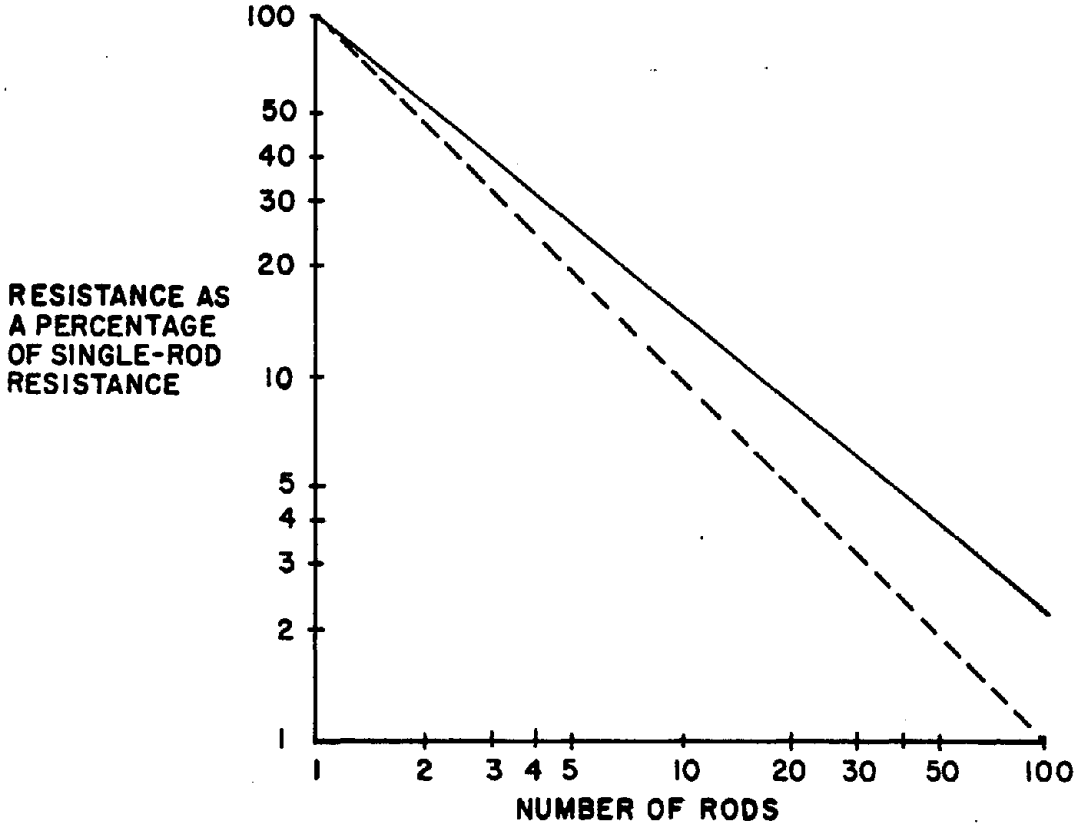


Figure 6.22. Resistance of Parallel Rods When Arranged in a Straight Line or Circle with Spacing Equal to Rod Length; Dashed Line Shows Expected Resistance While Solid Line Indicates Actual Resistance with Mutual Effects.

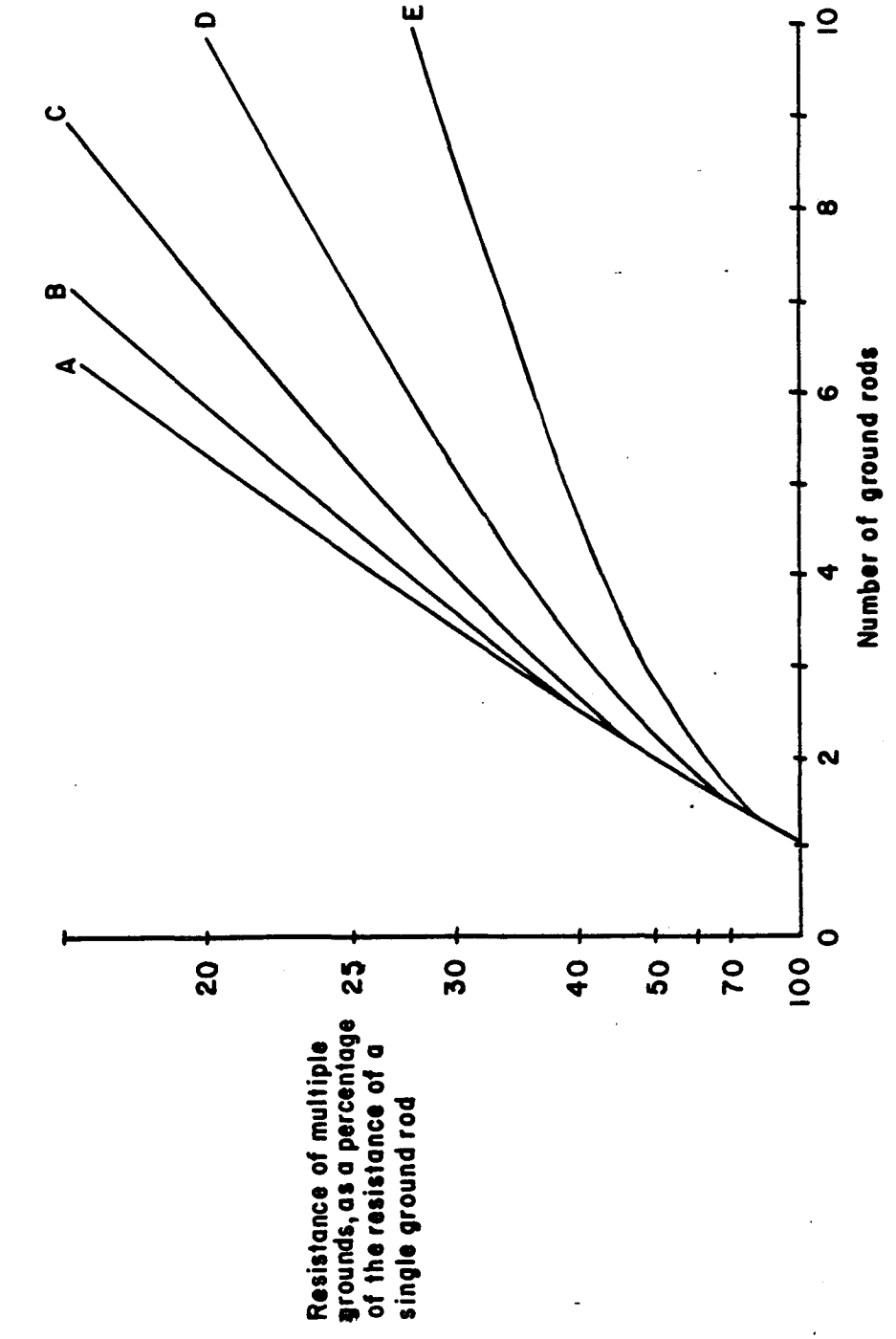


Figure 6.23. Variation of Earth Resistance as the Number of Ground Rods is Increased, for Various Spacings Between Rods.

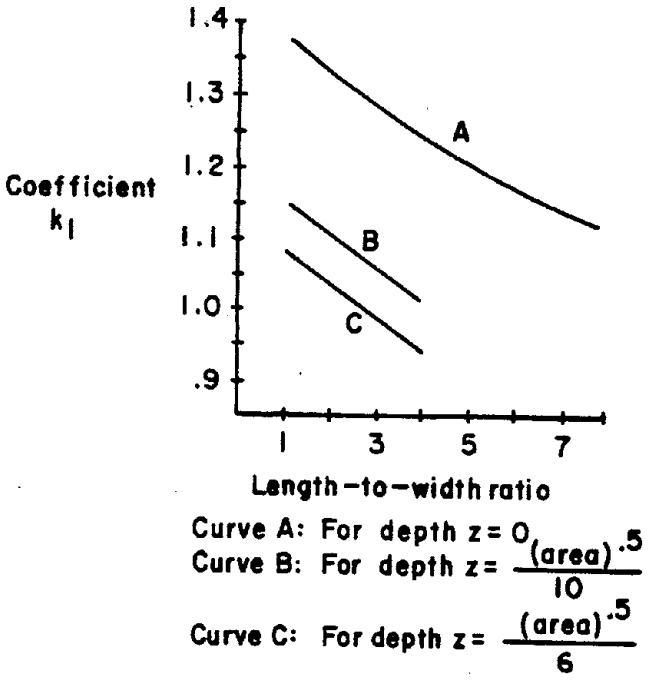


Figure 6.24. Values of Coefficient k_1 as a Function of the Length-to-Width Ratio of the Area.

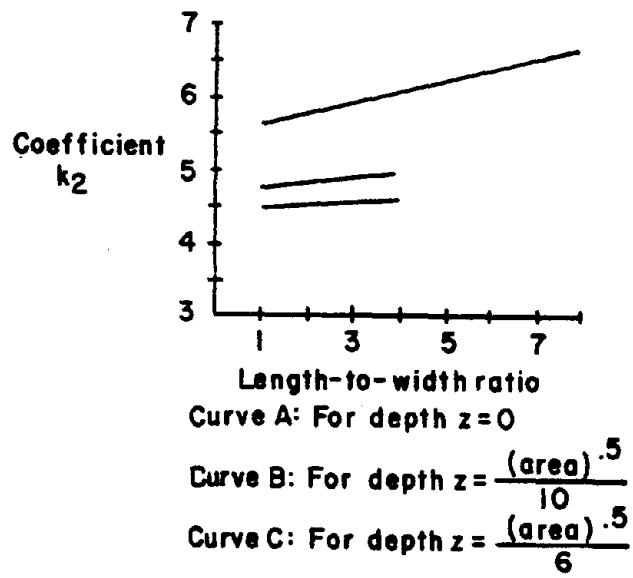


Figure 6.25. Values of Coefficient k_2 as a Function of the Length-to-Width Radio of the Area.

a typical mesh where the length and width are similar and the burial depth is a few feet or less, then $k_1 = 1.3$ and $k_2 = 6$.

In many cases, combinations of a rodbed and a mesh are used especially when driven rods are interconnected by bare conductors which are also buried in the soil. For these situations (39),

$$R = \frac{R_1 R_2 - R_m^2}{R_1 + R_2 - 2R_m} \qquad (6.11)$$

where,

R_1 = rodbed resistance
R_2 = mesh resistance.

The mutual resistance, R_m, is (39):

$$R_m = \frac{\rho}{\pi L}\left(\ln\frac{2L}{\ell} + k_1 \frac{L}{(B)^{0.5}} - k_2 + 1\right) \qquad (6.12)$$

where,

L = total length of mesh conductor
ℓ = length of one rod.

If the soil is of uniform resistivity, adding a mesh to a pre-existing rodbed, or vice versa, cannot be justified merely from the viewpoint of reduced resistance, since the reduction in resistance will seldom amount to more than 10 to 15%. However, the addition of a mesh to a rodbed will usually smooth out the potential-gradient distribution, and the addition of a rodbed to a horizontal mesh generally attenuates seasonal fluctuations in resistance (35,36).

Other electrode configurations are in use, but are not as widespread as the two which were covered above. Table 6.3 summarizes most of the other electrode types and gives formulas for determining their resistance (34). As a first approximation, the Laurent formula gives a quick and fairly accurate estimate of the ground resistance of any type of system (40):

$$R = \frac{\rho}{4r} + \frac{\rho}{L} \qquad (6.13)$$

where,

L = total length of buried bare conductor
r = equivalent radius of the system.

Table 6.3. Approximate Resistance Formulas for Various Electrode Configurations.

Configuration	Description	Formula
	One ground rod; length L, radius a	$R = \frac{\rho}{2\pi L}\left(\ln\frac{4L}{a} - 1\right)$
	Two ground rods; spacing s>L	$R = \frac{\rho}{4\pi L}\left(\ln\frac{4L}{a} - 1\right) + \frac{\rho}{4\pi s}\left(1 - \frac{L^2}{3s^2} + \frac{2L^4}{5s^4} \ldots\right)$
	Two ground rods; spacing s<L	$R = \frac{\rho}{4\pi L}\left(\ln\frac{4L}{a} + \ln\frac{4L}{s} - 2 + \frac{s}{2L} - \frac{s^2}{16L^2} + \frac{s^4}{512L^4} \ldots\right)$
	Buried horizontal wire; length 2L, depth s/2	$R = \frac{\rho}{4\pi L}\left(\ln\frac{4L}{a} + \ln\frac{4L}{s} - 2 + \frac{s}{2L} - \frac{s^2}{16L^2} + \frac{s^4}{512L^4} \ldots\right)$
	Right-angle turn of wire; length of arm L, depth s/2	$R = \frac{\rho}{4\pi L}\left(\ln\frac{2L}{a} + \ln\frac{2L}{s} - 0.2373 + 0.2146\,\frac{s}{L} + 0.1035\,\frac{s^2}{L^2} - 0.0424\,\frac{s^4}{L^4} \ldots\right)$

Table 6.3. Approximate Resistance Formulas for Various Electrode Configurations (Continued).

Configuration	Description	Formula
	Three-point star; length of arm L, depth s/2	$R = \frac{\rho}{6\pi L}\left(\ln\frac{2L}{a} + \ln\frac{2L}{s} + 1.071 - 0.209\,\frac{s}{L} + 0.238\,\frac{s^2}{L^2} - 0.054\,\frac{s^4}{L^4} \ldots\right)$
	Four-point star; length of arm L, depth s/2	$R = \frac{\rho}{8\pi L}\left(\ln\frac{2L}{a} + \ln\frac{2L}{s} + 2.912 - 1.071\,\frac{s}{L} + 0.645\,\frac{s^2}{L^2} - 0.145\,\frac{s^4}{L^4} \ldots\right)$
	Six-point star; length of arm L, depth s/2	$R = \frac{\rho}{12\pi L}\left(\ln\frac{2L}{a} + \ln\frac{2L}{s} + 6.851 - 3.128\,\frac{s}{L} + 1.758\,\frac{s^2}{L^2} - 0.490\,\frac{s^4}{L^4} \ldots\right)$
	Eight-point star; length of arm L, depth s/2	$R = \frac{\rho}{16\pi L}\left(\ln\frac{2L}{a} + \ln\frac{2L}{s} + 10.98 - 5.51\,\frac{s}{L} + 3.26\,\frac{s^2}{L^2} - 1.17\,\frac{s^4}{L^4} \ldots\right)$

Table 6.3. Approximate Resistance Formulas for Various Electrode Configurations (Continued).

Configuration	Description	Formula
	Ring of wire; ring diameter D, wire diameter d, depth s/2	$R = \frac{\rho}{2\pi^2 D}\left(\ln\frac{8D}{d} + \ln\frac{4D}{s}\right)$
	Buried horizontal strip; length 2L, section a by b, depth s/2, b, a/8	$R = \frac{\rho}{4\pi L}\left(\ln\frac{4L}{a} + \frac{a^2 - ab}{2(a+b)^2} + \ln\frac{4L}{s} - 1 + \frac{s}{2L} - \frac{s^2}{16L^2} + \frac{s^4}{512L^4} \ldots\right)$
	Buried horizontal round plate; radius a, depth s/2	$R = \frac{\rho}{8a} + \frac{\rho}{4\pi s}\left(1 - \frac{7a^2}{12s^2} + \frac{33a^4}{40s^4} \ldots\right)$
	Buried vertical round plate; radius a, depth s/2	$R = \frac{\rho}{8a} + \frac{\rho}{4\pi s}\left(1 + \frac{7a^2}{24s^2} + \frac{99a^4}{320s^4} \ldots\right)$

The equivalent radius of a grounding system varies depending upon the exact configuration, but a safe estimate is one-half of the length of the longest diagonal line contained by the system (36).

Contact resistance between the surface of the electrodes and the soil is not normally a significant factor if the bed has been in existence long enough for the soil to settle and compact, but in new beds it may amount to 20% of the total resistance (37).

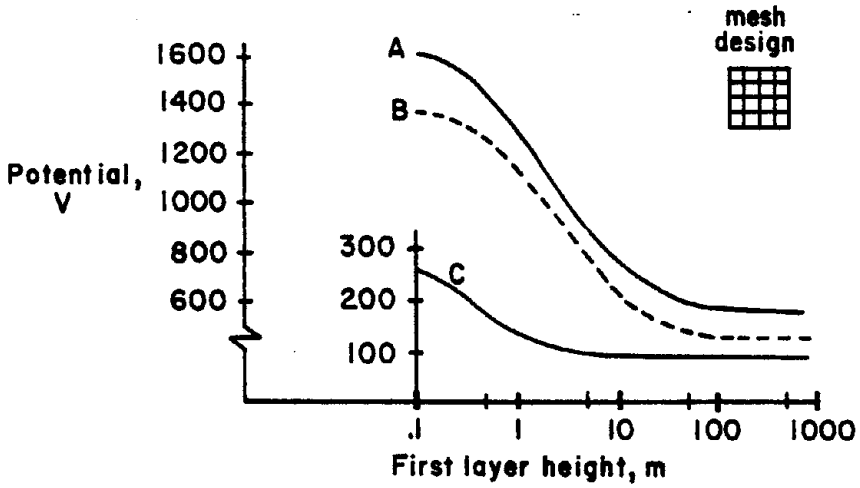
In summary, the best way to achieve a low-resistance ground is to maximize the periphery or areal extent of the grounding system. Conductor diameter has little effect upon resistance, and mechanical-strength requirements should be the primary consideration. Due to wide seasonal variations in soil resistivity of surface layers, deep-buried meshes or deep-driven rods are often preferable. This is also advisable if lower-resistivity layers are known to exist at depth. Further, driven rods are usually preferred over buried meshes for three reasons (22).

1. The expense of earth removal to bury the mesh is avoided.
2. Rods do not require the packing of earth around the buried electrodes to insure good earth contact.
3. The use of rods can obtain any desired resistance that can be achieved by any other ground-bed form.

In any case, although formulas are excellent for calculating the theoretical resistance of a grounding bed, the actual resistance should always be measured with an earth tester to make sure of the system's integrity.

6.5-3 Special Considerations

Two-layer Earth Structures. In many situations, the soil is not homogeneous but consists of two or more distinct layers which are approximately horizontal and which possess differing resistivity values. The effects of a two-layer structure upon ground resistance depend upon the top-layer thickness, the relative conductivity of the two layers, and the dimensions of the grounding system with respect to the first-layer thickness (41). Figure 6.26 shows the potentials and potential gradients for a mesh system in the first layer of a two-layer configuration where the thickness of the first layer varies from 0.1 to 1000 m (42). In this case, the first-layer resistivity ($\rho 1$) is 200 Ωm, and $\rho 2$ is 600 Ωm. The equivalent radius of the grounding grid is 10 m, and the reflection factor (K) as defined by the following equation is 0.5:



Curve A: Potential rise of mesh electrode above remote ground
Curve B: Potential rise of center of mesh above remote ground
Curve C: Potential difference between mesh electrode and center of mesh

Figure 6.26. Influence of First-Layer Height of Potentials.

$$K = \frac{\rho 2 - \rho 1}{\rho 2 + \rho 1}. \qquad (6.14)$$

It may be seen that the potential gradient depends almost solely upon the first-layer resistivity if the grounding system is wholly immersed in that layer. The effect of first-layer resistivity upon grounding-grid resistance increases with the thickness of that layer. Thus, if $\rho 1 < \rho 2$, ground resistance will decrease as top-layer thickness increases.

Soil-Heating Effects. The manner in which a grounding grid responds to the flow of current through it depends upon the magnitude and duration of the loading. Two types of loading have been recognized and will be dealt with separately.

Long-term loading of the safety-ground bed in a mine power system should consist only of currents due to unbalance, the charging of conductor capacitances, and that due to mutual inductance between conductors. At any rate, in a properly functioning system, the current magnitude should be on the order of a few amperes. If the bed is very extensive, ground-current dissipation in the soil may cause only a small rise in soil temperature. Due to the negative temperature coefficient of soil, the actual ground-bed resistance will decrease (35). If the temperature rise is high enough to evaporate some soil moisture, then the resistance will increase somewhat. Capillary action will tend to restore any moisture, however, and the soil itself will also conduct away some of the heat. Eventually, an equilibrium point will be reached where the system is once again stable, although the soil temperature and ground-bed resistance may be slightly altered. The maximum allowable ground-bed current is given by (38):

$$I = \frac{1}{R} (2\rho\lambda\theta)^{1/2} \qquad (6.15)$$

where,

ρ = soil resistivity (Ωm)

λ = soil thermal conductivity (1.2 W/m^{o}C)

θ = maximum allowable soil temperature rise (^{o}C).

If both sides of the equation are multiplied by R, the maximum permissible applied voltage is found to be:

$$V = (2\rho\lambda\theta)^{1/2}. \qquad (6.16)$$

Generally, the maximum allowable temperature is 100^{o}C, at which point total evaporation occurs. Therefore, θ may be replaced by (100 - T) where T is the ambient Celsius temperature. The preceding analysis is subject to two restrictions (43):

1. the thermal conductivity, λ, is somewhat temperature-dependent, and
2. soil moisture will start to evaporate at temperatures below 100°C.

Short-term overloading of the ground system may occur during certain fault situations but, in a properly functioning system, only the ground conductors (inside the trailing cables and in the overhead distribution lines) and the neutral resistor should be subjected to fault current. Should a situation occur in which the grounding bed is called upon to handle large currents for a short time, heat conduction through the soil may be ignored due to its low rate. In this situation, the maximum allowable soil temperature rise is given by (43):

$$\theta = \frac{0.24 i^2 \rho T}{\delta \sigma} \qquad (6.17)$$

where,

ρ = soil resistivity (Ωm)

i = current density of electrode surface (A/m^2)

T = time (h)

δ = soil density (kg/m^3)

σ = soil specific heat (kWh/°C-kg).

So far only the effects of a-c upon soil heating have been discussed. Direct current causes completely different phenomena. The first of these is polarization. The flow of d-c through water causes some of the molecules to dissociate into the constituent gases, hydrogen and oxygen. The resulting gas bubbles eventually form a film on the electrode surfaces, thereby insulating them from the surrounding soil, which leads to a dramatic rise in resistance.

In addition, d-c causes electroosmosis (also referred to as endosmosis). Here, moisture present in the soil (which is not electrolyzed) tends to migrate toward the negative electrode of the d-c source. Actually, cations present in the soil are attracted to the cathode, and the polar water molecule normally is attached to these positive ions. Again, an increase in resistance is the result.

Control of Potential Gradients. In addition to providing a low-resistance path to ground, the ground bed should also be designed so potential gradients in the soil surrounding the bed or step-and-touch potentials are held to a minimum for the protection of personnel.

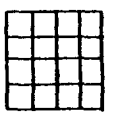
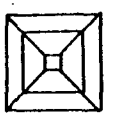
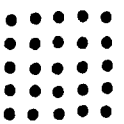
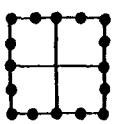
As a generalization, it can be stated that meshes are superior to rodbeds as far as potential-gradient control is concerned (35,42). This is illustrated by Table 6.4, which compares a variety of grounding systems, each having about the same total length of buried conductor (42). The electrodes were buried to a depth of 0.6 m. As can be seen, grid C (rodbed) shows significantly higher potentials than does grid A (mesh). The potential gradients around a mesh may be decreased by making the meshes smaller. Figures 6.27 and 6.28 show the improvement which can be obtained by burying the grounding system to a greater depth (44). It is obvious that the deeper a bed can be buried, the better will be the gradient control. A rodbed, where the rods are interconnected by bare conductors with the entire system buried to a depth of a few feet, should provide both a low resistance and a safe potential gradient. Building a fence around the perimeter of the ground bed is one way of limiting human exposure to hazardous potential gradients.

6.5-4 Resistance Measurement

Techniques. The accepted technique for determining the resistance to infinite earth of a grounding system is called the "fall-of-potential method" (31). Figure 6.29a shows a drawing of this arrangement (40). Three terminals are required: the ground under examination, a potential electrode, and a current electrode. The current electrode is spaced far from the ground system being tested, and the potential electrode is placed at some point on a straight line between the two. The resistance-measuring equipment is operated, and a reading is taken. (Here, a known current is passed through the current electrode, the voltage between the potential electrode and ground is measured and the resistance is the ratio V/I.) This process is repeated as the potential electrode is moved farther and farther from the grounding electrode toward the current electrode. A graph is then drawn, with the ground resistance as the ordinate and the distance between the ground and potential electrodes as the abcissa. Figure 6.29b shows two typical plots which may result (40). Plot "a" was taken with the current electrode at a greater distance than in plot "b." The flat portion of curve "a" is an indication that the current electrode is now far enough away from the grounding system that each is free from the other's effects. This is illustrated in Figure 6.30 by the "hemispheres of influence" surrounding the ground and current electrodes (45).

Figures 6.31 and 6.32 show the proper spacing for both current and potential electrodes for a given "equivalent radius" of the grounding system (36). The theory is based upon hemispherical electrodes so any real ground system must first be converted to an "equivalent hemisphere" (40). This may be done approximately by assuming that the equivalent radius is equal to one-half the length of the longest diagonal that can be placed inside the perimeter of the system (i.e., 50% of the

Table 6.4. Comparison of Grounding Grids with Other Types of Electrodes.

	Rod or mesh layout	Total length of buried conductor, m	Length of rods, m	Number of rods	Maximum mesh voltage, percentage of potential rise
A		160	-	0	18.9
B		174	-	0	12.7
C		175	7	25	32.4
D		176	5	16	23.2
E		176	-	0	17.6

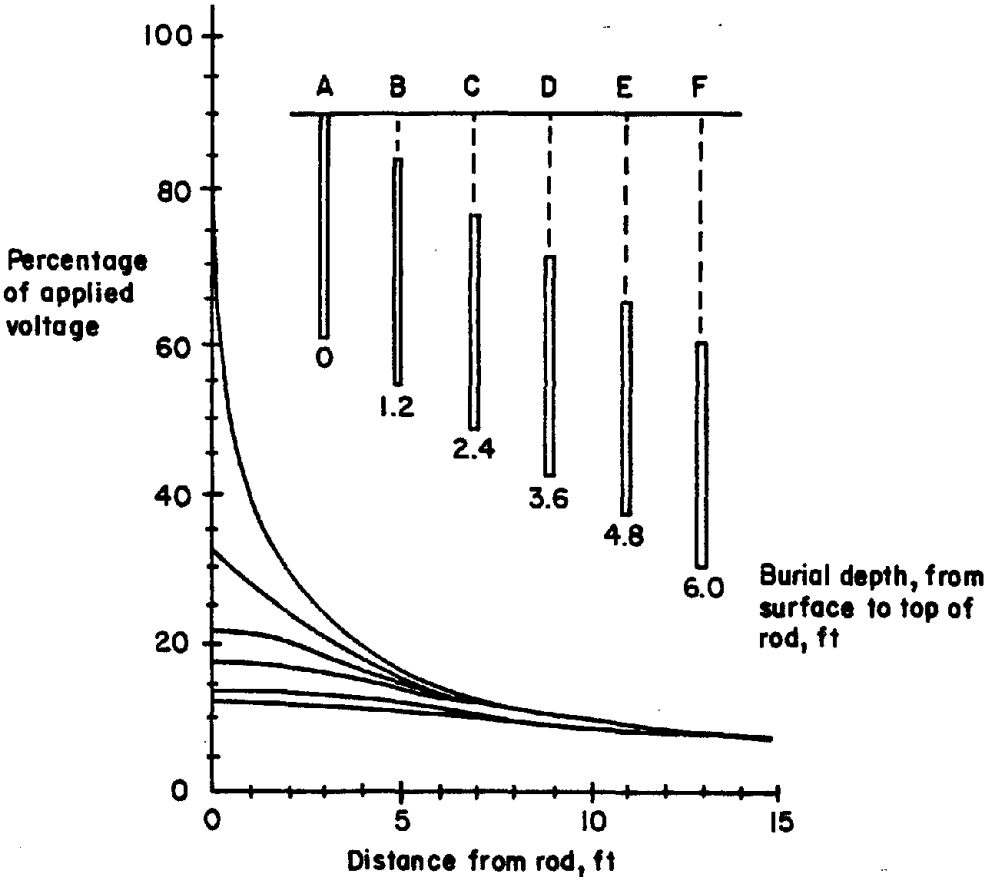


Figure 6.27. Potential on Ground Surface Due to Rod 6-feet Long, 1-inch Diameter, Buried Vertically at Various Depths.

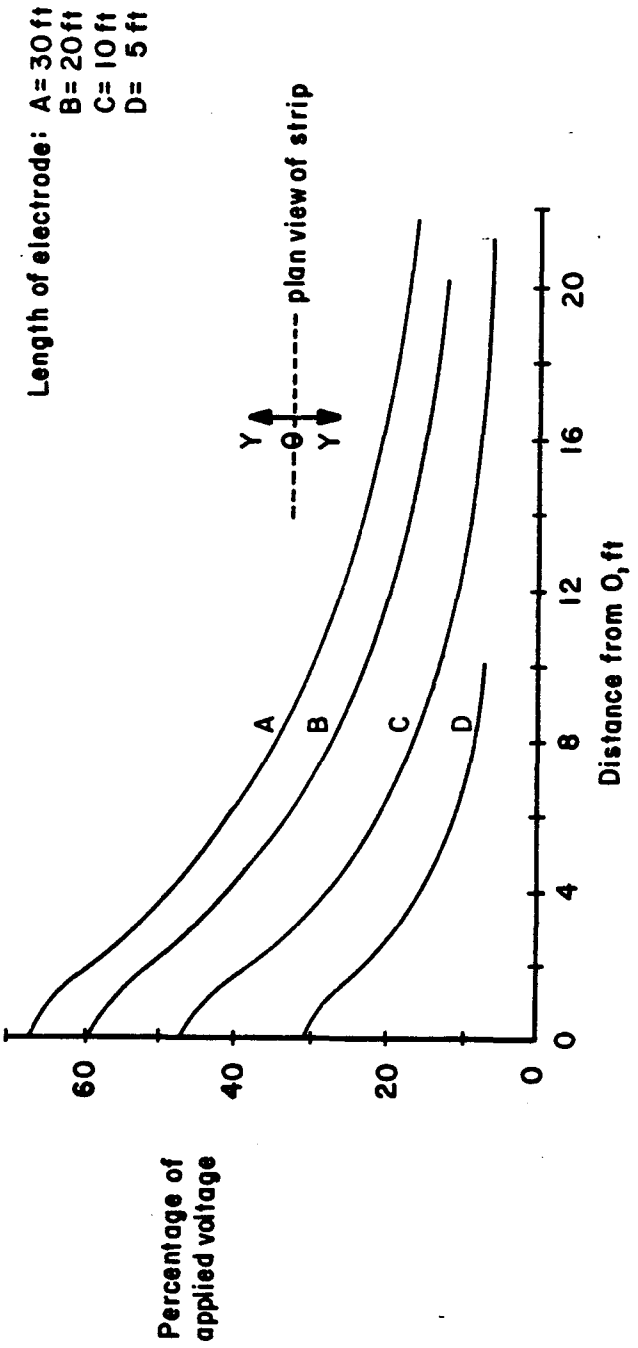


Figure 6.28. Potential on Ground Surface Due to Strips, 1 inch by 0.1 inch, of Various Lengths Buried Horizontally at a Depth of 2 feet; Values Given are Those Along a Line OY Perpendicular to the Length of the Strip.

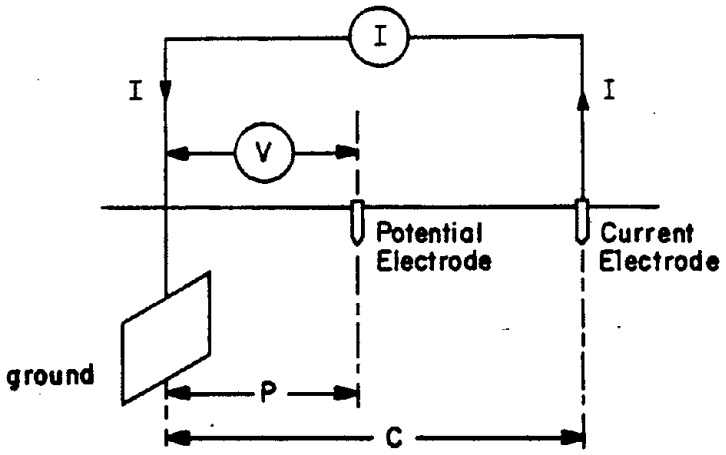


Figure 6.29a. Fall-of-Potential Method.

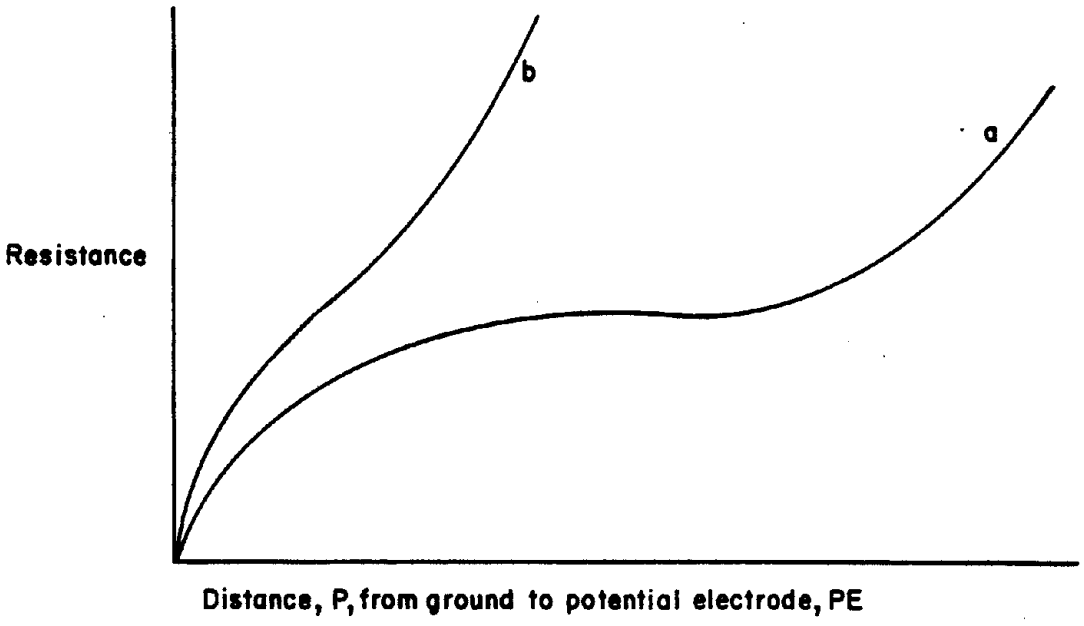


Figure 6.29b. Earth Resistance Curves.

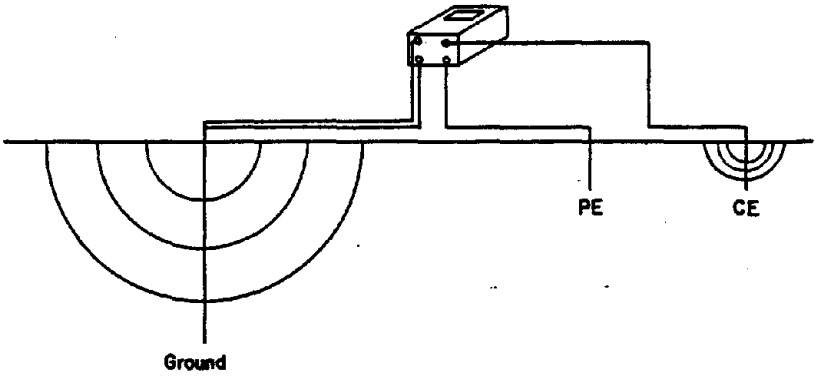


Figure 6.30. Concentric Earth Shells Around the Ground Concentration Being Tested and Around the Current Electrode.

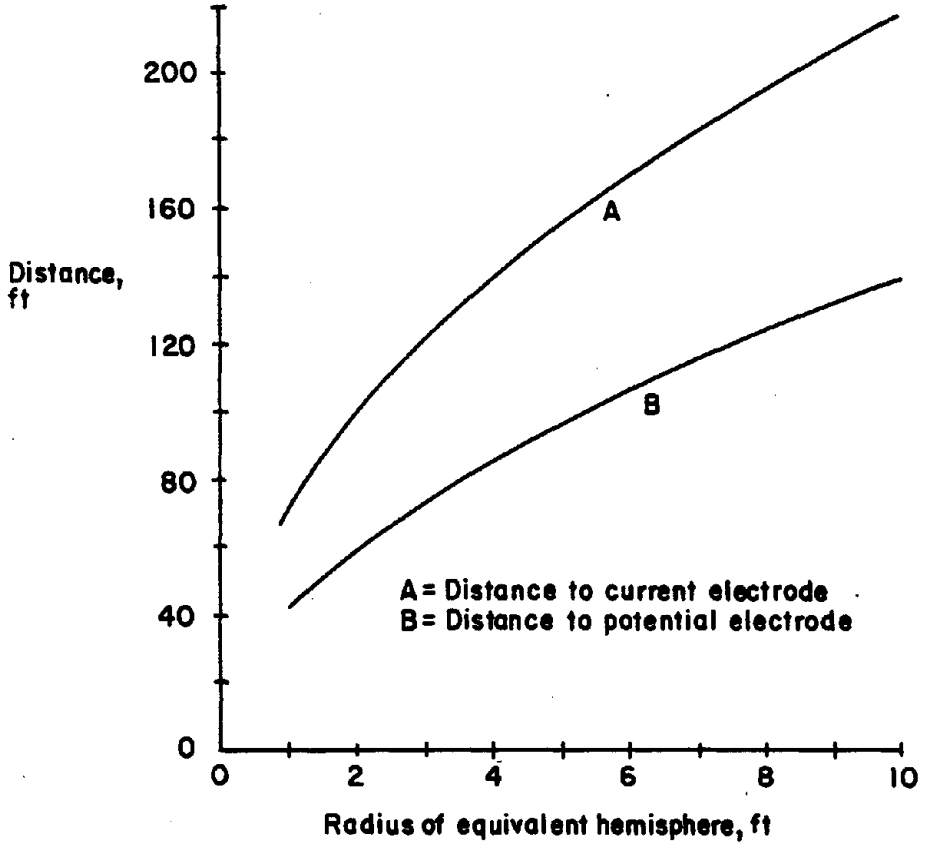


Figure 6.31. Correct Spacing of Auxiliary Electrodes to Give True Resistance Within 2%.

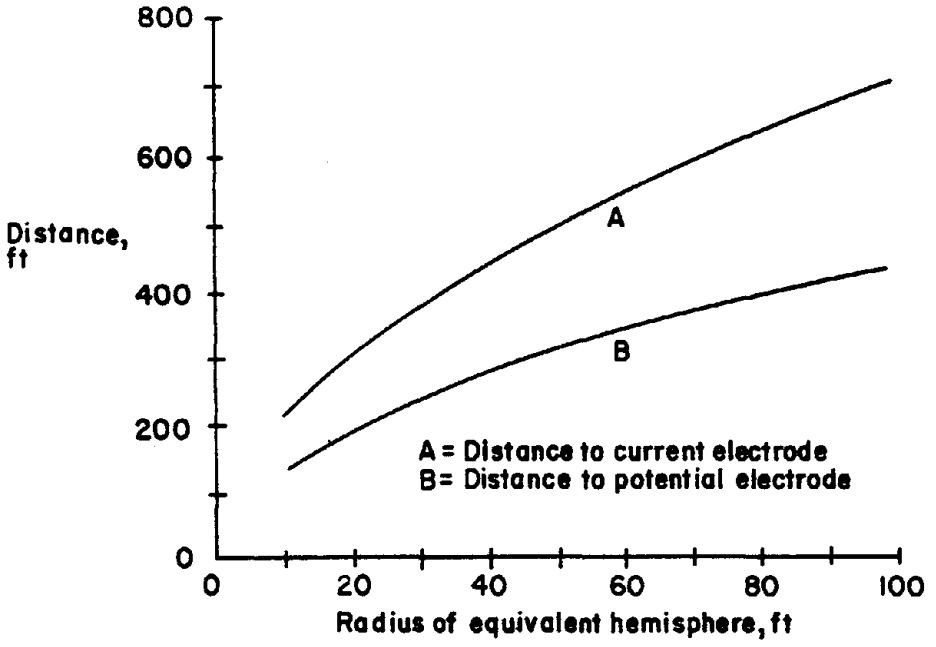


Figure 6.32. Correct Spacing of Auxiliary Electrodes to Give True Resistance Within 2.0%.

maximum bed dimension). The potential-electrode spacing, which yields the true value of ground resistance, is equal to about 61.8% of the current-electrode spacing. For large ground systems, the necessary spacings of potential and current electrodes may be impossible to attain. In that case, the same procedures as were outlined earlier may still be followed (varying the potential electrode spacing while keeping the current electrode, at some fixed spacing as far as possible from the grounding system). The true resistance may then be derived from the resulting graph using one of several available methods (40).

Ground Test Instruments. Certain precautions should be observed when the choice of a ground test instrument is made. A machine that uses d-c should be avoided due to problems with polarization and electroosmosis. Alternating current is satisfactory, but a frequency slightly removed from the actual power frequency is preferable so the effects of stray currents can be avoided. On the other hand, if a frequency is used which is far removed from the power frequency, erroneous results may occur since ground resistance (impedance) varies with frequency (46). The leads from the instrument to the electrodes should be spaced as far apart as possible to minimize mutual-inductance and capacitance effects. In a good instrument, the resistance of current and potential probes is not critical, but inferior equipment will give readings that vary widely depending upon the probe resistance. Nevertheless, great accuracy in earth-ground-resistance measurements is not critical because the earth-resistance techniques are not precise or accurate.

6.5-5 Soil Resistivity

In the discussions on resistance it was pointed out that soil resistivity, ρ, is an important parameter; specifically, ground-bed resistance is directly proportional to soil resistivity. The resistivity of a material has been defined in Chapter 3 as the resistance in ohms between the opposite faces of a unit cube of that material. Values of resistivity vary widely depending upon the substance being measured, and for rocks and minerals may range from 10^{-3} to 10^{17} Ωcm. A general classification is illustrated by Table 6.5 (47). Efforts have been made to relate resistivity values to geologic age of various rocks, and Table 6.6 is applicable in most cases, although there are exceptions (37). As a rule, resistivity increases with rock age (48).

In addition to geologic age, rock structure also enters into resistivity determinations. The resistivity of newly-formed rock depends mainly upon the amount of water contained in it. Young rocks will generally have a large pore volume and hence a fairly significant quantity of connate water; therefore, it will exhibit a low resistivity. As time passes and the rock is

Table 6.5. General Resistivity Classification.

Description	Resistivity, Ωcm
good conductor	10^{-3} to 10
intermediate conductor	10^{2} to 10^{9}
poor conductor	10^{10} to 10^{17}

subjected to forces which tend to consolidate, compress, or metamorphose it, the pore volume and water content will decrease, with a subsequent increase in resistivity (48). Hard crystalline rocks are usually bad conductors, but if crushed or badly fractured, their resistivity may decrease due to greater porosity (49). Resistivity values for some common soils are given in Table 6.7 (36).

When completely dry, most rocks and minerals are non-conducting, although some metallic orebodies will carry current (44). The main soil constituents have very high resistivities, and in fact, the oxides of silicon and aluminum are good insulators (38). Figure 6.33 gives a review of the resistivities for some common rocks, ores, and metals (49).

Factors Affecting Resistivity. There are several factors that can affect resistivity, and these are generally considered to include:

1. moisture content,
2. dissolved salts,
3. temperature,
4. soil type,
5. grain size and distribution, and
6. location.

The level of influence for each is described in the following paragraphs.

Soil containing no moisture has a very high resistivity. The addition of water causes a sharp increase in conductivity, but the decrease in resistivity rapidly levels off once the moisture content of the soil reaches about 16% by weight, as shown in Figure 6.34 (36). Tests by the U.S. Bureau of Standards indicate that resistivity increases markedly when moisture content falls below 20% (31).

The conductivity of water is itself a variable which causes noticeable effects. Very pure water, such as may be found high in the mountains, has a poor conductivity so mountain soil may

Table 6.6. Variations in Resistivity with Geologic Age.

Resistivity, Ωm	Quarternary	Cretaceous Tertiary Quarternary	Pennsylvanian Mississippian Triassic	Cambrian Ordovician Devonian	Pre-Cambrian and Combo. with Cambrian
1					
		Loam			
10		Clay			
		Chalk	Chalk		
30			Trap		
			Diabase		
100			Shale		
300			Limestone	Shale	
			Sandstone	Limestone	Sandstone
1000	Coarse sand and gravel			Sandstone	Quartzite
				Dolomite	Slate
3000	in surface				Granite
	layers				Gneisses
10,000					

Table 6.7. Typical Values of Resistivity of Some Soils.

Type of Soil	Resistivity, Ωcm
Loams, garden soils, etc.	500 to 5,000
Clays	800 to 5,000
Clay, sand and gravel mixtures	4,000 to 25,000
Sand and gravel	6,000 to 10,000
Slate, shale, sandstones, etc.	1,000 to 50,000
Crystalline rocks	20,000 to 1,000,000

Table 6.8. Effect of Temperature on Resistivity of Water.

	Temperature, °C	°F	Resistivity Ωcm
	20	68	7,200
	10	50	9,900
Water	0	32	13,800
Ice	0	32	30,000
	- 5	23	79,000
	-15	14	330,000

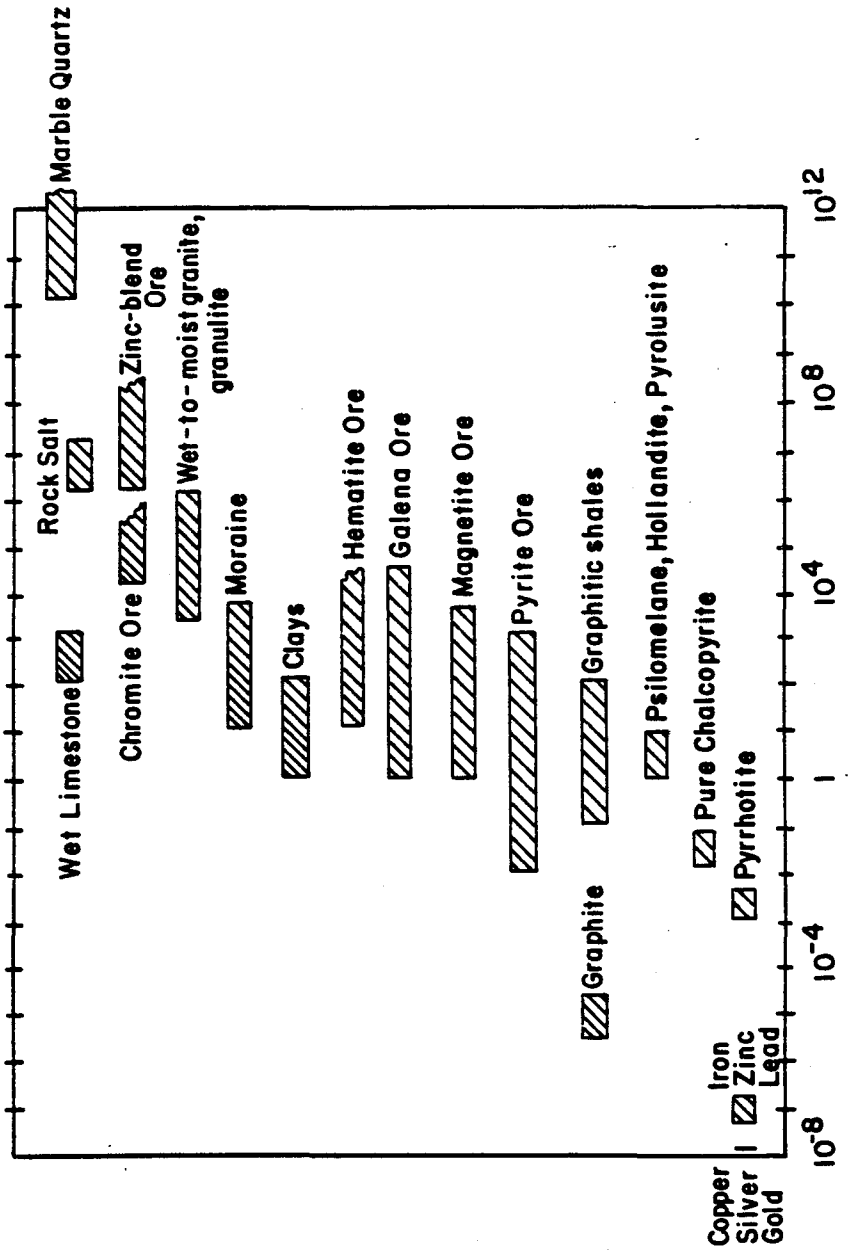


Figure 6.33. Resistivity Range of Some Rocks, Minerals and Metals.

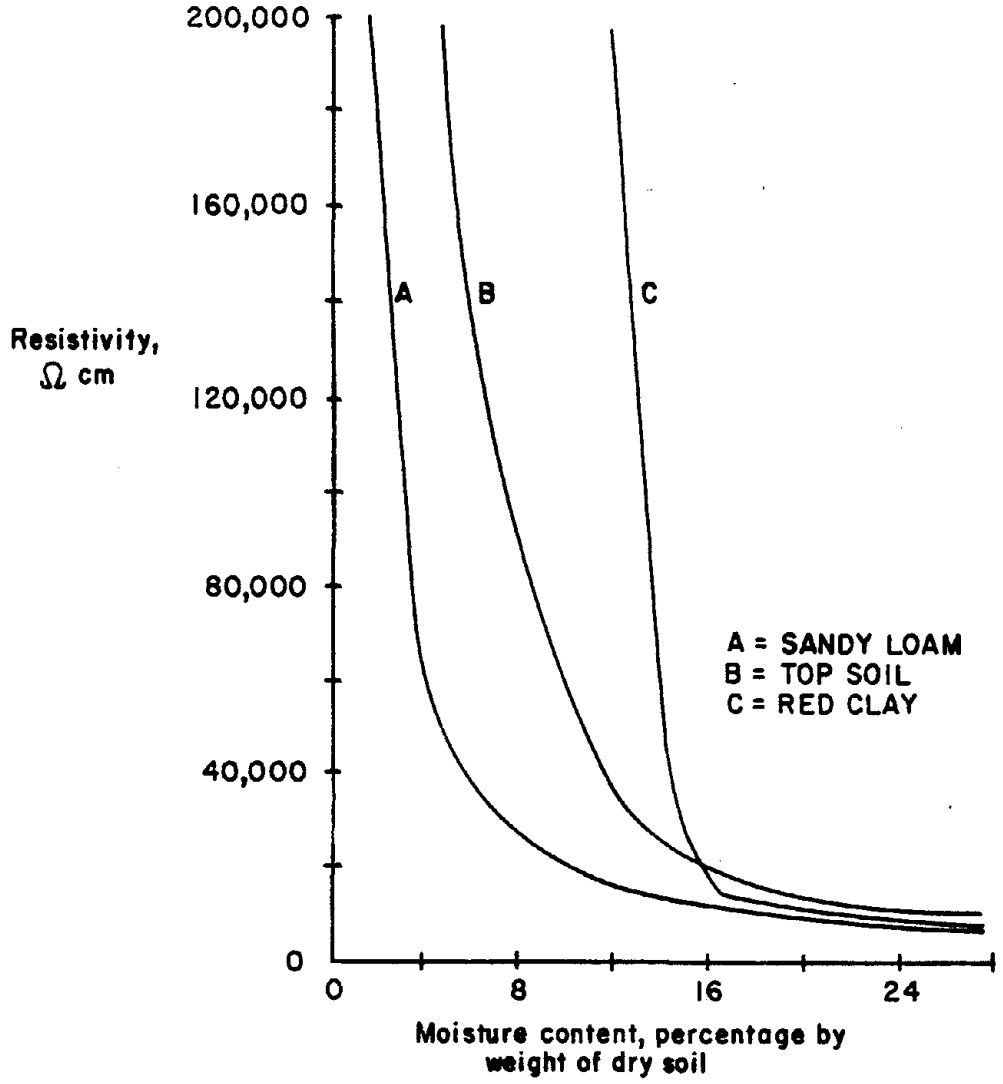


Figure 6.34. Variation in Soil Resistivity with Moisture Content.

be very wet and still possess a very high resistivity (44). To a large extent, it is the dissolved salts present in the water which make the solution conductive. Conduction is electrolytic in nature; that is, current flows via the movement of positive and negative ions in solution. Thus, the concentration of dissolved salt, the particular type of salt, and the solution temperature all have an influence upon the degree to which a dissolved salt will lower soil resistivity. Figure 6.35 shows the effect which various salts have upon resistivity (36).

Water has a large negative temperature coefficient of resistivity, and the transition from liquid to solid state is marked by a dramatic rise in resistivity (50). Additionally, most electrolytes have a negative temperature coefficient of resistivity, amounting to about -2.0%/°C (44). Table 6.8 illustrates this effect (51).

When a very high impulse current such as a lightning stroke enters a ground bed, the resulting voltage gradient may be so high that the soil breaks down. These current levels can be extremely damaging to the soil. Lower current levels flowing into a ground system for extended periods may heat the soil to the point where most of its moisture will evaporate. When this condition is reached, soil resistivity will increase drastically.

Different soils are characterized by various resistivity levels. To a large extent, this is due to the previously discussed effects of structure as it pertains to conductivity. Loams and clays possess a low resistivity, while shales, sandstone, and crystalline rocks occupy the high end of the scale (38).

The nature of the particles making up the soil or rock is another aspect of rock structures. Here, the influence upon conductivity is based upon the ability of the material to trap and retain water. Surface tension will cause water to cling to large soil particles or grains; with small-grained substances, moisture simply fills up the multitude of pore spaces between individual particles. The range of particle sizes and their packing determines how much of the volume occupied by a particular soil will be void space and thus available for filling by water. If most of the grains are the same size, total pore volume may range from 26 to 46%, depending upon the manner in which the grains are packed (47).

If a particular rock structure or formation is confined to a small geographical area, then it probably has a fairly uniform resistivity, excluding areas of subsequent igneous activity. Should the formation be widespread, however, chances are that variable resistivities will be noted depending upon location.

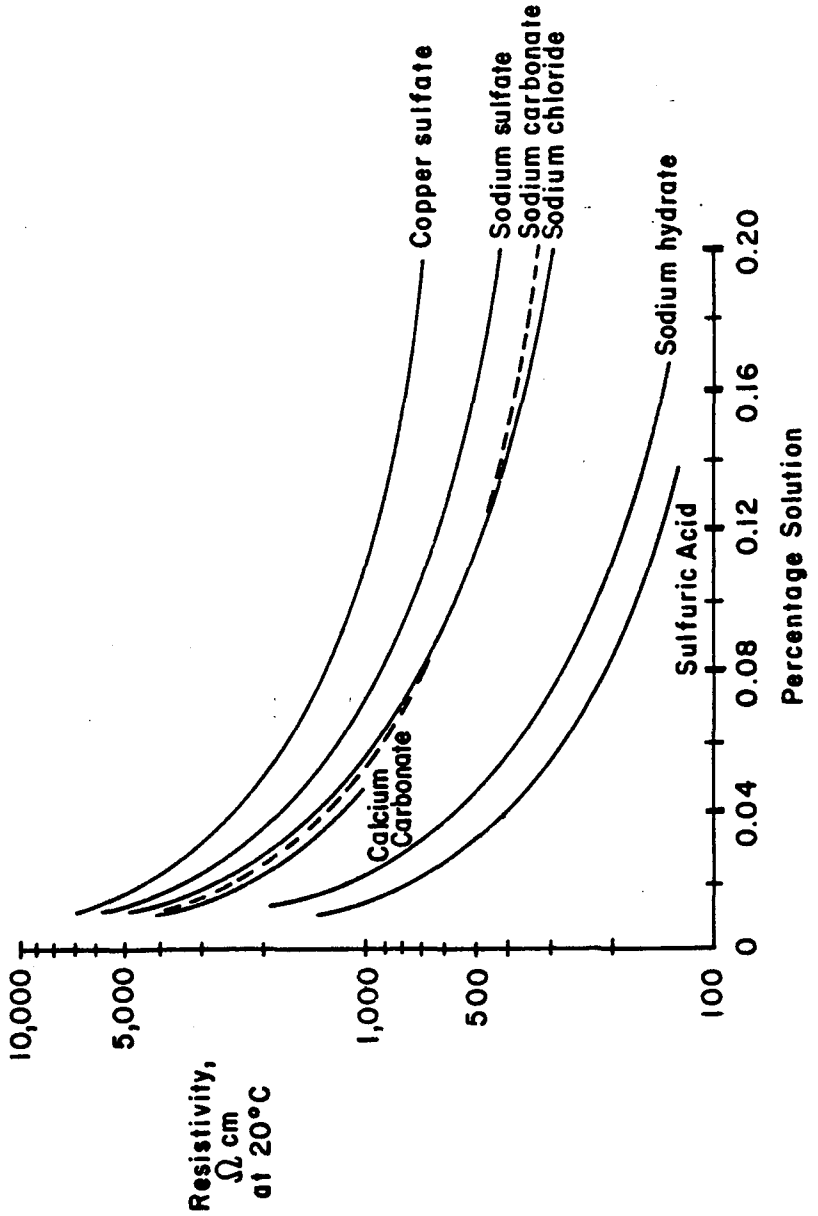


Figure 6.35. Typical Resistitivity Curves of Solutions.

This is due to the differences in local conditions which may have prevailed over a small area during actual deposition or formation of the rock strata. In addition, this may be caused by variations in the ground water properties from place to place within a large region (48).

Measuring Resistivity. The basic procedure for measuring soil resistivity involves the determination of the potential gradient on the earth's surface caused by flow of a known current through the area.

To illustrate the basic technique, assume the earth structure composed of two horizontal layers, the top one of high resistivity, ρ_1, and the lower one of low resistivity, ρ_2, as shown in Figure 6.36 (47). The thickness of the upper layer is given by h. A power source forces current flow through the ground between the outer electrodes. At very small electrode spacings, the apparent resistivity will approximate ρ_1 since most current flow would be confined to the upper layer. At very wide spacings (much larger than h), the apparent resistivity will be about the same as ρ_2, because the majority of the current would flow through the deeper layer.

Many methods are available for measuring earth resistivity, such as the techniques of Gish-Rooney, Lee, and Schlumberger. Most of the procedures (as named above) are based on the arrangement described by Frank Wenner (52) which is shown in Figure 6.37 (45). Four uniformly-spaced electrodes are used, and a current source is connected across the two outer terminals while the potential drop is measured across the inner terminals. When the electrode length "b" is small compared with the spacing "a" then the resistivity is (40):

$$\rho = 2\pi aR \qquad (6.18)$$

where,

ρ = resistivity (Ωm or Ωft)

a = spacing between electrodes (m or ft)

R = resistance = V/I (Ω).

Some problems which may arise from the use of this method are:

1. stray currents due to leakage for instance, from motors,
2. natural currents due to electrolysis of nearby ore,
3. polarization due to use of a d-c source,
4. inductance between lead wires, and
5. leakage from wires and instrument when in wet areas.

The first three problems are circumvented through the use of a-c source operating at a non-power frequency of an instrument which generates the equivalent of a square wave. The use of a well-

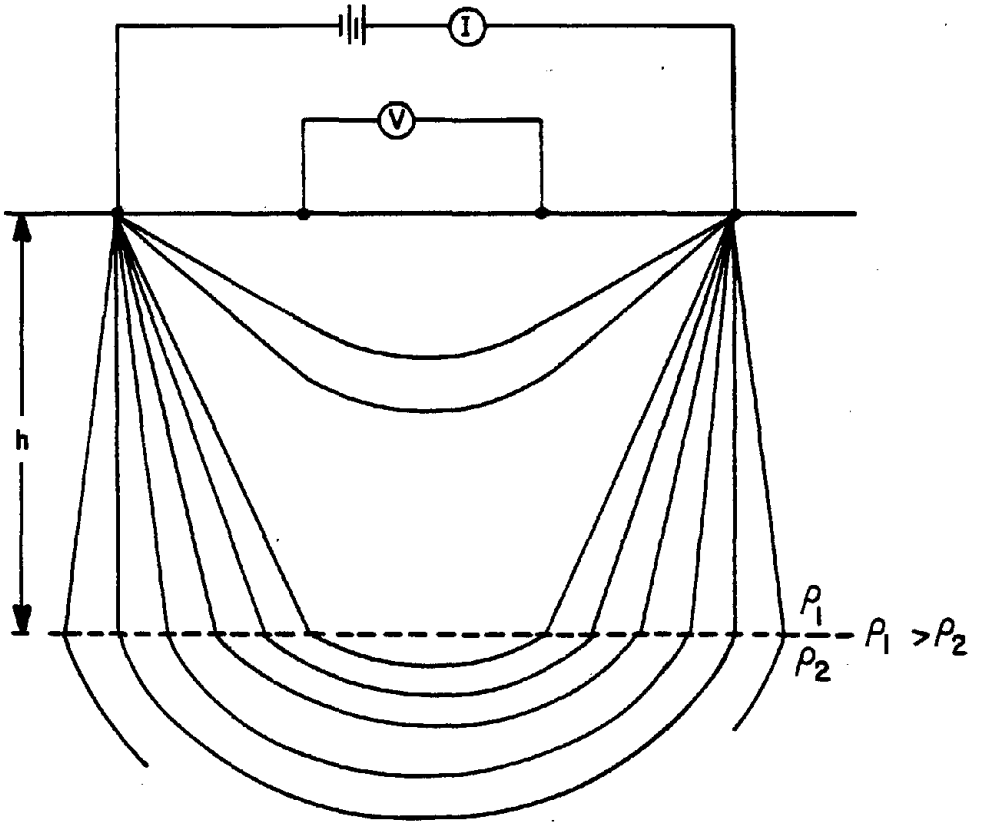


Figure 6.36. Diagram for a Four-Electrode Resistivity Survey Showing Lines of Current Flow in a Two-Layer Earth.

insulated instrument and wires solves the latter two difficulties. Employing all these factors, the megohmmeter (Section 4.9) is an excellent apparatus for use in work of this type.

To perform a resistivity survey, the megohmmeter is set up as shown in Figure 6.37. The instrument is operated, and a resistance value R is read from the built-in meter. The procedure is repeated at different electrode spacings. A graph may be made comparing the resistivity, ρ, with the electrode spacing a, as shown in Figure 6.38 (36). For each value of electrode spacing, there is a corresponding value of resistivity, ρ_a, seen by the instrument. This apparent resistivity is equal to the resistivity that a semi-infinite homogeneous earth would display at an equal electrode spacing and an identical value of R. In the example shown, the apparent resistivity decreases as electrode spacing increases. The overall shape of the curve indicates that the soil here is composed of two horizontal layers, with the overlying horizon having a higher resistivity than the lower one. As the electrode spacing, a, is increased, more and more of the current flow between the outer electrodes occurs in the deeper layer of the soil, and this is reflected in the continuous decrease in the apparent resistivity (48).

In a case like the one just described, a grounding grid composed of deep-driven vertical rods would be best, since the rods would penetrate into the underlying of higher conductivity and thus provide a more effective ground. Additionally, soil horizons near the surface are usually subject to wide seasonal variations in resistivity due to changes in ambient temperature and moisture (53).

Tagg (36) presents several methods whereby an accurate interface-depth determination may be calculated. Values are read from a "standard graph" and multiple calculations are then performed, followed by another graph construction, from which the correct depth is read. Figures derived in this manner are said to agree closely with the actual conditions as verified by core-drilling.

Chemical-Treatment Effect on Soils. The natural resistivity of some soils is so high that it is virtually impossible to construct a grounding grid with a satisfactorily low value of resistance. By injecting into the ground a substance whose resistivity is very low, the local soil resistivity can be effectively reduced, thereby lowering the resistance of a grounding grid. Such chemical treatment acts to increase the apparent dimensions of the metallic electrodes (54). The result of chemical treatment is to reduce ground resistance by a considerable amount, often as much as 15 to 90%. Figure 6.39 shows an example of this effect (31). Generally, the percentage improvement is greater for a very high-resistance ground.

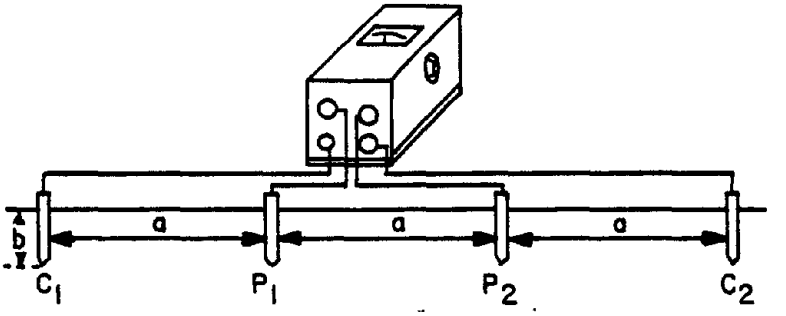


Figure 6.37. Connections for Wenner Four-Terminal Resistivity Test Using Megohmmeter; Distance "a" Should be at Least 20 Times "b".

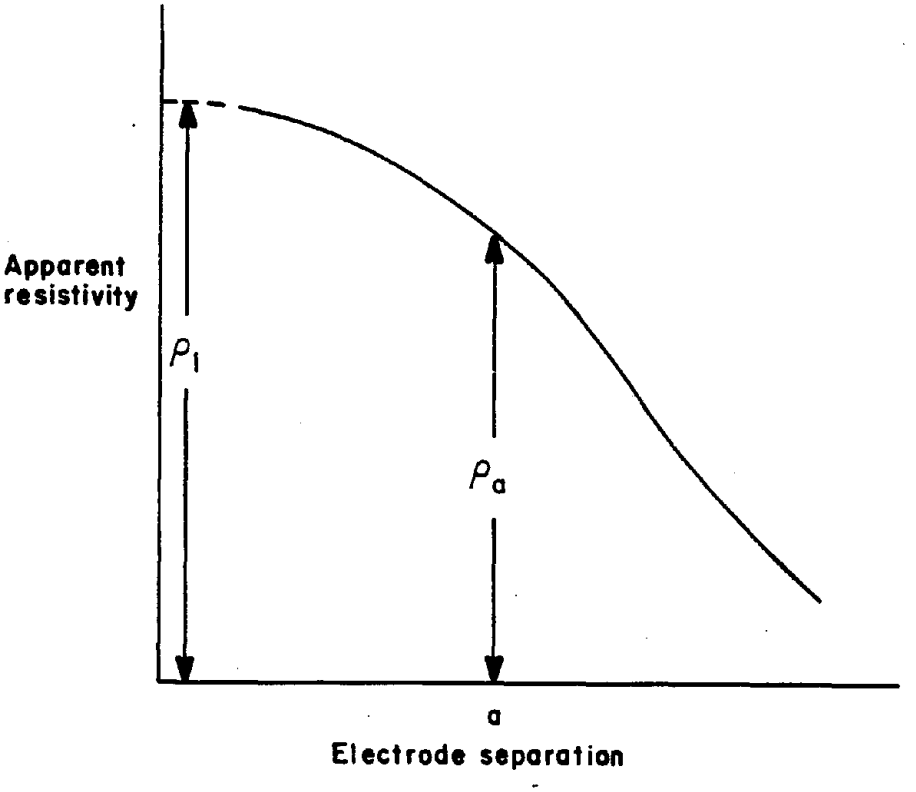


Figure 6.38. Typical Curve of Resistivity Versus Electrode Separation.

Substances which have traditionally been used as chemical additives include sodium chloride, calcium chloride, copper sulfate, and magnesium sulfate (31). Newer additives include gels composed of acrylamide, silicic acid, or copper ferrocyanide. In the past, electrodes were sometimes surrounded by a bed of coke, not a true chemical treatment but rather a partial soil substitute (44). The effectiveness of most treatments in lowering ground resistance is about the same, with the ultimate selection depending upon the criteria of cost, availability, and corrosive properties.

A prime disadvantage shared by most chemical treatments is the fact that they will attack (corrode) most metals (54). Magnesium sulfate has little or no corrosive effects, and graphite is also innocuous. Other additives generally speed up the decay of grounding electrodes.

Another disadvantage is that chemical treatments are dissipated and carried away by natural drainage through the soil (31). Acrylamide gel, which is not water-soluble, is an exception (51). The rate at which chemical additives are washed away depends upon the soil type and porosity as well as the amount of rainfall. Useful life may range from one-half to five or more years.

The cost of chemical treatment may be higher than the price of driving longer ground rods to reach deeper, lower-resistivity soil layers, but in some instances it is not feasible or desirable to increase penetration depth. Also, as shown in Figure 6.40, the seasonal variations in resistance, exhibited by grounding grids due to temperature and moisture fluctuations, are attenuated in those cases where chemical treatment has been applied (31).

The best method of application, illustrated in Figure 6.41, is to dig a circular trench of 18-inch inside the diameter and about one-foot deep around each ground rod (31). The additive is placed into the trench and then covered with earth. The area is then flooded with water to initiate the solution process. In this manner, the solution can permeate a greater volume of soil, while any corrosive action is minimized.

6.5-6 Corrosion Effects

Corrosion is a phenomenon which must be considered in the design of a grounding system. There are three basic ways by which underground corrosion can occur (55):

1. dissimilar metals connected together electrically and surrounded by an electrolyte such as soil;
2. dissimilar electrolytes in close proximity to the same piece of buried metal, and
3. stray electrical current leaving a buried-metal structure.

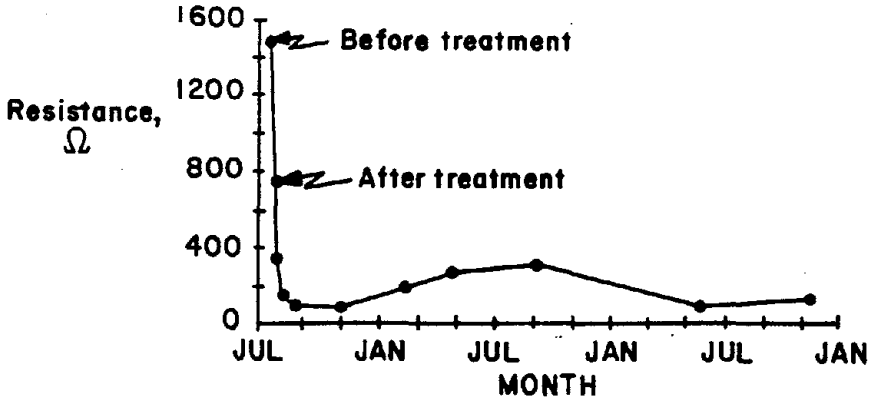


Figure 6.39. Reduction in Ground Mat Resistance by Soil Treatment.

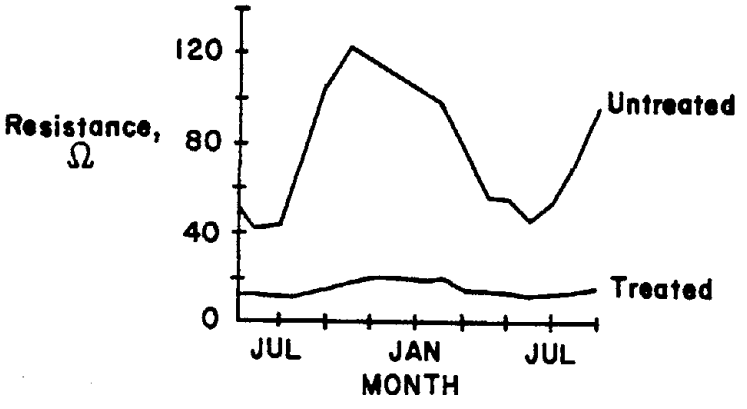


Figure 6.40. Seasonal Resistance Variations Attenuated by Soil Treatment.

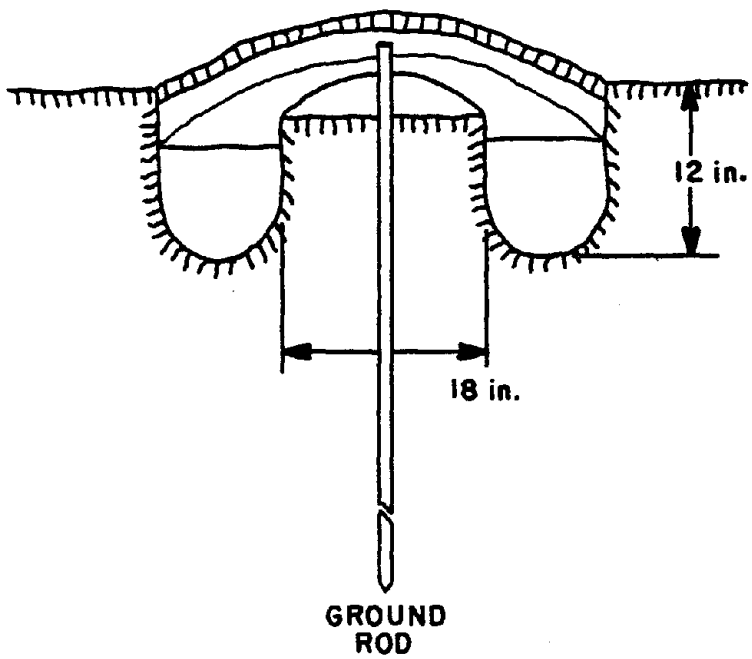


Figure 6.41. Trench Method of Soil Treatment.

In the first mode, variations in electro-chemical potential provide the key to the dilemma. The "standard half-cell," upon which most corrosion work is based, consists of a copper rod bathed in a saturated copper-sulfate solution. When measured with reference to the copper/copper-sulfate half-cell, each metal displays a certain characteristic potential, as shown in Table 6.9 (56). If two metals are joined and immersed in soil, the one whose potential is more negative will discharge current and be corroded, but the more positive ("noble") species will collect current and be protected. When only one metal is used, corrosion can still occur due to differences in soil composition. Metal in an oxygen-rich zone will be protected, while metal in a relatively oxygen-poor soil horizon will be attacked. Foreign metallic structures in the grounding-grid vicinity, such as pipes, cable sheaths, and building frames, may also set in conjunction with the ground bed to form an anode-cathode corrosion situation.

The engineer designing a grounding system is faced with the problem of solving two conflicting sets of demands. For safe grounding, a very low-resistance is desired between the soil and the buried metallic grid. To eliminate potential-gradient hazards, all metal structures should be tied together. However, corrosion protection requires that underground metallic structures be insulated from the soil's effects. Similarly, these structures should be isolated from one another (56). This seeming paradox may be remedied by making the correct choice of ground-bed conductor and by applying suitable preventive techniques.

Table 6.9. Typical Potentials of Metals in Soil Measured from a Copper Copper-Sulfate Reference Electrode.

Metal	Potential, V
Magnesium	-2.5
Aluminum	-1.3
Zinc	-1.1
Iron	-0.7
Copper	-0.2

Copper makes an ideal grounding conductor since it is corrosion resistant, has a high electrical conductivity, and is easy to clamp or weld (56). However, a good all-copper system is often ruined by tying it together with non-copper structures in the same locale, thereby leading to the corrosion of the less-noble species (55). If the ground bed must be located in an area where steel or lead are present, two options are available. First, an insulating coating may be applied to the "base" metals. If this is not feasible, an all-steel grounding system is preferable, or one composed of steel rods connected with insulated copper wire (57). The idea here is to minimize the exposed surface area of the more noble metal. Normally, steel electrodes can be improved by applying a heavy zinc coating or by driving zinc electrodes in addition to the steel. Known as sacrificial anodes, the zinc conductors will be preferentially attacked, thereby protecting the steel members. For extra protection, magnesium may be used instead of zinc. In highly corrosive soils, it may be necessary to utilize an external power source, which supplies d-c (to the soil) to nullify or "buck" the natural corrosion currents. This is known as cathodic protection (58). For externally-driven anodes, zinc or magnesium may be used; graphite and high-silica cast iron are also suitable.

It may be seen that judicious choice of grounding material and the use of corrosion-prevention techniques (such as cathodic protection) can provide a grounding grid that is both low in resistance and high in longevity.

6.5-7 General Ground-Bed Rules

The primary objective of a grounding system is ". . . to limit the potential rise above ground that appears on the frame and enclosures of the equipment connected to the power system" (59). Consequently, the station ground and safety ground should be spaced at least 50 ft apart, even though the law presently requires only a 25-ft separation (2). A typical voltage-gradient representation is shown in Figure 6.42 (59). The two grounds must be far enough apart so a lightning stroke to the station ground will not cause the safety ground to rise to more than 100 V above infinite earth.

Once the site has been selected, King and others (22) present an excellent guide for the design and construction of low-resistance driven-rod ground beds. Their simplified procedure consists of four steps.

1. Using the Wenner array, earth resistivity is measured along two lines at right angles to each other, centered across the proposed ground-bed site. Two measurements, with 6-ft then 18-ft spacings, are taken along each line.

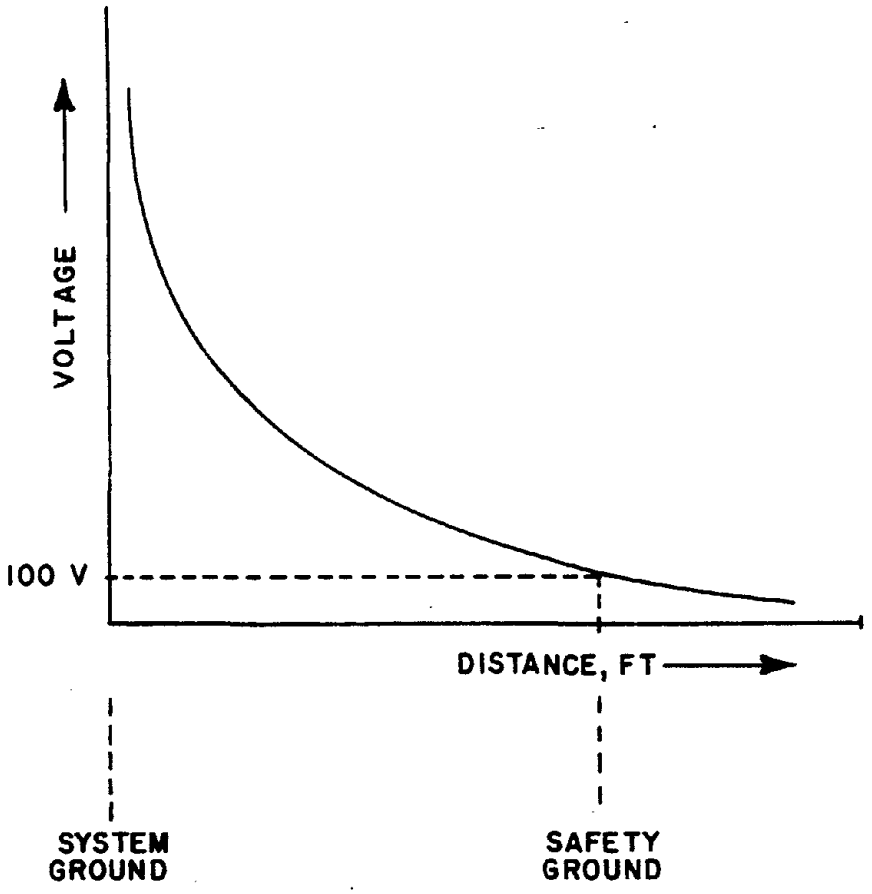


Figure 6.42. Voltage Gradients in the Earth During Ground-Fault Conditions.

2. Depending on the magnitude and homogeneity of the resistivities measured, the rod length, number, and arrangement are selected from tables. These tables are based on the same information presented earlier in this chapter and are too extensive to be reproduced here.
3. The selected rod configuration is driven, and the rods are interconnected with flexible, bare copper conductors. Recommended size is 4/0 AWG, and connection should be clamped or brazed, but never soldered (60).
4. The completed bed is measured by the fall-of-potential method to check that its resistance is below 5.0 Ω. If it is more, a new resistivity, ρ_n, is calculated by:

$$\rho_n = \rho_o \frac{R}{5} \tag{6.19}$$

where,

ρ_o = the old resistivity

R = the measured resistance.

Again, using the tables, additional rods are selected then driven. Afterwards, the resistance is again measured.

Whatever the procedure used to construct the bed, the resistance should be checked not only when it is installed but periodically thereafter to ensure that it is still functioning properly.

6.6 Grounding Equipment

Grounding Resistors. The basic resistance-grounded system consists of taking the neutral point and inserting a resistance. Four concerns are present when selecting the resistor: resistance, time rating, insulation, and connection.

The ohmic value of the resistor is determined by the line-to-neutral system voltage and the maximum ground-current limit. As stated earlier, when portable or mobile equipment are involved, the maximum limit on low- and medium-voltage systems is 25 A, and the upper limit on high voltage is set by the grounding-conductor resistance, as flow through this conductor can cause no machine frame to be elevated more than 100 V to earth. However, high-voltage limits are typically chosen at 25 or 50 A (50 A is the maximum allowed in some states). For instance, if grounding-conductor resistance is 3.3 Ω, maximum allowable ground current is 30 A, and 25 A is normally chosen. When the resistance-grounded system is feeding only stationary equipment, there is

no specified maximum ground current, but industry practice often specifies low-resistance grounding with a 400-A limit. For all applications, sizing the grounding-resistor ohmic value is simply performed by dividing the line-to-neutral voltage by the selected ground-current limit; conductor impedance is neglected. The technique is justified by the method of symmetrical components for a phase-to-neutral fault.

Ground current can be limited at a level less than the restricted maximum but, for high-resistance grounding, the smallest value chosen has two concerns: ground relaying and charging current. For maximum safety, ground protective circuitry should sense ground current at a fraction of current limit (see Chapter 8). Accordingly, reliable relay operation with electromechanical devices is a problem if maximum current is less than 15 to 20 A (61). The other limitation is that ground-fault current should always be greater than the system charging current (61,62). This is the current required to charge system capacitance when the system is energized (see Chapter 10). When very low ground-relay settings are used, the charging current can itself cause tripping.

The second main concern in selecting a grounding resistor is its time rating, or the ability to dissipate heat. A grounding resistor only carries a very small current under normal system operation but, with a ground fault, the current may approach full value. The high current exists until the circuit breaker removes power from the faulted circuit. This operation may take from a fraction of a second to several seconds, depending upon the protective circuitry used. Yet, with correct fault removal, the resistor physical size can be small, as very little heat is produced. However, protection devices have been known to malfunction and in these instances ground current might continue to flow until someone manually removes power (61). Thus it is mandatory that when portable or mobile equipment are involved, the resistor be able to dissipate the power produced from full ground current for an extended time. If not, the resistor can burn open, ungrounding the system. Two ratings that ensure safety are "continuous" and "extended-time." Essentially, they are the same, as the extended-time rating refers to a heat-dissipation ability for 90 days per year (61,63).

To provide a safety margin, the transformer-neutral side of the resistor (often called the "hot side") must be insulated from ground at a level to withstand the phase-to-phase system voltage. Both resistor ends are at ground potential with normal operation but, under a ground fault, the transformer end can approach phase-to-neutral potential. To afford good insulation, it is recommended that the resistor frame be placed on porcelain insulators, not temporary supports such as wood blocks (61).

Furthermore, for wye-connected secondaries, the transformer-neutral bushing must be insulated to at least phase-to-neutral voltage.

The last worry is resistor connection. The grounding resistor is installed between the transformer neutral and the safety ground bed. In substations it is important to use insulated conductors, as bare conductors can easily compromise separation between the system and safety ground beds. Grounding conductors must extend from the ground-bed side of the resistor. Finally, to minimize resistor conductor lengths, the resistor must be located on the power source end of distribution, as close as possible to the source power transformer. Distances greater than 100 ft are usually not allowed.

Grounding Transformers. Delta-wye, wye-delta, and delta-delta power transformers are extremely important in mine power distribution because they offer very high impedance to zero-sequence currents. Therefore, a ground fault existing on the secondary will do no more than raise primary line current. However, if the transformer has a delta secondary, there is no neutral point to which the grounding system can be connected. Other cases where this occurs involve mines where the utility owns the substation and supplies ungrounded delta power. For these situations, a separate grounding transformer is needed to obtain an artificial neutral. The two types of grounding transformers in general use are the zig-zag and delta-wye, with the former being more popular.

As shown in Figure 6.43, the zig-zag is a special three-phase transformer designed for deriving the neutral. The transformer winding interconnections are such that a very high impedance is shown to positive- and negative-sequence currents but a very low impedance is exhibited during zero-sequence flow.

A wye-delta grounding-transformer bank uses three identical single-phase transformers (see Figure 6.44). The primary windings, rated at line-to-neutral voltage, are connected in wye among the power-transformer secondary terminals and the grounding-resistor hot side, and the secondaries are connected in delta. Any secondary voltage rating can be used. Normally, no secondary current will flow, but during a ground fault, current will circulate in the secondary. This will cause the ground to be shared by the three transformers such that the neutral point will remain at constant potential (61).

Grounding-transformer capacity needs only to be large enough to carry the maximum ground-fault current. Their primaries cannot be fused as, again, an open fuse will essentially unground the system, creating a dangerous situation.

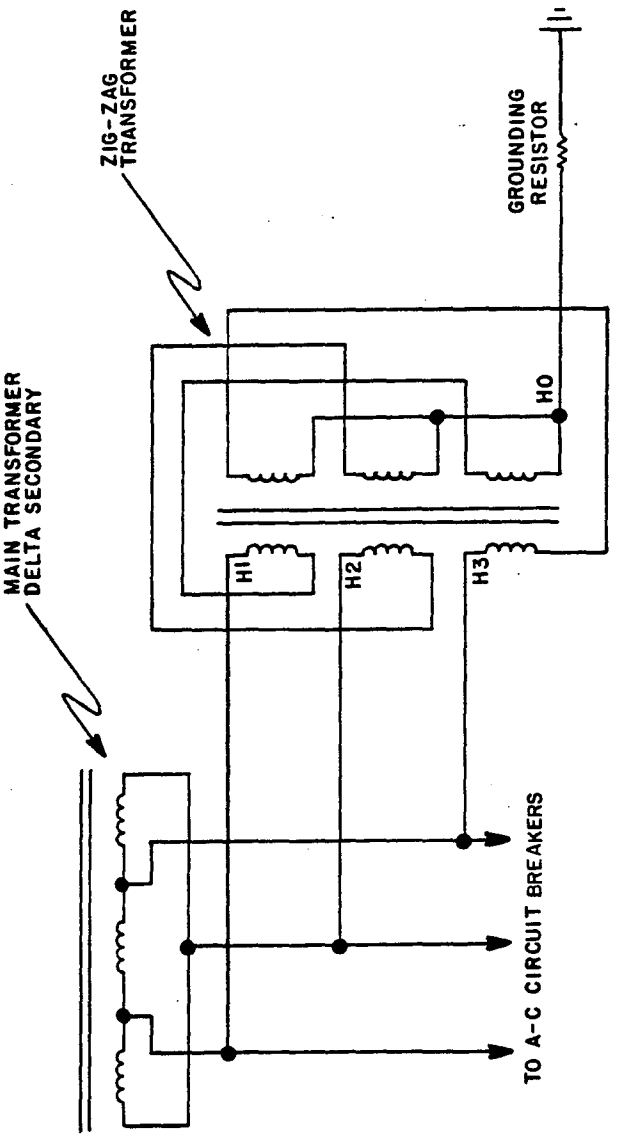


Figure 6.43. Delta Secondary with Zig-Zag Grounding.

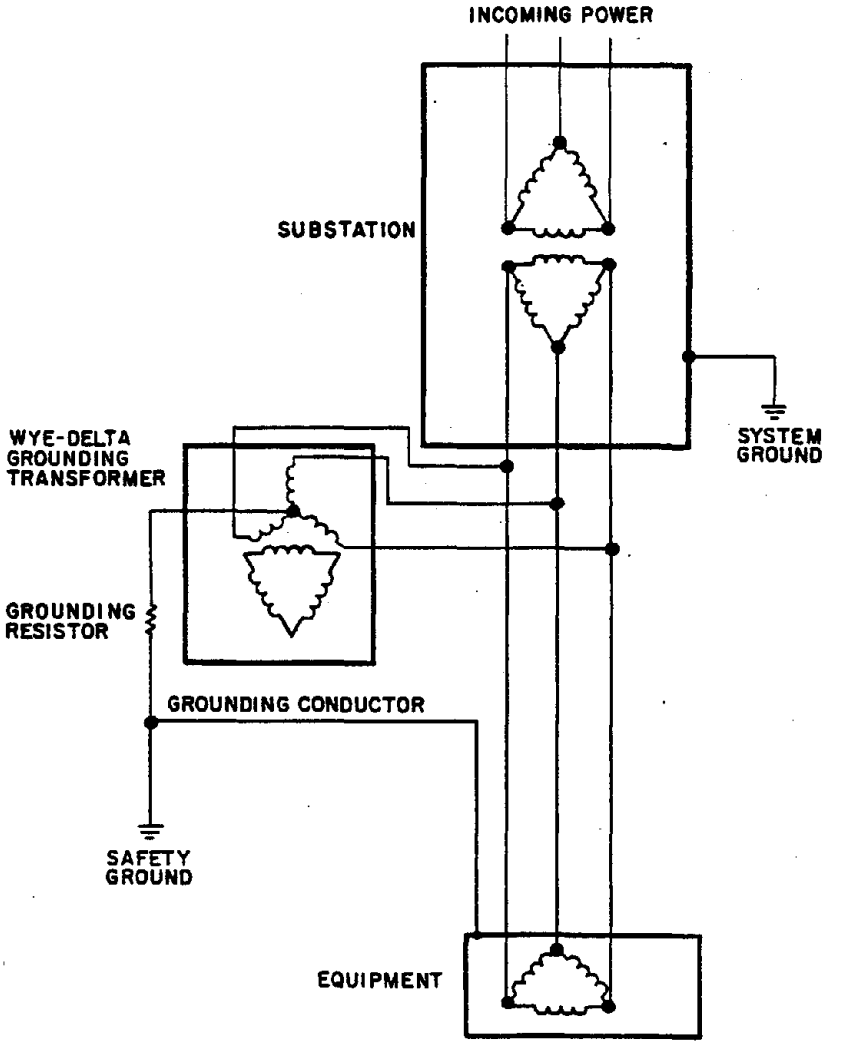


Figure 6.44. Delta Secondary with a Wye-Delta Grounding Transformer.

6.7 Summary

Several basic grounding methodologies exist, and each has its merits. However, the resistance-grounded neutral system is superior for mining applications involving portable or mobile equipment. The design of ground beds is a complex field, and many variables must be examined in an attempt to derive an optimum configuration. Nevertheless, a low value of resistance is of primary importance so dangerous potentials are not developed on machine frames. High potential gradients in the ground-bed area must also be avoided to prevent injury to personnel. A study of electric shock and its effects on humans is helpful in further delineating this subject. Formulas have been presented which may be used to predict the earth resistance of a particular metallic array or to determine how much buried metal is needed to achieve a desired value. In order to verify the ground-bed earth resistance, a description of ground test instrumentation, its utilization, and data interpretation is also included. When designing a ground bed, corrosion effects and soil-heating phenomena caused by current flow in the ground system must be considered.

The resistivity of the soil in which the ground bed is immersed has a significant effect upon its earth resistance. Resistivity in turn is influenced by other factors such as rock type, temperature, and moisture, and a thorough understanding of these relationships will be of use in metallic-grounding-network design. Again, instrumentation has been discussed, as well as practical applications such as the determination of the best location for a ground bed. Chemical treatment of soils to increase conductivity and attenuate seasonal resistivity variations has been reviewed.

Correct selection and coordination of protective circuitry is essential to gain the full benefits of a low-resistance ground bed. Protective circuitry must be installed to monitor current flow in the ground conductors or the potential drop across the neutral grounding resistor. When properly coordinated, this protective circuitry will quickly shut down faulty sections of the electrical system.

In the event of a fault or short-circuit on a piece of mine machinery, its frame may become "hot" or elevated above ground potential. An unsuspecting miner could be seriously injured or killed if the machine is touched. Fast-acting relays and circuit breakers will minimize the length of time during which this shock hazard exists, and the bad circuit will be isolated from the remainder of the system. Such is the subject of Chapters 8 and 9. The grounding conductors, which tie equipment frames to the safety ground bed, are discussed in the next chapter, "Distribution."

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Chapter 7

DISTRIBUTION[1]

7.1 General

The various types of cables, couplers, and splices that are major components of the mine power-distribution network will be discussed in this chapter. Since the depleting nature of mineral reserves requires the power-distribution components to be very mobile, their importance is magnified. Because they are handled frequently by miners, a safety hazard is introduced. Furthermore, cables that are damaged by mobile equipment become possible fire and gas-ignition sources. Therefore cable safety is a constant concern for mine operators and workers who must rely on proper installations and correct handling practices to minimize hazards. The purpose of this chapter is to provide the general information needed to design, install and maintain safe, efficient distribution networks.

Of course, the safety hazards of improper cable handling, installation and repair directly affect production downtime and operating costs. Considerable delays that result from cable, coupler, and splice failures have been recorded by many mining companies. In addition, operating-supply costs for replacement cables and repair materials are considerable. Therefore, engineers, mine management, and union workers should have the necessary knowledge of cable topics to design, install, and maintain a reliable cost-effective system.

7.2 Typical Distribution Configurations

Cables carry the electricity from the substation, where the power is taken from the utility company's lines, to the point of utilization at a mining machine, pump, conveyor belt, or other piece of equipment. Because there are many possible variations in mine distribution (see Chapter 2), several types of cables can be put to a similar use. Only the most typical distribution schemes are covered here; however, some important notable exceptions are included.

Several cable types may be used for any one application.

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[1] This chapter was written for the report by Dr. R.H. King, Assistant Professor of Mining Engineering, The Pennsylvania State University, and edited by the report author.

Some of the more common applications for underground coal mines are depicted in Figure 7.1 and for surface coal mines in Figure 7.2. Obviously, the circuits shown in Figures 7.1 and 7.2 do not represent exactly the total mine system. For instance, underground coal mines would not have one longwall, one continuous-mining section, and one conventional section. Normally, the mine would have several continuous-mining sections or several conventional sections in addition to one or more longwall units. Surface mines would usually have more than one dragline and one stripping shovel, yet all of them would not necessarily be electrically powered. For these reasons, the figures should be taken only as examples that were constructed to depict common cable uses.

A close examination of these figures shows several important points. The first is that the rated voltage of cables is different from the distribution voltage of the circuit. The "cable rating" means, in the simplest terms, that the insulation around the conductors will withstand the stresses produced by that voltage. The most common cable ratings are 600 V, 2 kV, 5 kV, 8 kV, 15 kV, and 25 kV. The 5-kV, 8-kV, 15-kV and 25-kV ratings are primarily used for stationary distribution and are generally not connected to mining equipment, except in surface mines. Usually 4.16-kV distribution requires 5-kV rated cables, 7.2 kV requires 8 kV, and 12.47 kV and 13.2 kV require 15-kV ratings. The utilization voltages of 250 Vdc, 440 Vac, and 550 Vdc usually require 600-V or 2-kV cables. The 600-V cables are generally being replaced by the 2000 V; consequently, none of the former are shown in Figure 7.1.

Another important point to be noted from Figures 7.1 and 7.2 is that some cables remain in a stationary location for several years while others are moved frequently. As might be supposed, the kind of cable used is tied to the application. The cables that are connected to mining machines are termed "portable" by the Insulated Cable Engineers Association (ICEA) Standards (1,2). The Code of Federal Regulations calls the specific variety of portable cables that are used in mines "trailing cables" (3). "Trailing cables" are flame resistant, flexible cables or cords through which electrical energy is transmitted to a machine or accessory.

Generally for underground mines, trailing cables are used on the inby (toward-the-face) end of the load center or distribution box. The portable cables that feed the load center, or are attached to the outby (toward the portal or shaft) end, have to be moved when the load center is advanced and retreated (perhaps once every two weeks), but they are not moved as often as the trailing cables. The most stationary cables are those which feed down the borehole and from the borehole to the portable switchhouses. These are the "feeder" cables. A special type, designated "Mine Power Feeder," can be used for installations that may not be moved for several years. (Note: The use

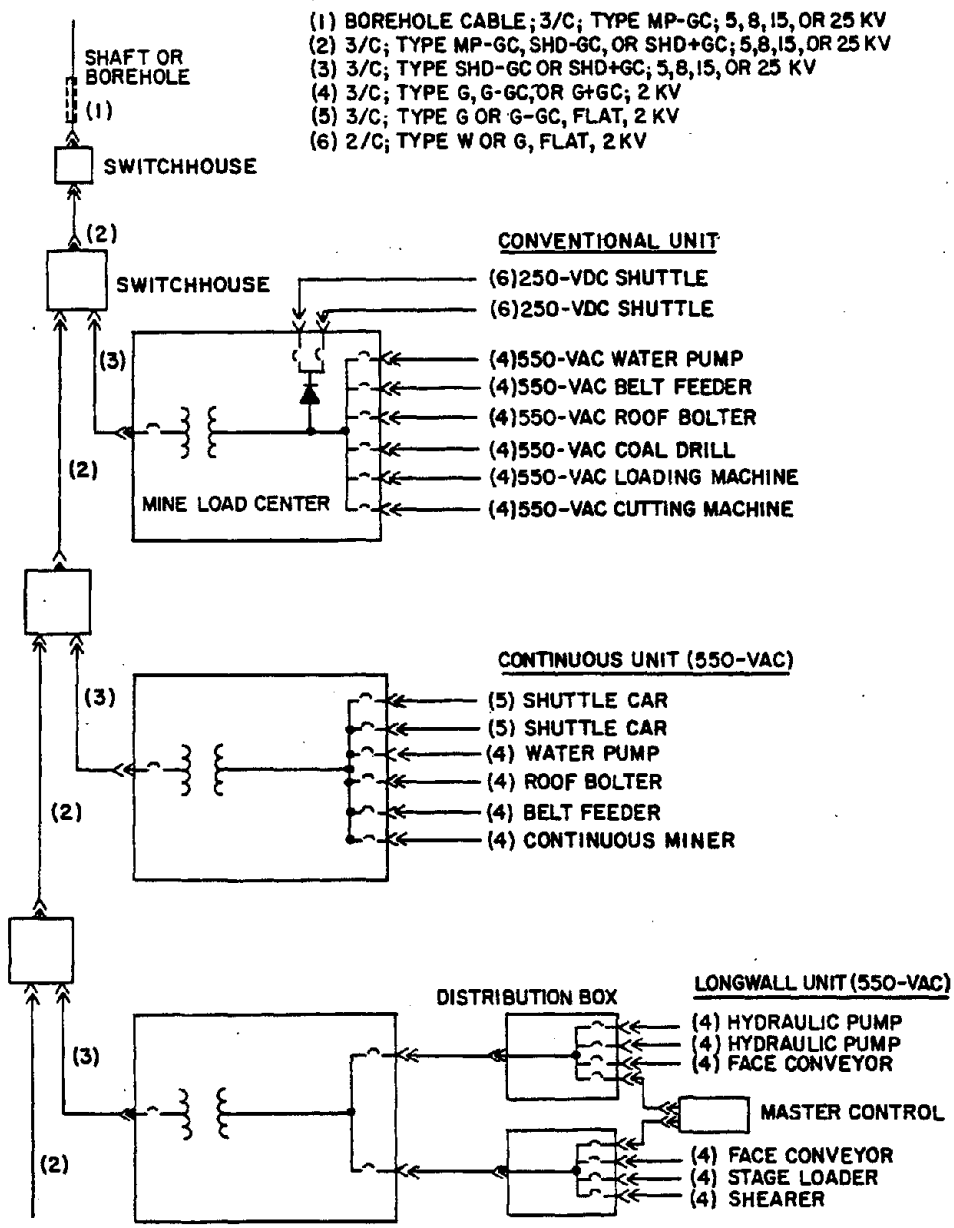


Figure 7.1. Cable Types for Typical Distribution Systems in Underground Coal Mines

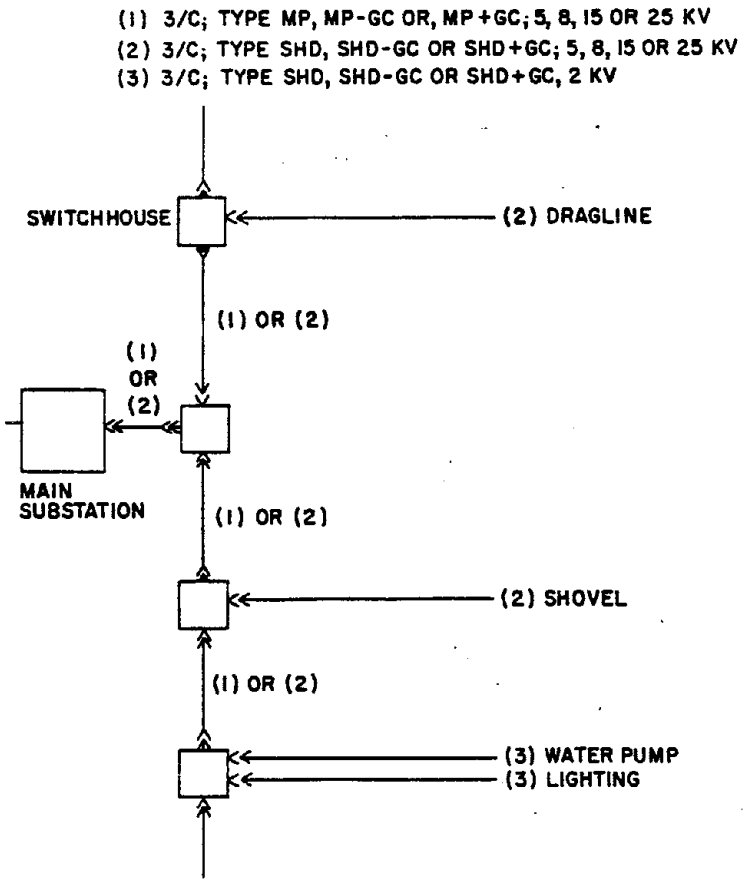


Figure 7.2. Cable Types for Typical Distribution in Surface Coal Mines.

of the word "feeder" here is to denote a cable type rather than a function in distribution. Sometimes, both feeder and portable cables can be used for feeder applications, where the cable supplies two or more major loads. (See reference 3.)

Similarly in surface mines, the cables that feed from the switchhouses or unit substations to mobile equipment are trailing. Those which are moved only occasionally, and are not connected directly to a machine, are portable cables. Stationary (or near so) cables can be feeder or portable types.

7.3 Cable Types

The cable-type descriptions in the two previous figures (e.g., 3/c, Type SHD-GC) specify how the major cable components are arranged. These types are related to standard specifications according to ICEA Standards (1, 2). Cable manufacturers' product-information literature also describes them. Figures 7.3 through 7.12 are provided to illustrate the following discussion.[2] Details of the conductors and insulation used in these cables are contained in Sections 7.4 and 7.5.

The three basic cable components are the conductors, the insulation, and the jacket. Several other important components such as fillers, binding or reinforcing twine, shielding, and armor are present in some cables. Basically, the term, n/c, describes the number (n) of power conductors (c) in a cable. The voltage levels at which the cable can operate safely are specified by the cable rating. "Type G" refers to cable that contains one or more uninsulated grounding conductors, and "Type W" means that no grounding conductors are present. The abbreviations "SH-D" and "SH-C" refer to different configurations of shielding which will be discussed in detail in Section 7.6. The presence of an insulated ground-check or pilot conductor is noted by the "GC" abbreviation. The ground-check conductor, or pilot wire as it is sometimes called, is necessary where ground-continuity monitoring is required and where the pilot-wire type of monitoring device described in Chapter 8 is used.

ICEA requires that the manufacturer of the cable be identified throughout its length. The voltage rating and cable type are also marked on the outer jacket. In addition, approval for flame resistance by MSHA and the State of Pennsylvania is marked on the jackets of underground-coal-mining cables.

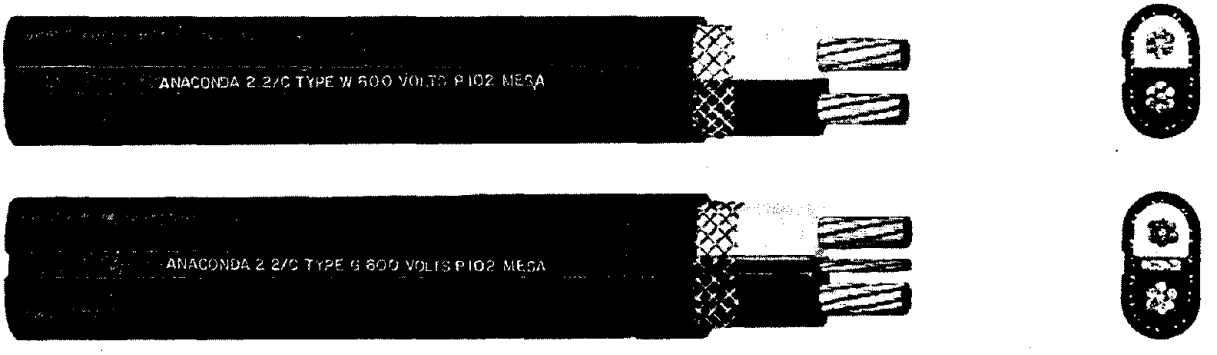
Figure 7.3 shows a single-conductor cable insulated for use at 600-V. This cable is not widely used. However, it has found application on twin-reel d-c shuttle cars and small locomotives with reels; therefore, it must be highly flexible.

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[2] Photographs courtesy of Anaconda-Ericsson Inc.



Figure 7.3. Single-Conductor, 600-V Cable (courtesy Anaconda Ericsson Company).



NOT REPRODUCIBLE

Figure 7.4. Two-Conductor, Flat Twin, Type W and G, 600/2000-V Cable (courtesy Anaconda Ericsson Company).

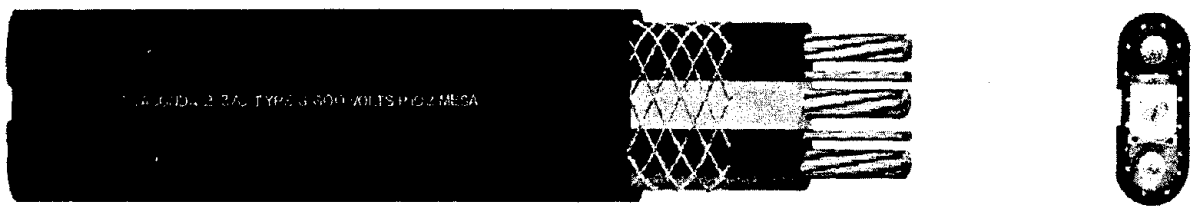


Figure 7.5. Three-Conductor, Flat Parallel, Type G, 600/2000-V Cable (courtesy Anaconda Ericsson Company).



NOT REPRODUCIBLE

Figure 7.6. Three-Conductor, Flat Parallel, Type G-GC, 600/2000-V Cable (courtesy Anaconda Ericsson Company).

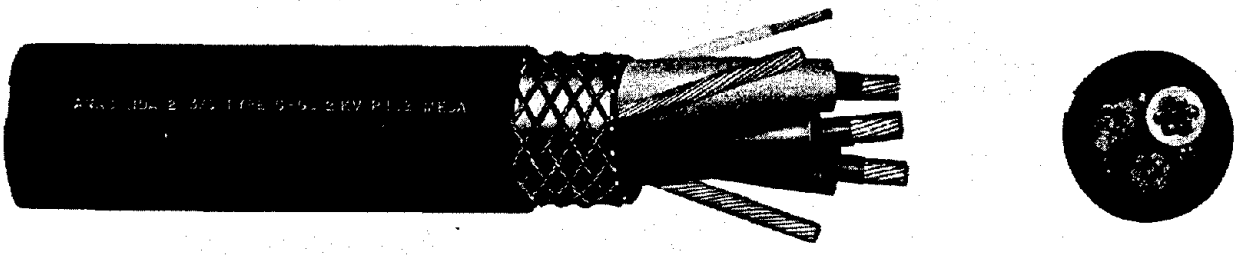
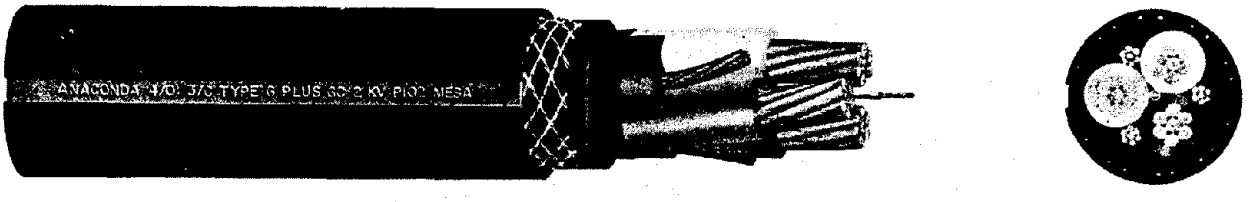


Figure 7.7. Three-Conductor, Type G-GC, 2000-V Cable (courtesy Anaconda Ericsson Company).



NOT REPRODUCIBLE

Figure 7.8. Three-Conductor, Type G+GC, 2000-V Cable (courtesy Anaconda Ericsson Company).

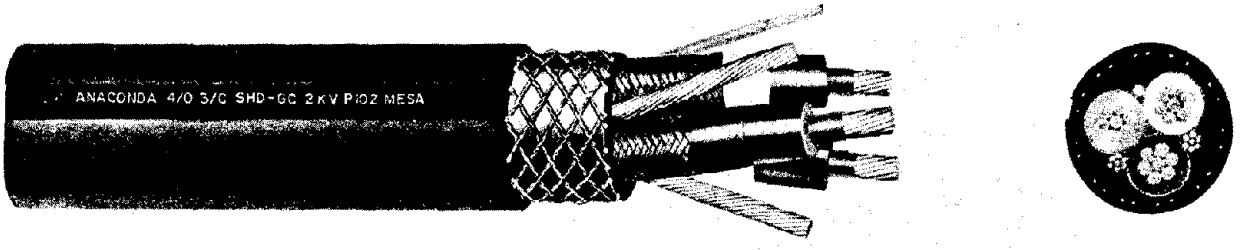
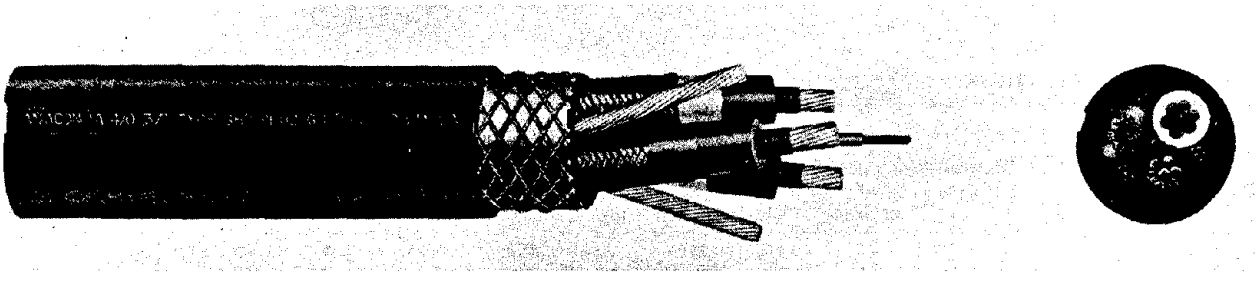


Figure 7.9. Three-Conductor, Type SHD-GC, 2000-V Cable (courtesy Anaconda Ericsson Company).



NOT REPRODUCIBLE

Figure 7.10. Three-Conductor, Type SHD-GC, 2000-V Cable (courtesy Anaconda Ericsson Company).

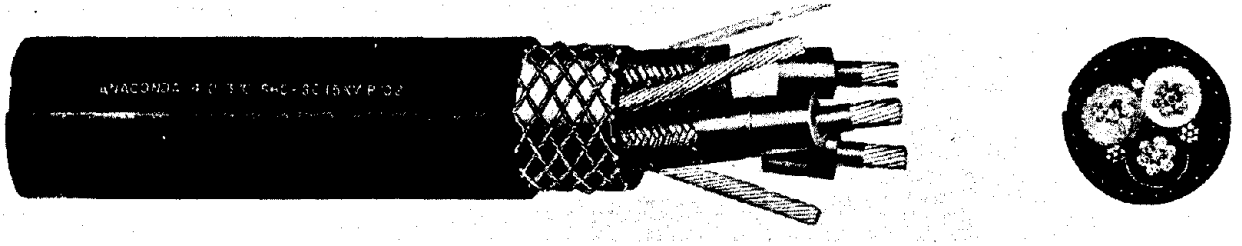


Figure 7.11. Three-Conductor, Type SHD-GC, 15-kV Cable (courtesy Anaconda Ericsson Company).



NOT REPRODUCIBLE

Figure 7.12. Three-Conductor, Type MP-GC, 15-kV Cable (courtesy Anaconda Ericsson Company).

The most common d-c shuttle-car cables are shown in Figure 7.4. The flat configuration is used since it allows an increased length on cable reels and is less susceptible to run-over damage than round cables. The type W is used where diode grounding (described in Chapter 8) is allowed in lieu of a separate grounding conductor. Because shuttle-car cables are damaged frequently, type W is preferred by some mine operators since it is easier to splice.

Flat cable types used for a-c shuttle cars are shown in Figures 7.5 and 7.6. The three power conductors are separated by two grounding conductors in Figure 7.5 and by one grounding and one ground-check conductor in Figure 7.6. These cables are also used on other equipment with reels, such as cutting machines and drills.

Alternating-current shuttle cars also utilize round cables in the Type G or Type G-GC configuration shown in Figure 7.7. These grounding conductors are placed in the interstices between the power conductors in the Type G, and a ground-check replaces one of the grounding conductors in the Type G-GC. In addition to limited use on shuttle cars, the majority of longwall shearer, face-conveyor, stage-loader, roof-bolter, feeder, and continuous-miner cables are of this type. In some instances, the G-GC configuration initiates induced voltages in the frame-ground system (see Chapter 15). Therefore, the symmetrical G+GC Type shown in Figure 7.8 was constructed. The three grounding conductors are laid symmetrically in each interstice, and the ground-check conductor is placed in the center of the cable.

These two round-cable configurations, G-GC and G+GC, are used extensively for medium- and high-voltage cables as well, with the addition of shielding. Federal law requires shielding on all surface coal-mine cables and on underground medium- and high-voltage coal-mine cables, unless the cable is rated at 2000 V and used in a reeled application (3). Therefore, the 2000 V rated SHD-GC cable, shown in Figure 7.9, and the SHD+GC cable in Figure 7.10 are common on such equipment as 950-Vac continuous miners and longwall shearers, and on low-voltage surface coal-mine equipment.

Some high-voltage cables are required to be flexible; for example, surface-mine shovel and dragline cables and underground-mine distribution cables which are connected to a portable load center. The SHD-GC cable shown in Figure 7.11 is intended for this application. It is rated at 2, 5, 8, 15, or 25 kV depending on insulation thickness. (Shielding construction can change with the voltage level).

Stationary power cables are often the MP-GC type shown in Figure 7.12. These cables can also be rated at 5, 8, 15, or 25 kV, but they are less flexible, have higher tensile strength, and are shielded differently than the SHD-GC Type. MP-GC cables are also designed to be used in boreholes, aerial installations, ducts, and direct burial.

These are the basic power-cable types used currently in the mining industry. Other configurations are made for specific applications. For example, one double-drum shearing machine model requires a six-conductor cable with two ground-check conductors and a grounding conductor. Cable manufacturers are usually willing to produce these special cables, but they are not a part of normal product lines and the possible variations are too numerous to include here.

The next sections (7.4, 7.5, and 7.6) describe the individual cable components in detail. In particular, the capabilities of these components should be understood in order to install, use, and specify cables properly. In addition, some insight into possible variations from the standard types that might be manufactured for special installations can be gained from a knowledge of the individual components.

7.4 Conductors

Materials. Much of the information in this section is based on data from the Mining Cable Engineering Handbook (4). The phase and ground currents are carried by either copper or aluminum conductors. Aluminum conductivity is 61% of the conductivity of copper; therefore, an aluminum conductor must have a cross-sectional area 1.59 times that of copper to have any equivalent d-c distance. However, copper conductors weigh 3.3 times as much as aluminum; so, even though the cross-sectional area of an aluminum conductor is greater, the total weight of an equivalent-resistance aluminum conductor is less. However, since copper is more flexible than aluminum, it is used in all portable mining cables. Because of lower cost, aluminum feeder cables are used, but problems in jointing are present, since improperly constructed joints allow aluminum oxides to form which increase resistance and cause heating at the connection. In addition, extreme care must be taken to exclude moisture from copper-to-aluminum joints since electrolytic corrosion of aluminum may occur.

Cable conductors, with the exception of bare trolley wire and MPF types, are composed of many fine strands. The method of reducing the diameter of copper rods, as received at a cable-manufacturing plant, to the proper diameters for stranding is a cold-drawing process where the copper rod passes through successively smaller dies. However, this process hardens the copper and makes it less flexible. Therefore, it must be

annealed if a soft temper is desired. Medium- and hard-temper wires are used for conductors that require hard tensile strength, but are not bent frequently. For instance, the MP-GC type uses harder-temper copper and a less-flexible stranding configuration, particularly for borehole suspension. Generally, soft temper has a strength of 24,000 psi, and medium-hard is 40,000 psi. Interestingly, copper conductors can become annealed in service if they are used at high operating temperatures for long periods of time. In fact, copper can loose five percent of its original tensile strength in 10,000 hours at 70°C. Therefore, when installing borehole and high-tension overhead cables, cable manufacturers should be consulted about their product's ability to resist annealing.

Copper strands are usually coated or "tinned" to prevent corrosion by insulation vulcanizing agents. Lead and tin alloys are commonly used in this operation which reduces the strand-surface conductivity.

Size. The cross-sectional area of conductors is, of course, closely related to current-carrying capacity. Since the proper capacity is a legal requirement and a desirable safe-operating practice, an understanding of the methods commonly used to specify cross-sectional areas and ampacities is necessary. In the United States, both the American Wire Gage (or Brown and Sharpe Gage) and circular-mil designations are used. As stated in Chapter 3, one circular-mil is the area of a circle that is one mil in diameter. The American Wire Gage (AWG) specifies steps or sizes between Number 36, 0.0050 inches in diameter, and Number 4/0, 0.4600 inches in diameter. There are 38 sizes between these two that closely conform to the wire-drawing-process steps. Table 7.1 specifies cross-sectional areas and equivalent circular-mil sizes for the AWG designations. The 38 intermediate sizes are calculated with a geometric progression relating the ratio of any diameter to the next smaller or larger by:

$$\sqrt[39]{\frac{0.4600}{0.0050}} = 1.1229. \qquad (7.1)$$

Short-cut conductor-size approximations can be made if a table is not available by applying some simple rules. For example, the diameter will be doubled or halved by moving six sizes up or down the table. The weight, area, and d-c resistance is doubled or halved by moving three gage sizes, and they are changed by a factor of ten over ten gage sizes. A convenient reference point from which to apply these rules is the number-ten wire since its diameter is about 0.1 inch, its d-c resistance is nearly 1 Ω per 1000 ft, and it weighs 10π lbs per 1000 ft. In applying these rules, it should be remembered that the outer diameter and weight of conductors depends on the stranding configuration which will be described later in this section.

Table 7.1. Conductor Sizes and Cross-Sectional Areas.

Conductor Size, AWG or MCM	Cross-sectional Area		Conductor Size, AWG or MCM	Cross-sectional Area	
	CM	mm^2		CM	mm^2
22	640	0.324	250	—	127
20	1020	0.519	300	—	152
19	1290	0.653	350	—	177
18	1620	0.823	400	—	203
17	2050	1.04	450	—	228
16	2580	1.31	500	—	253
15	3260	1.65	550	—	279
14	4110	2.08	600	—	304
13	5180	2.63	650	—	329
12	6530	3.31	700	—	355
11	8230	4.17	750	—	380
10	10380	5.261	800	—	405
9	13090	6.631	900	—	456
8	16510	8.367	1000	—	507
7	20820	10.55	1100	—	557
6	26240	13.30	1200	—	608
5	33090	16.77	1250	—	633
4	41740	21.15	1300	—	659
3	52620	26.67	1400	—	709
2	66360	33.62	1500	—	760
1	83690	42.41	1600	—	811
1/0	105600	53.49	1700	—	861
2/0	133100	67.43	1750	—	887
3/0	167800	85.01	1800	—	912
4/0	211600	107.2	1900	—	963

Federal regulations require grounding conductors to have at least one-half of the cross-sectional area of the power conductors and, when the power conductor is a number-eight size AWG, or smaller, the grounding conductor should be the same size as the power conductor. The ground-check conductor must not be smaller than a number-ten AWG (3).

Conductor size is important for mechanical strength as well as electrical conductivity. Many mining applications require conductors to be twisted and flexed repeatedly around sheaves and spooled on and off storage reels while the cable is under tension. As a result, the power conductors must be designed to withstand these mechanical forces. Tensile strength is discussed in Section 7.7.

Stranding. In order to obtain the required flexibility, mining-cable conductors are made with numerous small wires rather than a single-solid copper rod. These small wires are wound or laid together in specific patterns. Several wires

(37 in a shuttle-car cable) are wound together in a rope-stranded member or bunched together, then several (seven in a shuttle-car cable) of these ropes or bunches are spiraled together to form the conductor. Consequently, the total number of wires (259 in a shuttle-car cable) equals the number of bunches or ropes multiplied by the number of wires in each. The cross-sectional area of a stranded conductor is defined as the sum of the areas of its component wires.

In the simplest terms, flexibility is greatest when the largest number of small-diameter wires is used. However, a certain amount of tensile strength is required in mining cable conductors, and tensile strength is greatest when the fewest number of larger wires is used. More complicated factors, such as twisting and bunching, enter into the design, but the optimum combination must be found, and different applications necessitate different configurations. For example, one manufacturer's design utilizes seven wires in a number-two AWG, Type MP-GC, while the same size of Types G-GC and 2/c flat, Type G have 259 strands. The engineer must examine cable-stranding specifications carefully and select the one that best suits the application. Where historical information is not available, several types should be tried to find the best performer. Flexibility is also influenced by the method of insulating the power and ground-check conductors and applying an overall jacket, which will be discussed in the next section.

7.5 Insulation and Jacket

Insulation. Insulation is required to withstand stresses from heat, voltage, and physical abuse in mining cables. Its composition, therefore, must be very special since it must function not only to protect mine personnel from electrical shock, but also to effectively separate phase and grounding circuits.

Heating affects insulating materials in different ways, depending on their chemical composition. It is beyond the scope of this chapter to explain the chemistry of insulating materials and how each one reacts to the forces imposed by service in the mine electrical system. However, heating generally either softens insulation (so it loses physical strength) or causes the insulation to age or become brittle. Therefore, the effects of heat can cause insulation to lose its original shape, tensile strength, cut-resistance, elongation, and effectiveness as an insulator. The main sources of heat are the environment, related to the ambient temperature, and power (I^2R) loss in the cable conductors. Hence, cable heating is directly connected to the maximum current the conductors can safely carry.

Cable manufacturers usually prefer to use a thermosetting

insulation. It changes chemically by vulcanizing after being extruded over the conductors, into a material that softens very little within the rated temperature range. The most common insulating compounds in this group are neoprene, styrene butadiene (SBR), ethylene propylene (EPR), and cross-linked polyethylene (XLP). These compounds are usually mixed with other materials to achieve improved physical and electrical properties.

SBR is used in 600-V trailing-cable insulation. It has a high modulus of elasticity, has good flexibility, resists damage by crushing from runovers and rock falls, and has a 75°C temperature rating. EPR has replaced SBR in many trailing cables, allowing the cable rated voltage to be increased to 2000 V and the temperature rating to 90°C while maintaining the same insulation thickness as the previously used SBR and neoprene. The EPR emergency-overload rating is 130°C, and short-circuit rating is 250°C. XLP is also rated at 90°C for normal operation and is used in high-voltage mine-feeder and portable strip-mining cables. XLP is a rather stiff material, however, and is not recommended for reeling applications.

The voltage rating of an insulation is based on its ability to withstand a test voltage that is many times the anticipated operating voltage, for a specified period of time. The test procedure and specifications are published in ICEA standards (1, 2). Insulating compounds have different voltage ratings which are usually expressed as the amount of voltage that they can withstand per mil of thickness. Consequently, higher voltages can be used with any compound by increasing its thickness. Insulation thicknesses are also specified by IPCEA.

Particularly in high-voltage applications, insulation must resist damage from corona which is described in Chapter 15. The term, "partial discharge," describes the type of corona stress imposed on cables. Partial discharges deteriorate insulation by ion bombardment and chemical action from ozone, nitrogen oxides, and nitric acid. These discharges can occur in voids, such as between a stranded conductor surface and the insulation. Therefore, insulation voids must be minimized, and the insulation must resist the formation of this type of corona. ICEA standards specify corona extinction voltage levels for insulation (1, 2).

Ozone resistance is also important for high-voltage cable insulation, and sometimes for low voltage. Ozone is formed when electrical discharge is present in air. Ozone attacks compounds containing double carbon bonds, splitting the carbon chain and deteriorating the material. Radiating cracks are a physical symptom of this occurrence. An ozone-resistance test is required by ICEA for insulations that are classed as ozone-resisting.

Interestingly, insulation must withstand cold temperatures as well. Some of the open-pit iron mines in Minnesota and

Michigan have experienced temperatures as low as -50°C. Cables stored on the surface at underground-mine sites are also exposed to extremely low temperatures. Most problems occur when a cold cable must withstand mechanical stress, such as bending or impact.

Jacket. The main purpose of jackets is to provide protection for the inner components and hold the assembly in the designed configuration. Therefore, they are not required to pass voltage-withstand or insulation-resistance tests by ICEA. However, tests for tensile strength, elongation, and aging are required. In addition, ozone and discharge-resisting jackets must pass surface-resistivity and partial-discharge tests. Mining cable jackets must also withstand extensive temperature ranges and maintain their physical properties throughout. Furthermore, they must not deteriorate when exposed to direct sunlight, for example, in Arizona open-pit copper mines. Obviously, resistance to abrasion, crushing, tearing, and impact are extremely important. In addition, chemical action of acid or basic mine water and hydraulic fluids must not deteriorate the jacket, and underground-coal-mine cable jackets must be flame resistant. Finally, the jacket must exclude moisture and be very flexible.

One of the most commonly used materials for cable jackets is neoprene, a chlorprene polymer. Nitrile-Butadiene/Polyvinyl-chloride (NBR/PVC) is also used, especially where jacket coloring is desired. Chlorosulfonated polyethylene (CPS) or Hypalon is also used extensively, especially in combination with the 90°C EPR insulation. EPR is used where extreme cold is encountered and flame-resistance is not necessary.

7.6 Shields

ICEA defines shielding of an electric power cable as the practice of confining the electric field of the cable to the insulation of the conductor or conductors (1, 2). It is accomplished by means of conductor and insulation shields.

A conductor shield is employed to eliminate excessive voltage stress on voids between conductor and insulation. To be effective, it must adhere to or remain in intimate contact with the insulation under all conditions.

An insulation shield has a number of functions. It confines the electric field within the cable, in addition to maintaining symmetrical radial distribution of voltage stress within the dielectric, thereby minimizing the possibility of surface discharges by precluding excessive tangential and longitudinal stresses. It protects cables connected to overhead lines or otherwise subject to induced potentials, and limits radio interference. In addition, it reduces the hazard of shock if the shield is grounded.

Two distinct types of materials are employed in constructing cable shields. Nonmetallic shields may consist of a conducting tape or a layer of extruded conducting compound. The tape may be made from conducting compound, fibrous-tape faced or filled with conducting compound, or conducting fibrous tape. The other type, metallic shields, should be nonmagnetic and may consist of a thin metal tape, wire-woven braid, or a concentric serving of wires. The braid may be made up entirely of copper wires or have nylon twine in combination with copper wires. Nonmetallic and metallic elements may be used adjacently.

Both SH-D and SH-C configurations are possible. The SH-D is preferred since the grounding conductor is in intimate contact with the shield and phase-to-phase leakage is detectable because each individual power conductor is surrounded by the shield. The SH-C, a single braid over the entire assembly, may find some applications in low- and medium-voltage cables. However, special varieties must be produced to assure consistent, low-resistance contact between the shield and grounding conductors.

The high-voltage insulation shield is generally comprised of two parts. The first is an extruded layer or wrap of semi-conducting material which is applied directly over the insulation. The semi-conductive material is considered to have a 100% coverage but has an associated high resistivity. The second portion is metallic and applied over the semi-conducting layer. If this is composed entirely of copper braid, it covers 84% of the area, while the combination braid covers 60%. Wire shielding, a 60% coverage of uni-directional spirally-wound wires, may also be used. The insulation shield must be in intimate contact with the insulation under all conditions in order to be effective, and the metallic portion serves as a current-carrying medium for charging and leakage currents. Federal regulations require SH-D types for high-voltage underground-coal-mine cables. However, either the Sh-D or the SH-C insulation configuration is permitted for medium-voltage cables. Medium-voltage cables used on reels do not have to be shielded if the insulation is rated at 2 kV (3).

7.7 Underground Coal-Mine Environment

A recent U.S. Bureau of Mines funded research program at The Pennsylvania State University resulted in a description of the stresses that the underground mining environment imposes on cables (5). Generally, the stresses were a result of tension, temperature, flexure, twisting, abrasion, cutting, tearing, and crushing. Many of these same forces are present in other types of mines, such as surface coal and metal in addition to underground metal. However, the extensive use of a wide variety of cable types and the high incidence of failures in underground-coal operations dictated the study area.

Seven mines located in the states of Pennsylvania, West Virginia, Virginia, and Indiana were visited. At each mine, instantaneous tensions (jerking) on shuttle-car trailing cables were measured near the anchor point giving values as high as 2250 lbs. Normally, these tensions range from 300 to 1000 lbs. Rubber tires and shock absorbers used at shuttle-car cable anchor points were effective in reducing tensions. The spring-loaded variety worked effectively below 600 lbs and the rubber tire from 600 to 1400 lbs. The highest tensions occurred when the cable was backspooled and when slack cable was reeled into a storage reel. It was found that tensions on continuous-miner drag cables are equal to a coefficient-of-friction factor, that was determined to be 0.8, multiplied by the length of cable pulled. Of course, tensions are much higher when a drag cable is entangled or caught on a stationary object. An additional 75 to 100 lbs was required to pull the cable around a corner.

In one instance, a jacket temperature above 121°C was measured on a shuttle-car cable that was stored in the reel, while in many instances jacket temperatures above 87°C were recorded. Abrupt temperature changes resulted when these cables were spooled into a puddle of water.

Flexing occurred frequently as cables were bent around the reel, sheave wheels, the machine frame, pillar corners, and timbers. The diameter of bending on the shuttle-car frame was as severe as two or three times the cable diameter. In the case of continuous-miner cables, bending diameters of four or five times the cable diameter were reported. When combined with the previously mentioned tensile forces and the twisting discussed in the next paragraph, this severe bending decreases cable life.

Twisting occurred throughout a 0- to 90-degree angle between the shuttle-car machine frame and the sheave wheel. The twist here was confined to a distance of a few inches. Intense twisting also occurred as the cable approached the anchor point and between the reel and sheave wheel.

Cable damage also resulted when the shuttle cars ran over their own cable, crushing it. Sharp edges on the machine frame also cut the cable and, at times, the cables were gouged by steel wires in rubber-tire anchors and the sharp edges of stress-relief clamps. Abrasion also occurred due to cables being pulled over rocks and around pillar corners.

7.8 Cable Selection and Engineering Data

Information Required. The cable manufacturer can provide a proper cable for a mining company only if they know exactly what the operating conditions of the cable will be. Therefore, the purchaser has the responsibility for writing a purchasing specification that completely describes the operating environment. A

revision of an ICEA list of information to be supplied by the purchaser comprises Table 7.2. It will be used here to describe the step-by-step cable-selection process.

Many of the items in the Table 7.2 "System-Characteristics" category are obviously meant to assist the purchaser in identification of the cable type. For example, the number of power conductors (1a) is determined when a-c or d-c is specified. The need of one or more grounding conductors is noted when the grounding method (1b) is explained. The normal operating voltage (1c) leads to the selection of a cable voltage rating that includes the operating voltage and indicates the necessity of shielding. If the ground-continuity monitor requires a ground-check conductor, this should also be noted (1d). Any additional monitoring or remote-control system may also require pilot conductors. Because several cable jackets have cracked during installation, after being stored outside in extremely cold weather, the ambient temperatures of storage and use (1e) should be specified. The installation area (1f) will explain special requirements such as high-tensile-strength conductors and a flame-resistant jacket for a borehole cable. In addition, special environmental considerations (1g) that may affect cable life, such as an excessive exposure to sunlight in a western U.S. open-pit mine, should be noted. Delivery-time schedule (1i) and delivery location (1j) are obviously important considerations to be included so that a cable manufacturer can give the proper service. Finally, if changes to the electrical system (1k) are anticipated, they should be considered. Money can be saved if a cable that will accommodate both the present and future systems can be purchased rather than replacing a cable after a short operating period.

Length. After considering these topics, a description of the cable can be written. First the cable length (1a) must be specified. Usually this is a physical measurement, but other factors such as government regulations and voltage drop must be considered. Table 7.3 specifies trailing-cable lengths for underground coal mines where the standard 500-ft limit is not used for 60°C-rated insulation (a table for 90°C insulation is not available) (3). Many companies prefer to purchase a long length of cable, thereby receiving a price discount, and then cut the required lengths from this stock. Feeder cables are usually shipped to a shop where couplers are mounted onto the cable at 500-foot intervals before the cable, now in the desired lengths, is transported to the mine.

Ampacity. The selection of the correct conductor size will allow the cable to carry the required normal-operating and emergency-overload currents without overheating the insulation, withstand tensile forces, and limit the voltage drop. Current requirements (I) can be calculated from the operating phase-to-phase voltage (V), motor horsepower (hp), power factory (pf), and efficiency (η):

Table 7.2. Information to be Supplied by a Cable Purchaser.

1. System Characteristics:
   a. Alternating or direct current
   b. Grounding method (i.e., by conductor or diode circuit)
   c. Normal operating voltage between phases (a-c) or between conductors (d-c)
   d. Number of pilot or ground-check conductors and type of ground-check monitor
   e. Minimum ambient temperature of cable storage and installation
   f. Description of cable-installation area (surface mine, borehole, trailing cable, etc.)
   g. Environment of use (ambient temperature, amount of moisture, amount of sunlight, etc.)
   h. Maximum and normal operating current
   i. Time schedule
   j. Delivery point
   k. Future changes in the system

2. Quantities and Description of Cable:
   a. Cable length
   b. Cable type, number of conductors, and flat or round configuration
   c. Voltage rating
   d. Type of conductor (copper or aluminum)
   e. Conductor size
   f. Insulation type
   g. Jacket type and color
   h. Maximum outside diameter and tolerance
   i. Method of conductor identification
   j. Special markings (MSHA and P approval numbers, dating, etc.)
   k. End Attachments (couplers), type of attachment, location of installer, and method of installation

$$I = \frac{(hp)\ (746)}{(V)\ (\eta)}. \qquad (7.2)$$

The conductor size is then selected from an ampacity table such as Tables 7.4 and 7.5 (2). The table insulation rating should be consulted since, for example, 75°C ampacities are lower than 90°C values. If the ambient temperature is different from that specified in the table (40°C), the correction factors shown in Table 7.6 can be applied (2). In addition, cables that are used in confined areas such as reels can become overheated at the rated currents. Therefore, ampacity derating factors similar to those in Table 7.7 are provided. Emergency-overload currents that copper conductors can withstand without serious damage to the insulation are shown in the graph in Figure 7.13 (4). If the anticipated short-circuit currents are greater than those shown in the graph for the conductor-size selected, a larger conductor or a better grade of insulation should be selected (see Chapter 9 for calculation methods).

Table 7.3. Specifications for Portable Cables Longer Than 500 Feet.

Conductor Size AWG or MCM	Maximum allowable length, ft	Normal ampacity at 60°C copper temperature (40°C ambient)	Resistance at 60°C copper temperature Ω
6	550	50	0.512
4	600	70	.353
3	650	80	.302
2	700	85	.258
1	750	110	.220
1/0	800	130	.185
2/0	850	150	.157
3/0	900	175	.130
4/0	1,000	200	.116
250	1,000	220	.098
300	1,000	240	.082
350	1,000	260	.070
400	1,000	280	.061
450	1,000	300	.054
500	1,000	320	.050

Table 7.4. Ampacities for Portable Power Cables, Amperes Per Conductor.

Power Conductor Size, AWG or MCM	Single Conductor				Two Conductor	Three Conductor Round and Flat	Three Conductor Round			Four Conductor	Five Conductor	Six Conductor
	0-2000 V	2001-8000 V*	8001-15000 V*	15001-25000 V*		0-5000 V	0-8000 V	8001-15000 V	15001-25000 V			
	Unshielded	Shielded	Shielded	Shielded	Round and Flat 0-2000 V	Nonshielded	Shielded	Shielded	Shielded	0-2000 V	0-2000 V	0-2000 V
8	83	...	...	...	72	59	...	...	...	54	50	48
6	109	112	...	...	95	79	93	...	...	72	68	64
4	145	148	...	...	127	104	122	...	...	93	88	83
3	167	171	...	...	145	120	140	...	...	106	100	95
2	192	195	195	...	167	138	159	164	178	122	116	110
1	223	225	225	222	191	161	184	187	191	143	136	129
1/0	258	260	259	255	217	186	211	215	218	165	...	...
2/0	298	299	298	293	250	215	243	246	249	192	...	...
3/0	345	345	343	337	286	249	279	283	286	221	...	...
4/0	400	400	397	389	328	287	321	325	327	255	...	...
250	445	444	440	430	363	320	355	359	360	280	...	...
300	500	496	491	480	400	357	398	...	...	310	...	...
350	552	549	543	529	436	394	435	...	...	335	...	...
400	600	596	590	572	470	430	470	...	...	356	...	...
450	650	640	633	615	497	460	503	...	...	377	...	...
500	695	688	678	659	524	487	536	...	...	395	...	...
550	737	732	...	...	...	...	...	...	...	...	...	...
600	780	779	...	...	...	...	...	...	...	...	...	...
650	820	817	...	...	...	...	...	...	...	...	...	...
700	855	845	...	...	...	...	...	...	...	...	...	...
750	898	889	...	...	...	...	...	...	...	...	...	...
800	925	925	...	...	...	...	...	...	...	...	...	...
900	1010	998	...	...	...	...	...	...	...	...	...	...
1000	1076	1061	...	...	...	...	...	...	...	...	...	...

* These ampacities are based on single isolated cable in air operated with open-circuited shield.
NOTE--These ampacities are based on a conductor temperature of 90°C and an ambient air temperature of 40°C.

Table 7.5. Ampacities for Three-Conductor Mine Power Cables (2001 to 15000 V Copper and Aluminum).

Conductor Size AWG or MCM		Ampacities*			
		2001 to 8000 V		8001 to 15000 V	
Copper	Aluminum	Copper	Aluminum	Copper	Aluminum
6	...	93	...	...	...
4	2	122	124	125	128
2	1/0	159	165	164	168
1	2/0	184	189	187	192
1/0	3/0	211	218	215	221
2/0	4/0	243	251	246	254
3/0	250	279	278	283	281
4/0	350	321	342	325	344
250	400	355	360	359	367
300	450	398	395	401	393
350	500	435	425	438	424
400	...	470	...	473	...
450	...	502	...	504	...
500	...	536	...	536	...

*Ampacities are based on an ambient temperature of 40°C and a conductor temperature of 90°C taken from "Power Cable Ampacities," IPCEA Publication No. P-46-426 (IEEE Publication No. S-135). Vol. 1 for Copper Conductors and Vol. 2 for Aluminum Conductors, page 309.

Table 7.6. Correction Factors for Ampacities at Various Ambient Temperatures.

Ambient Temperature, °C	Correction Factors
10	1.26
20	1.18
30	1.10
40	1.00
50	0.90

Table 7.7. Ampacity Derating Factors for Cables on Reels.

Number of Layers	Multiplying Correction Factors
1	0.85
2	0.65
3	0.45
4	0.35

Tension. The tensile load on the cable should be determined, for example by using the information in Section 7.7 or making measurements in the mine. The power-conductor breaking-strength data in Table 7.8 should then be consulted to assure that the conductor size is large enough to carry the tensile load (4). Two things must be considered when using this table. First, grounding and ground-check conductors should not support any of the tensile load, so the overall cable breaking strength should include only the sum of the power-conductor values. Second, the working tension, especially in reeling applications, should not exceed 10% of the breaking strength because copper begins to elongate at that point.

Voltage Drop. Next, voltage regulation should be considered, since it depends on the length of cable from the voltage source (transformer) to the load, the impedance (which is determined by conductor size), the power factor, and the current drawn by the load. In a three-phase circuit, the per-phase voltage that is calculated from the drop in a single conductor can be converted to phase-to-phase voltage. Phase-to-phase drop can be calculated using the following formula:

$$V = \sqrt{3}\ IZ \qquad (7.3)$$

where

V = phase-to-phase voltage drop (V)
I = load current (A)
Z = single conductor impedance (from Tables 7.9 and 7.10 (4)) (Ω).

It is desirable to minimize voltage drop to obtain proper efficiency from motors, improve motor life, and utilize as much of the power purchased as possible for useful work. Consequently, voltage regulation, the ratio of voltage drop to receiving-end voltage expressed in percent, should be maintained as small as practical. Voltage regulation is usually not a problem with underground coal-mine trailing cables because of the maximum lengths listed in Table 7.3. However, it can be, and often is, the determining factor in selecting distribution conductor sizes for underground mines and all conductors in surface mines.

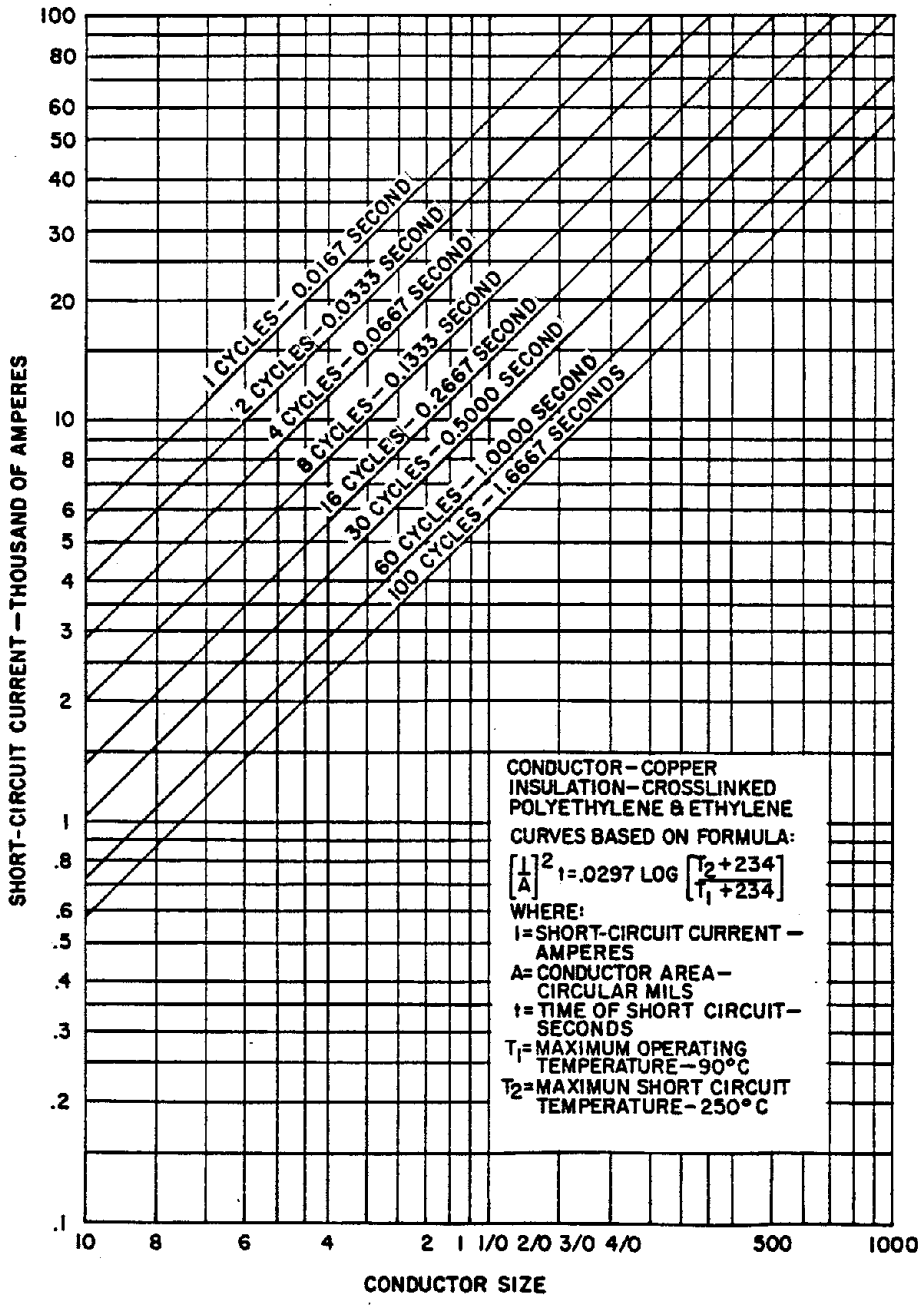


Figure 7.13. Allowable Short-Circuit Currents for Insulated Copper Conditions.

Table 7.8. Solid-Wire Breaking Strength.

Size	Approximate Tensile Strength					
	HARD		MEDIUM		SOFT	
	65000, psi		55000, psi		40000, psi	
	Lbs.	kg	Lbs.	kg	Lbs.	kg
4/0	8143	3693.6	6980	3166.1	5983	2713.8
3/0	6720	3048.1	5666	2570.1	4744	2151.8
2/0	5519	2503.4	4599	2086.1	3763	1706.9
1/9	4518	2049.3	3731	1692.4	2985	1354.0
1	3688	1672.8	3024	1371.7	2432	1103.1
2	3002	1361.7	2450	1111.3	1928	874.5
3	2439	1106.3	1984	899.9	1529	693.5
4	1970	893.6	1584	718.5	1213	550.0
5	1590	721.2	1265	573.8	961.5	436.1
6	1280	580.6	1010	458.1	762.6	345.9
7	1030	467.2	806.7	365.9	605.1	274.5
8	826.1	374.7	644.0	292.1	479.8	217.6
9	660.9	299.8	513.9	233.1	380.3	172.5
10	529.3	240.1	410.5	186.2	314.0	142.4
11	423	191.9	327	148.3	249	112.9
12	337	152.9	262	118.8	197	89.4
13	268	121.6	209	94.8	157	71.2
14	214	97.1	167	75.7	124	56.2
15	170	77.1	133	60.3	98.6	44.7
16	135	61.2	106	48.1	78.0	35.4
17	108	49.0	84.9	38.5	62.1	28.2
18	85.5	38.8	67.6	30.7	49.1	22.3
19	68.0	30.8	54.0	24.5	39.0	17.7
20	54.2	24.6	43.2	19.6	31.0	14.1
21	43.2	19.6	34.4	15.6	24.6	11.2
22	34.1	15.5	27.3	12.4	19.4	8.80
23	27.3	12.4	21.9	9.93	15.4	6.99
24	21.7	9.84	17.5	7.94	12.7	5.76
25	17.3	7.85	13.9	6.30	10.1	4.58
26	13.7	6.21	11.1	5.03	7.94	3.60
27	10.9	4.94	8.87	4.02	6.33	2.87
28	8.64	3.92	7.02	3.18	4.99	2.26
29	6.97	3.16	5.68	2.58	4.01	1.82
30	5.47	2.48	4.48	2.03	3.14	1.42

Table 7.9. Resistance and Reactance of Portable Power Cable.

Conductor Size AWG or MCM	R [ac][1] Ω/1000 ft. 75°C	90°C	X_L [60 H_z][2] Ω/1000 ft. 2 kV G-GC G+GC	2 kV SHD-GC	5 kV SHD-GC	8 kV SHD-GC	15 kV SHD-GC	25 kV SHD-GC
8	.838	.878	.034					
7	.665	.696	.033					
6	.528	.552	.032	.038	.043			
5	.418	.438	.031	.036	.042			
4	.332	.347	.031	.035	.040	.043		
3	.263	.275	.031	.034	.039	.042		
2	.209	.218	.029	.033	.038	.040	0.44	
1	.165	.173	.030[3]	.033	.036	.039	.042	.046
1/0	.128	.134	.029	.032	.035	.037	.040	.044
2/0	.102	.107	.029	.031	.034	.036	.039	.043
3/0	.081	.085	.028	.030	.033	.035	.038	.041
4/0	.065	.068	.027	.029	.032	.034	.036	.040
250	.055	.057	.028	.030	.031	.033	.036	.039
300	.046	.048	.027	.029	.031	.032	.035	.308
350	.039	.041	.027	.029	.030	.032	.034	.037
400	.035	.036	.027	.028	.030	.031	.033	.036
500	.028	.029	.026	.028	.029	.030	.032	.035
600	.023	.024	.026	.027	.028	.030	.032	.034
700	.020	.021	.026	.027	.028	.029	.031	.033
800	.018	.019	.025	.026	.028	.029	.030	.033
900	.016	.017	.025	.026	.027	.028	.030	.032
1000	.014	.015	.025	.026	.027	.028	.030	.032

See Table 7.10 for notes.

Table 7.10. Resistance and Reactance of Mine-Power-Feeder Cable.

Conductor Size AWG or MCM	R (ac) Ω/1000 ft. 90°C	X_L (60 H_z)[5] Ω/1000 ft. 5 kV MP-GC	8 kV MP-GC	15 kV MP-GC
6	.510	.041	.044	
5	.404	.040	.042	
4	.321	.038	.041	
3	.254	.037	.039	
2	.201	.036	.038	.042
1	.160	.035	.037	.041
1/0	.127	.034	.035	.039
2/0	.101	.033	.034	.038
3/0	.080	.032	.033	.036
4/0	.063	.031	.032	.035
250	.054	.030	.031	.034
300	.045	.029	.031	.034
350	.039	.029	.039	.033
400	.034	.029	.030	.032
500	.027	.028	.029	.031
600	.023	.028	.029	.031
700	.020	.027	.028	.030
800	.017	.027	.028	.030
900	.016	.027	.027	.029
1000	.014	.026	.027	.029

[1]a. Sizes #8-#1 AWG based on tinned copper 94.16% conductivity.
b. Sizes #1/0 AWG and larger based on tinned copper 96.16% conductivity.
c. Resistance increased by increments per ASTM B-172, Note 7, to compensate for stranding factor.
d. Skin effect calculated according to Arnold's Table, National Bureau of Standards Bulletin 169,
e. Nominal cross-sectional areas.

[2]a. Based on conductor dimensions given for Class-H Rope-Lay conductors in Table 2.5 of IPCEA S-19-81.
b. Extruded-strand shield thickness .015".
c. Insulation thickness according to nominals given in Interim Standard #6 to IPCEA Pub. No. S-68-516.
d. Diameter adder of .075" to allow for semiconducting tape and metal braid shield.

[3]a. Deviations from normal progression due to changes in insulation.

[4]a. Based on bare copper 100% conductivity.
b. Nominal cross-sectional areas.
c. Resistance increased by increments per ASTM B-8, Note 3, to compensate for stranding factor.
d. Skin effect calculated according to Arnold's Table, National Bureau of Standards Bulletin 169.

[5]a. Based on conductor dimensions given for Class B Concentric Stranded conductors in Table 2.2 of IPCEA S-19-81.
b. Extruded strand shield thickness .015".
c. Insulation thickness according to nominals given in Interim Standard #5 to IPCEA Pub. S-68-516.
d. Diameter adder of .033" to allow for semiconducting tape and copper tape shield.

The main voltage-regulation concern in mining is the maximum limits under which motors can safely operate. As stated in Chapter 5, the allowable tolerance on all rotating machines is ± 10%. In surface mines where utilization is at distribution, this would relate to a maximum voltage drop of 10% from nominal voltage from the substation to the machines under normal load conditions. In underground mines, because of load centers, such is not as simple. The maximum voltage drop must be restrained again to 10%, but this can occur across the trailing cable alone. Accordingly, the load-center primary must be maintained as close to its normal rating as practical. To obtain the objective is a very difficult task in practice, as load centers are usually at the extreme end of the distribution system. Fortunately, and also for voltage-regulation purposes, most mine-load-center transformers are designed with two 2.5% taps above and below rated primary voltage. Therefore, under normal load conditions, the maximum allowable voltage drop in the distribution system from the substation to the load centers is 10%.

It is interesting to compare the 10% allowance with other applications. For lighting, the National Electrical Code[2] recommends 1.0%. Other industries consider 2.0% as good-to-excellent regulation but with perceptible lighting changes and 4.0% as satisfactory.

7.9 Cable Installation

General. Cables must be installed correctly in order to minimize the damage from the forces of tension, bending, twisting, physical wear, cold, heat, and chemical reaction. Cable-maintenance costs can be reduced, cable life improved, and safety enhanced by proper installation. In other words, the considerable amount of engineering expertise expended in the design, manufacture, and selection processes can be wasted if the cable is not utilized properly at the mine.

Borehole Cables. The technique used to install borehole cables is very important. Even though the mining or electrical engineer may not have to plan and supervise this operation frequently, this is the main power-supply cable for the entire or a large part of an underground mine. Safety and production are highly dependent on a correct technique.

A considerable amount of tension is imposed on borehole cables depending on the weight of the cable and the depth of the mine. Proper conductor selection, installation procedure, and suspension method are necessary to assure that the cable

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

provides trouble-free service for the life of the mine. Shaft cables are also subject to damage from moving skips and spillage. An extremely wet environment is often encountered, which may cause corrosion and icing problems. In addition, considerable safety precautions must be taken to keep the cable from breaking loose and falling into the borehole during installation. If the power conductors have enough strength to support the weight of the cable during and after installation, a messenger wire with cable-gripping clamps is not necessary. Otherwise, the messenger-wire suspension method or a metallic armored cable must be used.

If an unarmored cable such as an MP-GC is used, the following formula will calculate the safety factor for the tensile strength:

$$SF = \frac{0.80\ AT}{W} \qquad (7.4)$$

where,

A = total area of power conductors (in^2)
T = tensile strength of copper, psi (24,000 psi for soft drawn and 40,000 for medium-hard drawn)
W = weight of the length of cable to be suspended (lbs).

If the safety factor is greater than seven, an end suspension, as shown in Figures 7.14 and 7.15, may be used without a messenger (6). Equal tensioning of the conductors is imperative.

If a messenger is used, it must be made from a corrosion-resistant material such as galvanized steel. Clamps or wire-type cable grips are used at specified intervals to secure the cable to the messenger. The cross-sectional area and tensile strength of the messenger must be such that it can support the total weight of itself, the clamps, and the cable. Proven and tested clamps of the best quality should be used, or they will become the weak link in the installation. The high gripping force necessary on the cable jacket should be spread over a large area so the jacket is not damaged by pinching. In addition, a jacketing material that is not subject to cold-flowing should be utilized to prevent the clamps from loosening. A useful formula for determining cable-clamp spacing is:

$$S = \frac{9DL}{W} \qquad (7.5)$$

where,

S = distance between clamps (ft)
D = cable diameter (in.)
L = clamp length (in.)
W = weight per foot of cable (lbs).

Generally, clamp spacing is greater than 25 ft and should not be more than 50 ft.

A steel-wire covering or armor is used on borehole cables

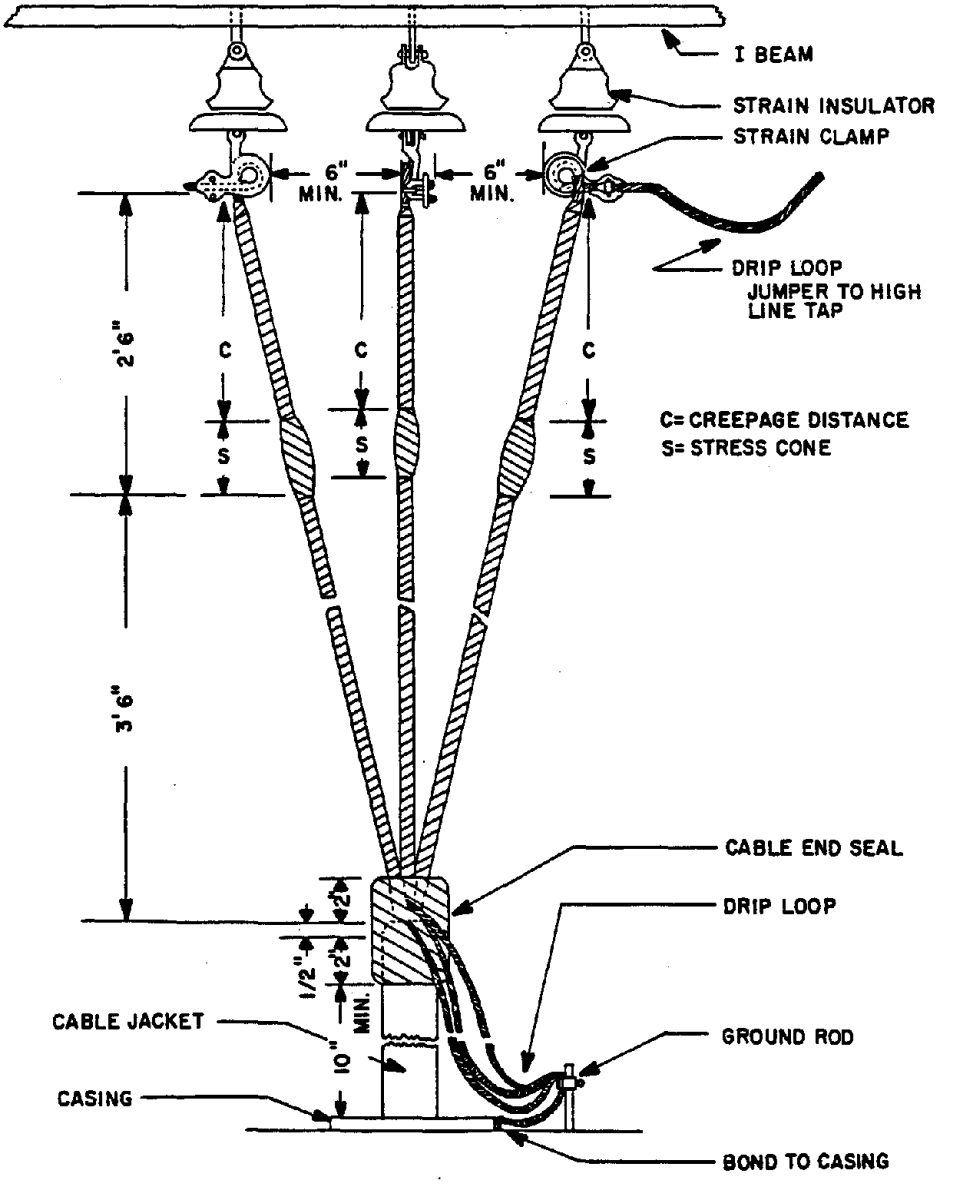


Figure 7.14. End-Suspension Termination for Borehole Cable.

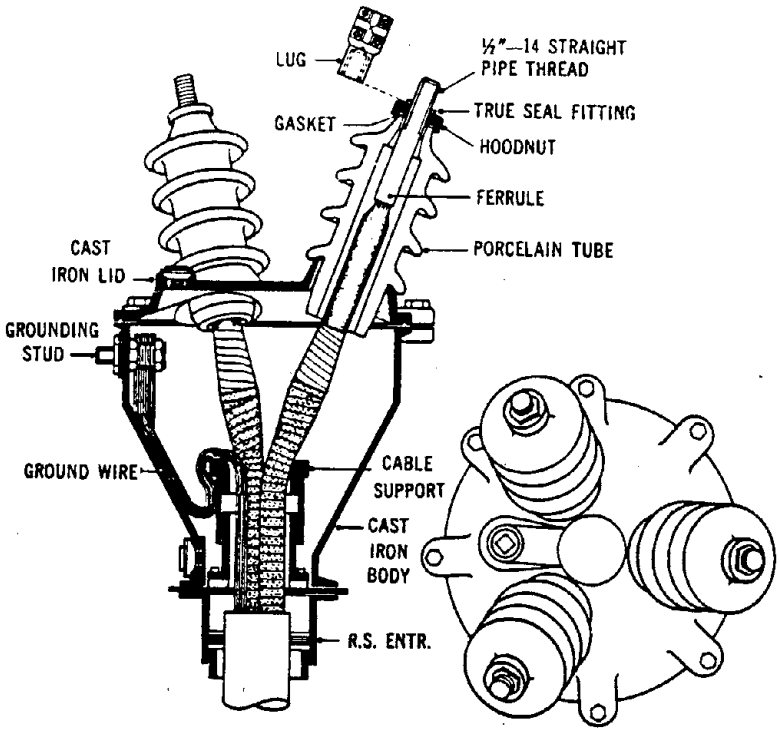


Figure 7.15. Cable Terminations for Applications up to 15 kV (All or a Portion of the Cable Weight is Supported by the Pothead).

where depth or location precludes the use of a messenger. If this type of cable is chosen, the steel wire carries the tensile load, and the tension safety factor can be determined by:

$$SF = \frac{0.60\ (BS)}{W} \qquad (7.6)$$

where,

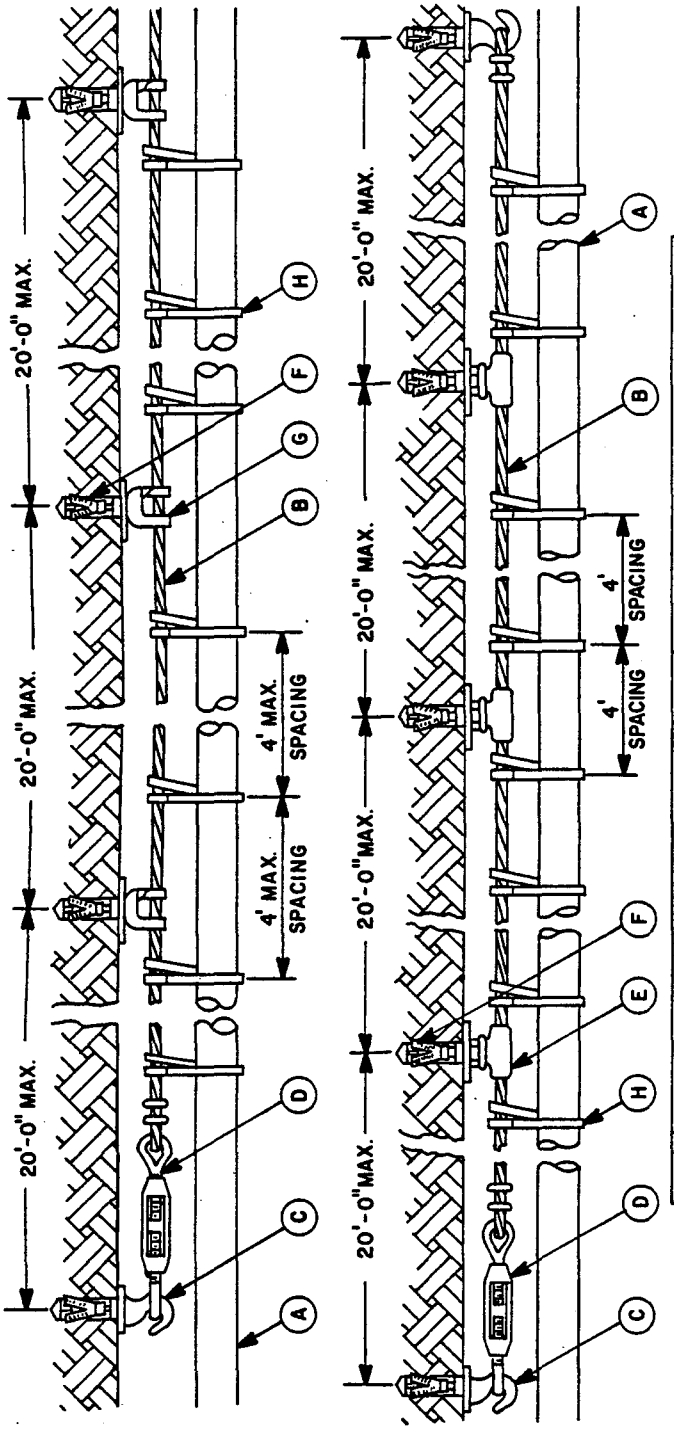
SF = safety factor
BS = breaking strength of each wire multiplied by the number of wires (lbs)
W = weight of cable length to be supported (lbs).

The minimum safety factor for armored cable is five. Armored cable may be necessary in shaft installations as protection against jacket damage from skips, cages, and spillage.

In some instances, cables can be installed in shafts by mounted the reel in the cage, anchoring the cable end at the surface, and unreeling the cable as the cage is lowered. Clamps are installed at the correct spacing by stopping the cage.

Cables can be either raised or lowered through a borehole. Usually raising is preferred because of the need to have a brake on the surface as well as a pulling force at the bottom when a cable is lowered. In either case, the borehole should be straight and free of obstacles. Also, it is important to locate the hole in an area that is protected from ground movement which may occur as a result of the mining operation. When a structure is used at the top of the borehole to support the cable weight, it should not only be strong enough but also be placed on a substantial concrete base, and any sheave wheels utilized during the installation should be larger than the minimum bending radius specified. Rollers should be used to prevent jacket damage from dragging the cable on rough surfaces and to minimize the pulling force by reducing friction. Crews working at the top and bottom should have a good communication system, and the personnel working at the bottom should be adequately protected from injury should the cable break loose and fall.

Feeder Cable. Mine-power-feeder cable is another important installation. It must be located in an area that is protected from mobile equipment damage. Usually, it is supported from the roof or back on properly spaced, insulated hangers, which may be supported by a messenger wire. Messenger supports are usually installed at 20-ft intervals and cable support clips placed on a 3/8-in. messenger wire at 4-ft spacings as shown in Figure 7.16 (7). Recommended static load per clip is 100 lbs. An 1-1/4-in. diameter hole is drilled in the roof to place a 6-in.-long expansion-shell bolt for the messenger-wire support. The cable is not allowed to contact any combustible materials, and in underground coal mines it must be guarded where miners regularly work or pass under it, unless it is 6-1/2 ft above



A	A-C CABLE	F	EXPANSION SHELL
B	MESSENGER CABLE	G	SISTER HOOK
C	DEAD END HOOK	H(1)	CABLE CLIP-1-7/8" DIA.
D	TURNBUCKLE	H(2)	CABLE CLIP-2-5/8" DIA.
E	BULLDOG CLAMP	H(3)	CABLE CLIP-3-7/8" DIA.

Figure 7.16. Messenger-Wire Support for Mine Power-Feeder Cable.

Table 7.11. Recommended Minimum Bending Radii,

1. Power Cables Without Metallic Shielding or Armor:

Thickness of Conductor Insulation		Overall Diameter of Cable					
		inches	mm	inches	mm	inches	mm
		1.000 and less	25.4 and less	1.001 to 2.000	25.4 to 50.8	2.001 and over	50.8 and over
mils	mm	Minimum Bending Radius as a Multiple of Cable Diameter*					
155 and less	3.94 and less	4		5		6	
170-310	4.32-7.87	5		6		7	
325 and over	8.26 and over	...		7		8	

2. Interlocked-Armor Cables:

Minimum bending radius is seven times the overall diameter except where specified in Sections 1 and 4 of this table.

3. Flat-Tape and Wire-Armored Cables:

Minimum bending radius is 12 times the overall diameter.

4. Tape-Shielded Cable:

Minimum bending radius is 12 times the overall diameter.

5. Wire-Shielded Cable:

Note Sections 1, 3, and 6 in this table.

6. Portable Cables:

Minimum bending radius is six times the overall diameter (minor diameter for flat cables) for cables rated less than 5001 V and eight times the diameter for cables rated over 5000 V.

*These limits do not apply to bending around curved surfaces in tension during installation. Larger bends are required for such conditions.

the floor or rail. Where extra lengths of cable are stored, they should be in large figure-eight configurations in a well-ventilated area. The ICEA recommended bending radii in Table 7.11 should be observed for both mine-power-feeder and portable cable as they are being installed (1,2). Damage can be averted if a cable that has been stored on the surface during the winter is allowed to sit in the mine or in a workshop to warm before being flexed. In addition, the installation procedure should not put twists in the cable. That is, the reel should be turned so the cable is unrolled rather than pulled from the end of the reel.

7.10 Testing and Fault Location

Cable Testing. Generally, cables are not tested frequently at a mine. However, there are instances where they should be. Manufacturers test components that are used in manufacturing and do limited tests on completed cables. ICEA standards describe the types of tests performed by manufacturers (1,2). In addition, when couplers are added to cables at a cable-repair shop, further testing is necessary. Again, this test may not be performed at the mine, but the person responsible should require the cable-repair shop to test the assembly properly. The mine should require that every cable removed from service be tested before re-installation. If this is done, many costly in-service failures, production losses, and safety hazards can be prevented.

Visual observation of cable condition is an important and simple test that can be made even when the cable is in service. It is important to require machine operators to walk to and from their equipment along the cable and visually examine the jacket for damaged areas. Outside diameter and shore hardness can also be obtained on in-service cables. Significant reduction of overall diameter is an indication of excessive tension, while increased hardness results from excessive temperature or bending. Therefore, at times some relatively simple methods can be used to evaluate cables.

More extensive evaluations can be made if the cable is out of service so the conductor ends are accessible. Obviously, an ohmmeter can be used to test for broken conductors; however, more sophisticated equipment, described later in this section, is necessary to locate the open circuit. Insulation damage may be detected by using a "Megger" or a "hipot." Each of these instruments can give an indication of the ability of the insulation to withstand the operating voltage without allowing excessive phase-to-phase or phase-to-ground leakage currents. Portable meggers and d-c hipots can be used in the field, and a-c hipots are sometimes available at cable-repair shops. In order to test non-shielded cables completely, they must be surrounded by a grounding medium such as a water bath. Without the water bath, only the insulation directly between phases and between

phases and grounding conductors can be examined. If a shield or armor is present, either can be used as a grounding medium for the test.

Two basic types of insulation testing can be accomplished with these methods: acceptance and maintenance. For acceptance testing, the ICEA standard procedures and voltage levels should be followed (1,2). However, maintenance testing requires lower voltage levels to avoid damaging the cable from testing. Nevertheless, the voltage level and duration of test should be adequate to assure that the cable will perform safely in the intended service. As a general rule-of-thumb, maintenance-test voltage is at 50% to 70% of the ICEA approval-test values, and the voltage should be at least as high as the cable rating. Insulation resistance values from megger testing, and leakage currents at specified test voltages from d-c hipot testing, can be used for preventative-maintenance scheduling. If records are maintained, these tests can be used to indicate replacement schedules and prevent in-service breakdowns.

Fault Location. Fault location is another type of testing that is extremely important in the mining industry. Since it is less time consuming to repair or splice a cable in the mine than to replace the cable, quick and accurate location is important. The U.S. Bureau of Mines has evaluated several methods (8).

Some faults are low-resistance short circuits that can be found by visual inspection. Unnoticeable short circuits can be "blown" by applying a high-energy power source to make them visible. This practice is not recommended in mines because of the resultant safety hazards of fire and personnel injury. The cable may be damaged in other areas as well. Other faults that cause low-resistance open-circuits and high-resistance short circuits are extremely difficult to locate.

A "thumper" or capacitance-discharge fault locator has been used successfully in surface mines and in cable-repair shops; however, safety hazards associated with it restrict use in underground mines. A capacitor is charged until a spark gap breaks down, sending a pulse along the cable. The pulse will discharge across a short, if the resistance is low enough, and return. In addition, the pulse will not propogate across a high-resistance open circuit at the same intensity as it was transmitted. An acoustic sensor can then be used to locate the area where the signal caused by the pulse becomes diminished.

The time-domain reflectometer (TDR) is another partially-successful method for locating faults. It works on the principle of a reflected pulse which either reinforces or reduces the original signal, depending on whether the discontinuity is an open or a short. The time of arrival of the echo is proportional to the distance to the fault. The distance is then visually

displayed on a meter. An accessory probe is necessary for exact fault location when a TDR is used, particularly because the precise measurement of distance along a cable is difficult in a mine. A tone transmitter can be used in conjunction with an audio probe to precisely locate the fault. An infrared probe can also be used to locate faults where temperature increases are evident. Probes sensitive to 1° or $2^{\circ}F$ are available. However, a current source must be attached to the cable end.

7.11. Splices and Terminations

Low-Voltage Portable Cables. Splicing methods vary significantly between low-voltage portable and high-voltage distribution cables. Therefore, two sets of guidelines will be presented.

Portable cables are frequently damaged by mobile equipment in the restricted space inherent in coal-mining operations. Normally, the damage is repaired by splicing: the joining of one or more severed conductors and replacement of insulation and jacket. Figure 7.17 illustrates a typical single-conductor splice. Although the repair seems simple, the difficulty of the splicing process is exemplified by the many safety hazards and frequent production delays that result from defective splices (9).

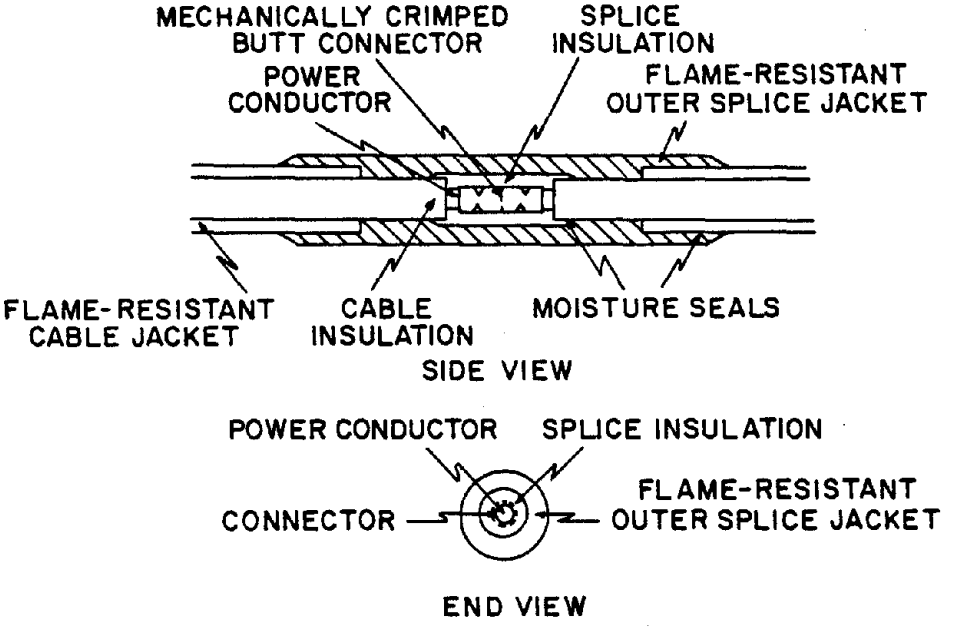


Figure 7.17. Low-Voltage Portable-Cable Splice.

Assuming the damaged area is quickly located, an average splice time for a two-conductor cable is 20 min. Some operators estimate this delay is incurred once per day per operating section. If one ton per min. is averaged throughout the shift, each unit could lose 4800 tpy from splice delays. An estimated cost for materials and labor to make a splice is $20. The expenditure could result in a $4800 annual cost per section. The estimated expense does not include wages of other personnel waiting for the repair to be completed. Nevertheless, labor and materials cost is minor compared to the income lost from decreased production.

Briefly, the steps required to make a splice are:

1. remove the defective area;
2. prepare the cable by staggering conductor joints, removing insulation and jacket for the connector, and cleaning the cable jacket;
3. apply connector;
4. replace primary insulation; and
5. replace jacket.

If the completed splice is to be classified "permanent," it must be:

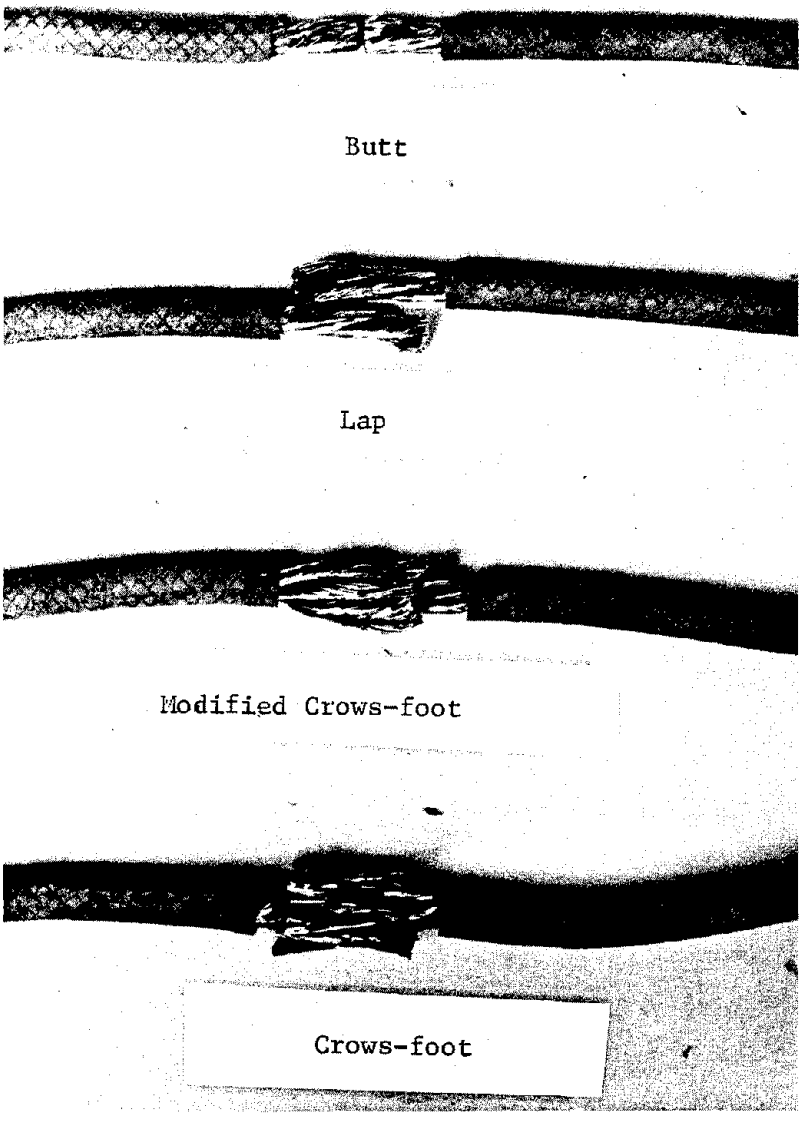
1. mechanically strong with adequate electrical conductivity and flexibility,
2. effectively insulated and sealed so as to exclude moisture, and
3. vulcanized or otherwise treated with suitable materials to provide flame-resistant qualities and good bonding to the outer jacket.

If all requirements are not met, the splice is classed as "temporary," and only one such splice is allowed in an underground-coal-mine trailing cable, and this can only be used for a 24-hr period following splice installation.

Four common methods of joining cable conductors, as shown in Figure 7.18, are:

1. butt connection - the two ends of the conductor are butted together and joined by a connector;
2. lap connection - the two conductors are laid parallel and clamped in place;
3. crows-foot connection - the seven wire bunches making up the conductors are separated in both conductors ends, and intermeshed together; and
4. modified crows-foot connection - the seven wire bunches in one of the conductor ends are separated as in the crows foot connection, and the other conductor end is inserted in the middle of the "crows foot."

In addition to the four methods of connecting the conductors, there are also three connector types (excluding illegal square



NOT REPRODUCIBLE

Figure 7.18. Common Conductor Jointing Arrangements.

knots) that are shown in Figure 7.19.

1. Crimp connector. The cylindrical shaped connector is compressed onto the connectors via a mechanical, hydraulic, or hammered crimping tool.
2. Hammered connector (commonly termed "beat ring"). The diameter of a C-shaped connector is reduced by hammering it, thereby gripping the conductors.
3. Band connector. The diameter of the circular-shaped band-connector is reduced by a special tool, thereby gripping the conductors.

These connectors are used in the mine rather than at a cable-repair shop, where a low-temperature brazing operation is used to join individual ropes within the connector. Butt welds are also used.

As in the conductor connections, there are many methods of insulating and jacketing (shown in Figure 7.20). Some of the more common methods are the following.

1. Heat shrink. An insulation or jacket tube is positioned over the connection or splice and heated, causing the tube to shrink down over the splice.
2. Expandable tubing. Tubing expanded by a plastic cord is shrunk down on the connection or splice when a plastic cord is removed.
3. Tape. Several wraps of rubber tape are layered on the conductor connection or splice, followed by several layers of MSHA-approved, flame-resistant plastic tape.
4. Slip-on cold-splice jacket. An adhesive is applied over the tape-insulated assembly of spliced connectors, and a jacket tube is slid over the repaired area.
5. Injected insulation. A sheet of jacketing material is wrapped around the splice area, the ends are taped onto the cable jacket, and an insulating compound is injected through a hole in the jacket. The insulation sets in a few minutes.

An analysis of underground cable use revealed shuttle cars required the most frequent cable repairs. The analysis also indicated that splices must have good conductivity, flexibility, resistance to moisture penetration, insulation, tensile strength, flexibility, and resistance to abrasion (9).

When the trailing-cable splices repetitively bend around sheave wheels and reels, conductor failure normally occurs near the edge of square knots, mechanical crimp connectors, or welds. Because the connection causes a rigid section, a sharp bend occurs at the connection edge as the cable attempts

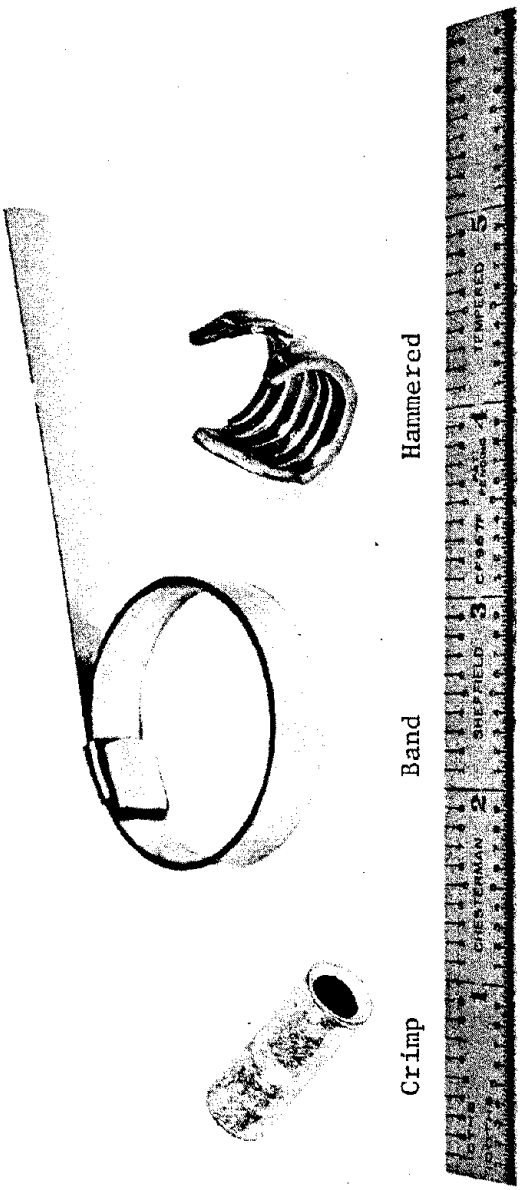


Figure 7.19. Common Splice Connectors.

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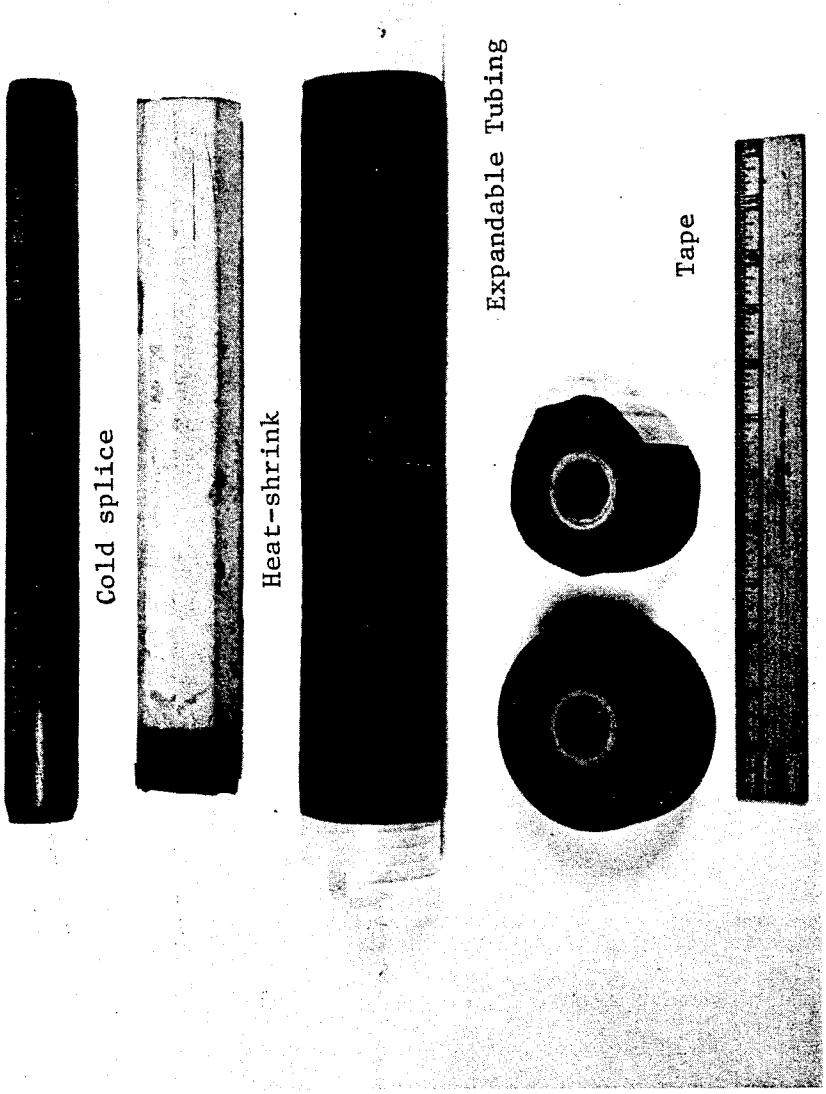


Figure 7.20. Common Splice Insulating and Jacketing Materials.

NOT REPRODUCIBLE

to conform to the sheave-wheel circumference. Consequently, the conductor breaks at that point.

Several methods can be used to improve flexibility:

1. reduce the rigid section length by making "lap" or "crows foot" rather than a "butt" connection;
2. use a crimping tool having a crimp that is tapered toward the connector edge;
3. install a connector with rounded or flared ends;
4. wrap a stiff tape, such as fiberglass-reinforced tape, around the bare conductor adjacent to the connector so support will be provided to reduce the sharp bend; and
5. use as large a diameter sheave wheel as possible to reduce sharp bending.

Flexing also damages insulation; small nicks in the insulation made by mistake during cable preparation are stretched into holes large enough to allow arcing between conductors. Additionally, movement of sharp connector edges wears holes in insulation, and wires broken by bending puncture insulation. Splice-jacket to cable-jacket adhesives will not withstand shear and tensile stresses caused by bending, and they release, allowing moisture to penetrate into the splice. The following techniques are useful in preventing insulation damage.

1. Do not knick primary insulation or jacket during cable preparation.
2. Use crimping tools that do not leave sharp edges on the connector. If sharp edges are present, dull them with a hammer or file.
3. Wrap a stiff tape around the bare conductor adjacent to the connector edge to help contain broken wire ends.
4. Clean the cable jacket thoroughly before applying jacket adhesive.
5. Follow manufacturers' directions with heat-shrink jacket types and heat them thoroughly. This allows the adhesive to flow and bond properly.
6. Apply adhesive throughout the total splice length, not just at the ends. Even though the jacket ends may separate from the cable, the additional adhesive will resist moisture penetration into the splice.
7. Insert all the individual wire strands into the connector.

Most insulation breakdowns result from abrasion or punctures. Too much insulation results in bulky splices with diameters much larger than the original cable. This insulation is commonly caught in the spooling device on cable reels. Furthermore, a bump or high place on a cable will contact an abrasion surface more often and more forcefully than the normal cable. Therefore, a splice jacket should conform closely to the original cable dimensions.

Occasionally arcing inside a splice will result in enough heat to destroy insulation. Federal regulations do not require primary insulation to be flame-resistant. Therefore, if a blow-out occurs or the outer jacket is otherwise torn open, arcing within a splicecan set the inner insulation on fire. As long as it is open to the atmosphere, it will burn.

Insulating techniques are variable depending on the type of splice kit used. The materials contained in the kits are electrically adequate for low- and medium-voltage trailing cables. Manufacturers' instructions are provided in each kit, and if followed, will result in a well-insulated splice. The basic guidelines to follow with insulation are not to leave any void spaces and reinsulate to the original thickness of the cable. When using tape, two layers one-half lapped are recommended.

Abrasion failures are a result of cable rubbing on abrasive surfaces and being run over. They are best prevented by proper cable handling; although, the proper choice of the outer-jacket material can improve abrasion resistance. Vulcanized and heat-shrink jackets provide best resistance to abrasion,with cold splices next,and flame resistant types lowest in abrasion quality.

Many splice failures result from tension on the cable. Strengths of No. 2 Type G, No. 2 Type W, and No. 4 Type W are 3800, 2400, and 2400 lb, respectively. Testing revealed splice strengths well below these values. Welded splices averaged 84% of the original cable strength, while mechanical crimps averaged 53%. Considering mechanical crimp types, average strengths were 46% for lap, 51% for butt, and 76% for crows foot. Except for welded joints, all failure modes were conductors pulling out of connector sleeves, not conductor breaks. The following will improve tensile strength.

1. Crimp squarely in the connector center, not near the edge.
2. Always use the correct size connector for the conductor being spliced.
3. If two connectors are recommended by the manufacturer, both must be used. Do not omit one.
4. Apply the pressure recommended by the manufacturer. Over-crimping breaks wires and under-crimping allows the conductor to slip out of the sleeve when tensioned.
5. Insert all individual wire strands into the connector.
6. Push the conductor as far into the connector as possible.
7. Use the proper crimping tool.
8. Measure lengths accurately to ensure that all conductors are equal. The shorter conductor will attempt to hold most of the tension and fail pre-

maturely rather than equally distributing the load.

9. Do not tension cables more than necessary. If a cable is caught or tangled when being dragged, free it before continuing. Do not set hydraulic pressure on shuttle-car reels higher than necessary. Do not attempt to drag unusually long lengths of cable.

Conductivity is very good on all properly constructed connections. Heating occurs in splices only as a result of failures from flexing, tension, moisture penetration, or shorting through inadequate insulation.

High-Voltage Distribution Cable. High-voltage splices are normally made on stationary distribution cables in underground mines or on drag cables in surface mines. Consequently, the problem of flexibility is lessened; however, other problems are introduced by the presence of shields and semi-conducting layers. Generally, higher voltage means that more care must be taken to achieve a near-perfect splice, that is, one that closely approximates the qualities of the original cable.

The basic low-voltage splicing procedure is the same for high voltage. However, the cable insulation and jacket are usually pencilled as shown in Figure 7.21 to improve the bond and increase the leakage-path length, and lessen the chance of a direct vertical path to a ground plane (6). Extra care and skill are necessary since damage to the insulation during splicing, such as a small cut, will cause more rapid dielectric failure at higher voltages. In the same context, a small protrusion, such as a sharp-edged connector or loose wire, will be a more noticeable failure initiator as the voltage increases.

The presence of semi-conductive tape and braid or tap shielding are components not encountered in low-voltage repairs that require extra caution. The shielding system must be separated from the conductors, so residue on the insulation from the semi-conducting tape is completely removed before the splice insulation is reapplied. In addition, the wires from a braid shield must not protrude into the insulation. The shield must be replaced completely, and the grounding conductor must be placed in intimate contact with the shield.

Terminations. Terminating a cable, especially in high-voltage circuits, is similar to splicing except that a stress cone must be included. The stress cone is needed to prevent insulation damage from high electrical stresses that result from the termination. Premolded, permanent, and hand-taped are the most common types of stress cones. A termination assembly, commonly called a "pothead" is shown in Figure 7.22 (6). A pothead is hermatically sealed inside a metal shell. Porcelain insulators enclose and protect the cable ends. Since potheads offer more protection from the environment, they are generally preferred over the less-expensive taped terminations.

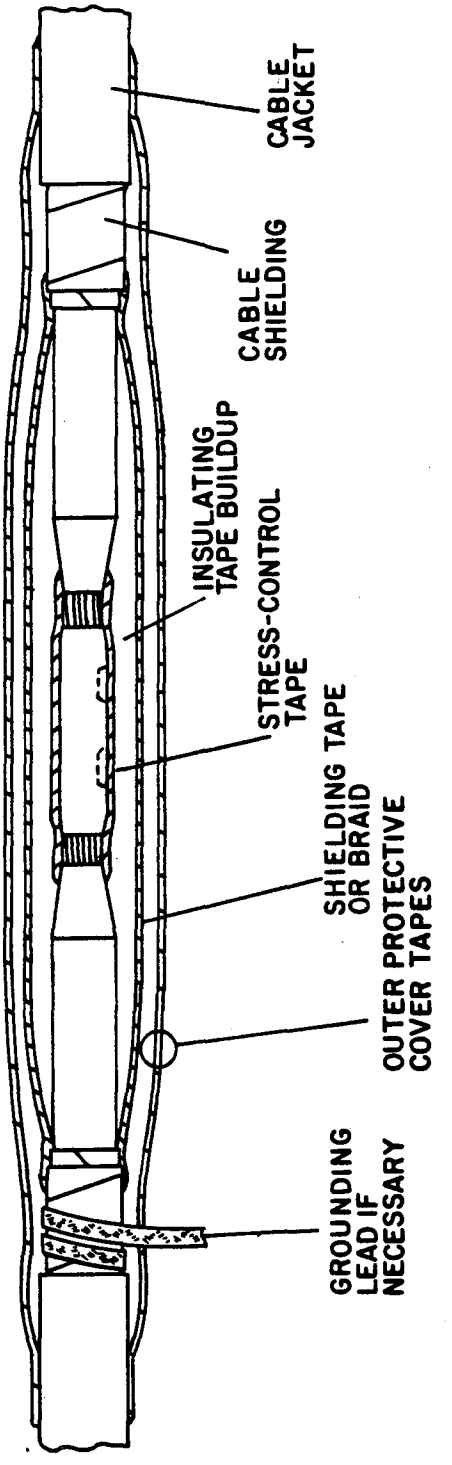


Figure 7.21. Typical Taped Splice in High-Voltage Shielded Cable.

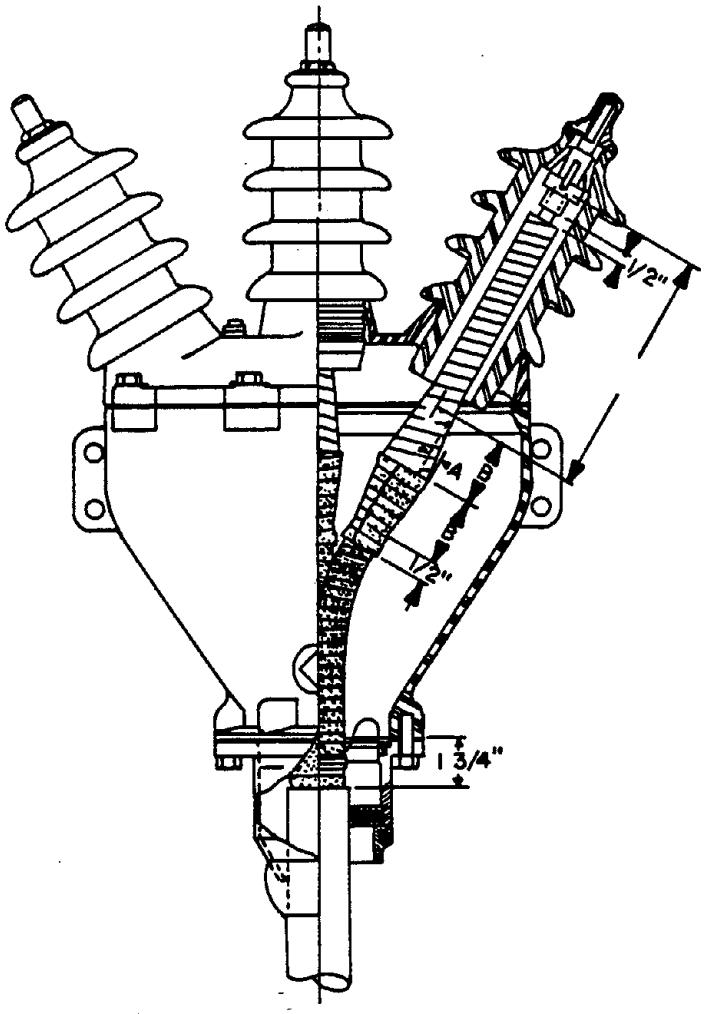


Figure 7.22. Typical Pothead.

A hand-taped cone is made by building-up the insulated conductor with tape to the proper diameter in the conical form shown in Figure 7.22. Half-lapped semi-conducting tape is placed over the cone, and metallic braid tape over that. A ground strap or pigtail must be attached to the shield tape. The termination is then jacketed. The end of the shield components must be smooth and even to avoid failure.

7.12 Couplers

General. Underground and surface coal-mine cable connectors, or couplers, are a very important component in the complex mine electrical system. The experience of many mine operators shows that couplers are a very significant operating-supplies cost in addition to being a potential cause of major production delays. Like other components of the mine electrical system, they can cause personnel injury from electric shock if installed or used incorrectly. Proper design, installation, and use of cable couplers can improve safety and reduce production delays. The object of this section is to describe current coupler use in mines and make recommendations for proper coupler design, installation, and use.

Coupler performance depends on the design of the several individual components shown in Figure 7.23 (10). Selecting the proper materials and configuration for each of these parts to make an assembly that is easy to install, use, and maintain and yet is competitive in the market place with other couplers is a difficult task.

Application. Couplers are used on varying sized cables that transmit a wide variety of voltages; consequently, different designs are necessary. For example, high-voltage requires better insulation properties than medium- or low-voltage installations, to cope with the increased problems of corona and tracking at levels greater than 8 kV. In addition, different constructions are made for stationary (often high voltage) and mobile installations (low and medium voltage).

The type of mounting also influences coupler type. Some are installed "in-line" on cables, while others may be "gear-mounted" such as the couplers in the frame of a load center. The two coupler halves, plug and socket, may contain either male or female contacts and insulators. Usually, however, the socket is used on the power-supply side of the connection, and female contacts and insulators are used to reduce the possibility of a mine worker touching an energized male connector.

Besides utilization voltage and mounting considerations, coupler selection must take into account the task to be performed.

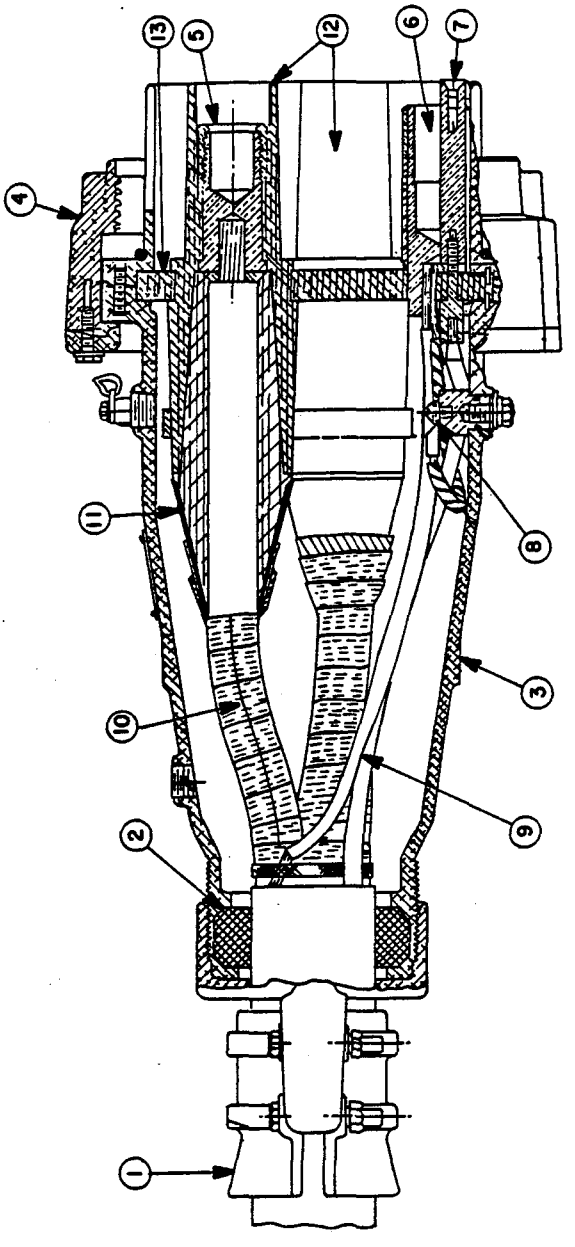


Figure 7.23. Coupler Components.

Some of the more common uses are:

1. extending, retracting, or repairing high-voltage power distribution lines;
2. connecting low-, medium-, and high-voltage cables to switchgear;
3. attaching leads from a battery charger to battery-powered equipment;
4. extending power or control circuits to a longwall face with permissible multi-pin connectors; and
5. providing a quick change-out feature to reduce downtime from damaged portable cables.

High-voltage power distribution cables are normally purchased in 500- to 1000-ft lengths with a coupler attached to each end. The supplier usually sends the cable to a reliable cable-repair shop before it is transported to the mine, since proper high-voltage coupler installation is extremely difficult. In some instances, mine operators prefer to make the installation in their own shops.

The couplers are used to add a section of cable as mining advances away from the power source and to remove sections when necessary. Additionally, couplers mounted at 1000 or 2000 ft along the power-distribution line facilitate replacement of damaged cable sections.

High-voltage power distribution cables are coupled to one end of the load center that is located on each mining section. The high-voltage coupler is used to uncouple the cable from the load center before the center is moved or repaired and to allow additional cable lengths to be added or removed at the load-center connection. Low- and medium-voltage couplers are used to visibly disconnect power from mobile machinery and to replace damaged cables.

Two other tasks, not as common as those already mentioned, necessitate special designs. First, a requirement exists on battery-powered equipment to make a safe, quick connection to a charger. Therefore, couplers are mounted on the machine as well as on the charger leads (see Chapter 13). The other task is the need to connect and disconnect cables for power and control circuits that are extended to the highly-mobile longwall face by using multi-pin permissible connectors.

Future applications may include the use of machine-mounted couplers to reduce the time necessary to remove a damaged cable and install a new or reconditioned one. Quick change-out is very important, especially in the state of Pennsylvania where most mine operators are only allowed five non-vulcanized, mechanically-crimped splices in a trailing cable. However, even where it is not required by a state law, mine operators must remove cables that have an excessive number of splices in order to reduce down-time caused by repeated splice failures. Most low- and medium-voltage gear-mounted plugs can be installed on mining machines that do not have cable reels.

Components. The functions of the main components that make up a coupler (contacts, insulation, and housing or shell) must be considered. The fundamental qualities required of each component for efficient utilization in an underground mine are summarized in Table 7.12. A particular quality listed in the table may be more important for one of the previously-listed five general uses and less important for others. The importance of each requirement, as well as a more detailed discussion of the qualities listed in Table 7.12, is provided in the following.

Male and female pins that mate as the coupler is connected must be of adequate size and have low contact resistance to prevent excessive heating when carrying current. Continuous-miner motor-starting currents, and currents drawn while the machine is cutting, have been high enough to melt some coupler contacts. This occurs particularly on high horsepower (greater than 400 hp) continuous miners operating at 440 or 550 Vac. Some mine operators have increased the operating voltage for these machines to 950 Vac to avoid problems of handling large, heavy cables and couplers (as is recommended in Chapter 5).

Poor mating of male and female contacts is usually a result of frequent coupling and uncoupling during which the coupler may be dropped and the contacts bent or dirt enters the connection. Another cause of bent contacts is poor alignment during coupling. Heating is caused by the high-resistance connector that results from bent contacts.

Coupler manufacturers have attempted to reduce the damage to contacts from dropping by recessing the contacts in the housing. Several guidance systems are currently used to facilitate alignment. However, the ultimate solution is to handle couplers carefully instead of dropping them or attempting to force a connection when contacts are misaligned.

Another connection, between the cable conductor and connector pin, is a possible failure point. Set screws, soldering, thermit welding, and brazing are common methods of securing the connection. Severe vibration from dropping or from bouncing and bumping on a mobile machine such as a battery scoop may loosen a set screw or crack a weld. Then the high-resistance broken connection heats, which can cause insulation deterioration and a fault. In addition, care must be taken to remove flux used in brazing or soldering these connections as it will destroy the insulation.

Voids and protrusions in an improper mating are extremely important at voltages greater than 8 kV because they create corona inception points. Corona is an insulation-destroying mechanism that is explined further in Chaper 15.

Table 7.12. Coupler Qualities.

Contacts	Insulation	Shell or Housing
The coupler contact system should have: 1. adequate current-carrying capacity and low resistance, 2. the ability to withstand repeated coupling, 3. protection from worker abuse, 4. a reliable and easy-to-make connection to the cable conductor, 5. oxidation and corrosion resistance, 6. uncoupling feature that allows a pilot or ground check to disengage first and the ground wires to uncouple last, 7. a guidance system to prevent misalignment and bending during coupling, and 8. a feature to allow replacement of bent or damaged contacts.	The coupler insulation system should have: 1. adequate dielectric strength, 2. adequate corona-extinction level, 3. adequate tracking resistance, 4. stress-relief feature, 5. adequate impulse level, 6. flame resistance, 7. resistance to moisture penetration, 8. insulators that allign easily for coupling, 9. resistance to cracking, chipping, and bending, 10. resistance to heat deterioration, 11. the ability to withstand repeated coupling, and 12. a feature that discourages phase reversal during mounting and coupling.	The outer covering should have: 1. a reliable easy-to-make ground wire connection, 2. a cable strain-relief mechanism, 3. a guidance system that improves the ease of allignment for coupling, 4. a durable material composition, 5. the ability to withstand repeated coupling, 6. corrosion resistance, 7. grommet or packing gland of the correct size for the cable used, 8. as little weight as possible, and 9. a feature that facilitates ease in coupling and uncoupling.

To ensure that coupler insulation does not break-down in normal service, it should have a dielectric strength equal to or greater than that of the cable entering the connection. Additionally, for high-voltage installations, the surface of the insulation should resist "arc tracking" (high-current arc discharges across the insulator surface which may carbonize the material and form a conductive track). It is important to keep high-voltage insulators clean and dry since tracking resistance is decreased by water and dirt on the insulator surface. A common cause of moisture contamination is dropping the coupler on a wet mine floor.

Earlier, it was mentioned briefly that voids and protrusions may initiate corona. Corona is formed at these localized "unconformities" by voltage gradients which become high enough to ionize the air around the insulation and thus allow the air to become an electrical conductor. At times, either electron bombardment or chemical degradation by caustic acids formed in the ionization process will cause the insulation to deteriorate. Therefore, the insulation should be composed of a material that resists the formation of corona and its products. But equally important is the overall coupler design. It should be constructed so the voids and protrusions are easy to eliminate during coupler assembly.

Insulation, particularly if it has been weakened by corona, is subject to breakdown by high-impulse voltages called transients. Transients, which usually occur during switching, are present on high-, medium-, and low-voltage systems (see Chapter 10). Insulating materials must be able to withstand repeated applications of these high voltages. A stress cone, similar to the item described for terminations, must be incorporated in high-voltage couplers.

Besides having the previously-mentioned electrical properties, insulation must be able to withstand four mechanical abuses: moisture, heat, breaking, and bending or folding. The mining atmosphere is frequently humid, and water sometimes drips from the roof and lies in puddles on the floor. Consequently, couplers must resist moisture penetration to prevent line-to-line and line-to-ground current leakage along the conducting water path. Workers must be especially careful when using couplers in a wet area to prevent moisture from entering the housing.

Another mechanical property, heat, may cause faults if insulation deteriorates. Therefore, the dielectric material used must withstand high temperatures without deteriorating.

Another failure occurs during connecting when the male and female insulators surrounding the contact pins may hit if they are not exactly aligned. When this occurs, soft insulators will buckle and brittle ones will crack or break. Coupler manufacturers have accomplished a lot in recent years to produce materials that resist buckling and cracking, in addition to incorporating alignment guides.

Federal regulations specify a metallic or "no-less-effective" shell that is connected to the cable grounding conductor to prevent electric shock to workers handling the coupler (3). (Note: there is an exception to this ground connection with some ground-check monitors, see Chapter 8.) The housing should cover all of the inner components of the connection and insulation systems as is shown in Figure 7.23. As can be noted in the same figure, the grounded-metal shell is also the coupling mechanism. A threaded connection is used in the figure; however, a pivot-pin and catch assembly is prevalent on some square couplers. Since couplers are sometimes dropped or hit by falling roof rock or rib coal, the housing and connection mechanism must be very rugged.

The engagement mechanism which pulls and fastens the plug and socket together must withstand repeated use. Couplers are often disconnected to replace cables, move equipment, and remove power from equipment being repaired. Low- and medium-voltage connectors are disconnected more frequently (at least once a shift) than high-voltage connectors and, therefore, must have a quick but rugged fastening mechanism. Coupling and uncoupling can be a difficult task when the fastener is stuck, particularly for some of the heavy high-voltage devices which weigh up to 80 lbs. In fact, some miners have torn gear-mounted load-center couplers (which are mounted in the load-center frame with a left-handed thread) out of the equipment by stripping the threads when attempting to disconnect cable-mounted couplers that are right-hand threaded.

The cable entrance is another important function of the housing. If the coupler is classified "explosion proof" by MSHA, an explosion that occurs inside the shell should not ignite a methane-air mixture surrounding it. Consequently, a "packing gland" (see Figure 7.23 and Chapter 14) with asbestos fiber packed tightly between the cable and bushing is used. Different sizes of cables can be used in one housing by varying the thickness of the asbestos packing. Explosion-proof couplers are allowed inby the last open crosscut in underground coal mines by all state and federal regulations. Connectors without packing glands can be used inby the last open crosscut if they have a pilot or ground check circuit that interrupts the power before the housing is opened. Instead of packing, non-explosion-proof couplers have a rubber grommet that allows cables of different diameters to fit into the same housing.

A cable strain-relief clamp is located on the outside of the cable entrance. It prevents cable tension from pulling the conductors out of their connections. The clamp may be drawn down on the cable jacket by tightening two bolts on either side. If the bolts are not sufficiently tight, the clamp will not prevent tensile pull-out and, if too tight, the clamp will damage the cable insulation.

Both packing glands and strain-relief clamps are made to fit either one cable-jacket size or a small range of sizes. Thus, knowledge of cable outer dimensions is necessary to match the coupler cable entrance to the cable. Tables 7.13 and 7.14 contain typical dimensions for round and flat cables, respectively, (3). Variations in these values are allowed as long as the proper packing gland or strain relief is used.

7.13 Trolley Systems

General. The trolley system is a potential hazard for fires, ignition of methane, and shock since it utilizes uninsulated conductors. The danger in underground coal mines is greater than in surface mines because of limited space and the presence of methane. However, safety in all mines which utilize trolley wires for electric track haulage can benefit from proper design, selection, and installation of the system components.

Several conductors are used in the trolley circuit: trolley wire, feeder cable, railbond cable, and steel track rails. The trolley wire supplies power directly to a rail-mounted vehicle, such as a mine locomotive, through a collector called a "shoe" or "harp". The trolley-wire and collector connection may cause frequent severe arcing which can damage either part and cause an obvious ignition hazard. Proper position of the trolley wire, particularly at curves and switches, correct holding force on the collector, and the required amount of lubrication are necessary to minimize arcing.

A feeder cable supplies power to the trolley wire. Consequently, both must be sized properly to provide enough current-carrying capacity to minimize heating and voltage drop. In addition, rectifiers must be positioned at adequate intervals to supply the proper voltage to the feeder.

The grounding path utilizes the steel rails, which must have adequate conductivity to minimize the total-system resistance. Rails are laid in segments, and the connections between them become loose or the rails break so rail-bond cable is installed to maintain continuity. Rail-bond cable is attached at each rail joint, and as a further precaution, between the two rails at specified intervals (cross bonds).

Trolley Wire. The trolley-wire conductor used in mines is hard-drawn copper; however, brass is available for high-speed surface transportation. Round, grooved, figure-eight, and figure-nine (deep-section) wire shapes shown in Figure 7.24 are available (7). At one time, round wire was prevalent, but the clamps that are necessary to support it caused the collector to jump and arc so it was replaced with the figure-eight shape. Additional problems occurred with the figure-eight because it twisted and kinked when being reeled and unreeled during installation, and

Table 7.13. Typical Diameters for Round Portable Power Cables in Inches, 601- to 5000-V.

Conductor Size, AWG or MCM	G-GC 2 kV	SHC-GC 2 kV	SHD-GC 3 kV	SHD-GC 3-5 kV
4	1.25	1.39	1.62	1.78
3	1.40	1.55	1.77	1.90
2	1.48	1.62	1.84	1.98
1	1.55	1.71	1.92	2.09
1/0	1.74	1.89	2.04	2.18
2/0	1.84	2.02	2.18	2.34
3/0	1.99	2.16	2.29	2.46
4/0	2.12	2.30	2.45	2.62
250	2.30	2.48	2.62	2.76
350	2.75	2.97	-	-

Table 7.14. Typical Dimensions for Flat Portable Cables in Inches, 600-V.

Conductor Size AWG	Two-Conductor Type W Major	Two-Conductor Type W Minor	Two-Conductor Type G Major	Two-Conductor Type G Minor	Three-Conductor Type G Major	Three-Conductor Type G Minor
8	0.84	0.51	-	-	-	-
6	0.93	0.56	1.02	0.56	1.65	0.67
4	1.05	0.61	1.15	0.61	1.85	0.75
3	1.14	0.68	1.26	0.68	1.99	0.77
2	1.24	0.73	1.35	0.73	2.10	0.81
1	1.40	0.81	1.55	0.81	2.43	0.97
1/0	1.51	0.93	1.67	0.93	-	-
2/0	1.63	0.99	1.85	0.99	-	-
3/0	1.77	1.03	2.00	1.03	-	-
4/0	1.89	1.10	2.10	1.10	-	-

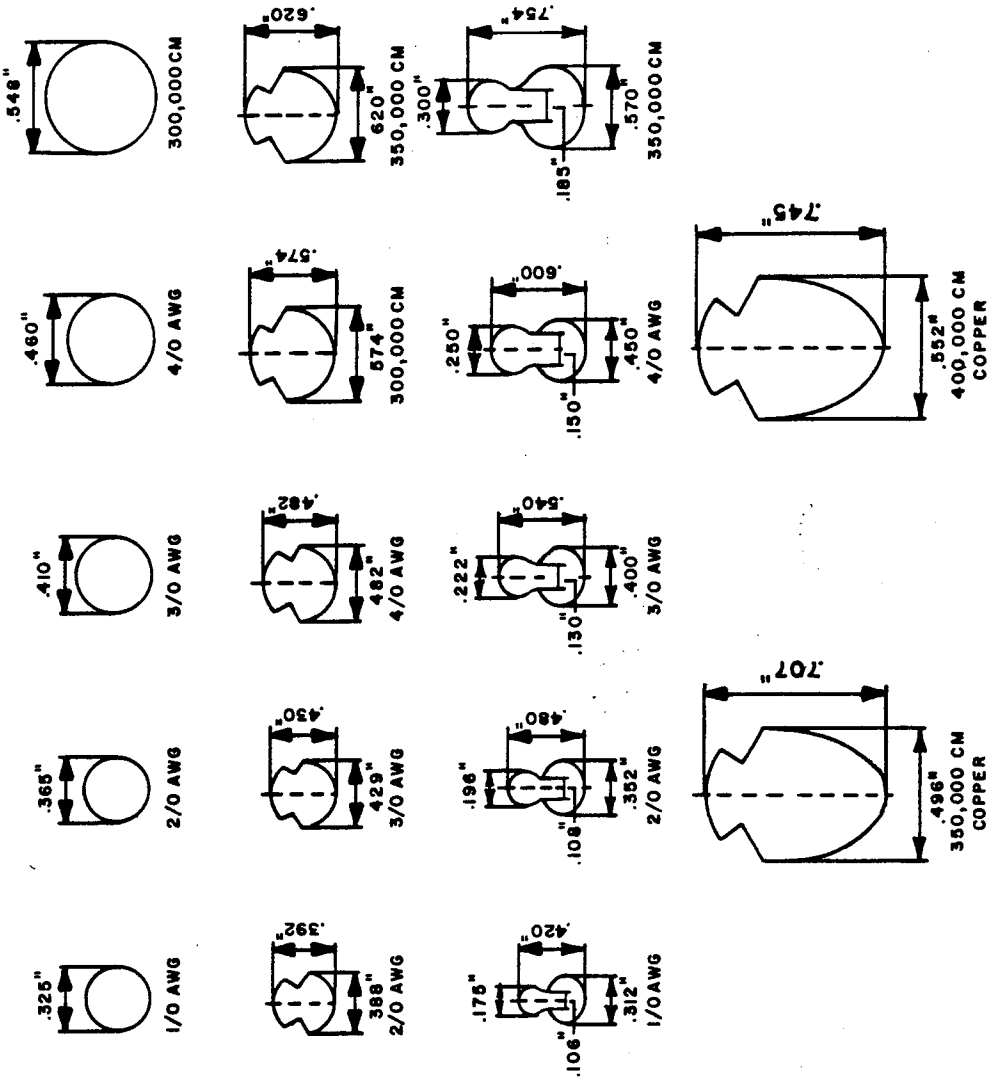


Figure 7.24. Trolley-Wire Cross Sections.

it frequently pulled out of hangers on curves. Consequently, the grooved type was developed and, along with the figure-nine, has almost completely replaced the round and figure-eight shapes. In Figure 7.24, it is noted that the width of the 350-MCM grooved wire (0.620 inches) requires large splices and other fittings, and it is too large for proper tracking of the collector. Therefore, at this size and above, the figure-nine or deep-grooved shoe is commonly used. The upper section of the wire, to which the roof- or rib-mounted support clamp will attach, has the same width dimension whether grooved, figure-eight or figure-nine wire is used. Table 7.15 gives the necessary specifications for proper wire-size selection (7). The most common is 350- or 400-MCM (both often called 6/0) figure nine.

Feeder. In order to reduce voltage drop and supply the necessary current, an uninsulated, stranded, feeder cable is hung alongside the trolley wire. Both aluminum and copper feeders are used, and their size depends on the load drawn by the track vehicles and the voltage regulation desired. Common sizes are 1000-MCM copper or 1590-MCM aluminum. Table 7.16 specifies copper feeder data (7). As noted in the table, feeder can be purchased with a weatherproof jacket.

Supports, Lubrication, and Turnouts. As is shown in Figure 7.25, the feeder cable and trolley wire can be hung side by side to gain additional roof clearance, or the feeder can be used as a messenger, as shown in Figure 7.26, to increase the roof-mounted support-bracket spacing (7). A cushioning effect is provided for the trolley wire in this configuration, since the wire is free to flex under pressure.

Typical brackets for supporting trolley and feeder are shown in Figures 7.25 and 7.26. The amount of deflection or sag between supports can be calculated by:

$$D = \frac{3WL^2}{2T} \qquad (7.7)$$

where,

D = sag, in.,
W = weight, lbs. per ft,
L = distance between supports, ft,
T = tension, lbs.

Since the figure-nine 350-MCM conductor has a breaking strength of 12,000 lbs, it can safely be tensioned to 1200 lbs, 10% of the breaking strength. This will reduce sag and keep the wire straight and level. The dead-end hooks and turnbuckles shown in Figure 7.27 are used to install tension in the wire.

Recommended roof-mounted-support maximum spacing for a semi-catenary installation (Figure 7.26) is 20 ft, and direct suspension (Figure 7.25) spacing should be less than 15 ft.

Table 7.15. Trolley-Wire Specifications.

Nominal Size	Cross-Sectional Area			Weight		D-C Resistance or Volts Drop per Ampere at 20°C (68°F)			Minimum Breaking Load	Elongation in 10-inches
	Nominal	Actual								
Awg or MCM	MEM	MEM	Square Inches	Pounds per M Feet	Pounds per Mile	Ohms or Volts per M Feet	Ohms or Volts per Mile	Pounds per Square Inch	Pounds	Percent
ROUND					97.16% CONDUCTIVITY				HARD-DRAWN COPPER	
1/0	105.6	105.6	0.0829	319.5	1687	0.1011	0.5339	54,500	4,518	2.40
2/0	133.1	133.1	.1045	402.8	2127	.08021	.4235	52,800	5,519	2.80
3/0	167.8	167.8	.1318	507.8	2681	.06362	.3359	51,000	6,720	3.25
4/0	211.6	211.6	.1662	640.5	3382	.05045	.2664	49,000	8,143	3.75
300	300.0	300.0	.2356	908.0	4794	.03558	.1879	46,400	10,930	4.50
GROOVED					97.16% CONDUCTIVITY				HARD-DRAWN COPPER	
2/0	133.1	137.9	0.1083	417.6	2205	0.07741	0.4087	50,200	5,437	2.80
3/0	167.8	167.3	.1314	506.4	2674	.06380	.3369	48,500	6,373	3.25
4/0	211.6	212.0	.1665	641.9	3389	.05035	.2659	46,600	7,759	3.75
300	300.0	299.8	.2355	907.6	4792	.03560	.1880	44,200	10,410	4.50
350	350.0	351.2	.2758	1063.0	5612	.03040	.1605	42,800	11,800	4.50
FIGURE-8					97.16% CONDUCTIVITY				HARD-DRAWN COPPER	
1/0	105.6	105.6	0.0329	319.5	1687	0.1011	0.5340	51,800	4,294	2.40
2/0	133.1	133.1	.1045	402.8	2127	.08021	.4235	50,200	5,246	2.80
3/0	167.8	167.8	.1318	508.0	2682	.06361	.3359	48,500	6,392	3.25
4/0	211.6	211.6	.1662	640.5	3382	.05044	.2663	46.600	7,745	3.75
350	350.0	350.1	.2750	1060.0	5597	.03049	.1610	42,800	11,770	4.50
FIGURE-9 DEEP-SECTION					97.16% CONDUCTIVITY				HARD-DRAWN COPPER	
350	350.0	348.9	0.2740	1056.0	5576	0.03060	0.1616	42,800	11,730	4.50
400	400.0	397.2	.3120	1202.0	6347	.02687	.1419	41,300	12,890	4.50

Table 7.16. Copper Feeder-Cable Data.

Size A.W.G.	Section Area: Circular Mils	Section Area: Square Inches	Section Area: Square Millimeters	Diameter Overall Inches: Bare	Diameter Overall Inches: Weatherproof (Minimum)	Weight Pounds per 1000 Feet: Bare	Weight Pounds per 1000 Feet: T.B.W.	Breaking Strength Pounds Bare Wire: Hard Drawn	Breaking Strength Pounds Bare Wire: Annealed	Size A.W.G.
0000	211600	.1662	107	.4600	.6163	641	767	8143	5320	0000
000	167800	.1318	85.0	.4096	.5659	508	629	6722	4220	000
00	133100	.1045	67.4	.3648	.5211	403	502	5519	3340	00
0	105500	.08289	53.5	.3249	.4812	320	407	4517	2650	0
1	83690	.06573	42.4	.2893	.4456	253	316	3688	2100	1
2	66370	.05213	33.6	.2576	.3826	210	260	3003	1670	2
3	52640	.04134	26.7	.2294	.3544	159	199	2439	1325	3
4	41740	.03278	21.2	.2043	.3293	126	164	1970	1050	4
5	33100	.02600	16.8	.1819	.3069	100	135	1591	880	5
6	26250	.02062	13.3	.1620	.2870	79	112	1280	700	6
7	20870	.01635	10.6	.1443	.2693	63	...	1030	550	7
8	16510	.01297	8.37	.1285	.2535	50	75	826	440	8

Table 7.16. Copper-Feeder Cable Data (Continued).

Size A.W.G.	Circular Mils	Square Inches	Square Millimeters	No. of Wires in Strand	Diameter Overall Inches Bare	Diameter Overall Inches Weatherproof (Minimum)	Weight Pounds per 1000 Feet Bare	Weight Pounds per 1000 Feet T.B.W.	Breaking Strength Pounds Bare Wire Hard Drawn	Breaking Strength Pounds Bare Wire Soft (Minimum)	Resistance Ohms per 1000 Feet at 20°C (86°F) Standard Annealed
	2,000,000	1.571	1014	91	1.630	1.880	6175	7008	87,790	43,830	.005289
	1,750,000	1.374	887	91	1.526	1.776	5403	6193	77,930	38,350	.006045
	1,500,000	1.178	760	61	1.411	1.661	4631	5380	65,840	32,870	.007052
	1,250,000	.9817	633	61	1.288	1.538	3859	4508	55,670	27,390	.008463
	1,000,000	.7854	507	61	1.152	1.402	3088	3674	45,030	21,910	.010578
	900,000	.7069	456	61	1.094	1.313	2779	3332	40,520	19,270	.011753
	800,000	.6283	405	61	1.031	1.250	2470	2992	36,020	17,530	.013223
	750,000	.5890	380	61	.998	1.217	2316	2822	34,090	16,430	.014104
	700,000	.5498	355	61	.964	1.183	2161	2650	31,820	15,340	.015112
	600,000	.4712	304	37	.893	1.112	1853	2235	27,020	13,150	.017631
	500,000	.3927	253	37	.813	1.001	1544	1894	22,510	10,960	.021157
	450,000	.3534	228	37	.772	.960	1389	1724	20,450	9,860	.023508
	400,000	.3142	203	19	.726	.914	1235	1553	17,560	8,765	.026447
	350,000	.2749	177	19	.679	.867	1081	1345	15,590	7,669	.030225
	300,000	.2356	152	19	.629	.817	926	1174	13,510	6,574	.035262
	250,000	.1963	127	19	.574	.762	772	985	11,260	5,478	.042315
0000	211,600	.1662	107	19 or 17*	.528	.684	653	800	9,617	4,637	.04999
000	167,800	.1318	85.0	10 or 17*	.470	.626	518	653	7,366	3,677	.06304
00	133,100	.1045	67.4	7	.414	.570	411	522	5,926	2,916	.07949
0	105,500	.08289	53.5	7	.368	.524	326	424	4,752	2,312	.10024
1	83,690	.06573	42.4	7	.328	.484	258	328	3,804	1,834	.1264
2	66,370	.05213	33.6	7	.292	.417	205	270	3,045	1,525	.1594
3	52,640	.04134	26.7	7	.260	.385	163	206	2,433	1,209	.2009
4	41,740	.03278	21.2	7	.232	.357	129	170	1,938	959	.2535
5	33,100	.02600	16.8	7	.206	.331	102	140	1,542	761	.3195
6	26,250	.02062	13.3	7	.184	.309	81	115	1,228	603	.4029
7	.....	....	....	..	....	....	...	...	...	...	.5080
8	16,510	.01297	8.37	7	.146	.271	51	78	777	379	.6406

* Sizes A.W.G. 0000 and 000 cable are usually made of 7 strands when bare and 19 strands when insulated.

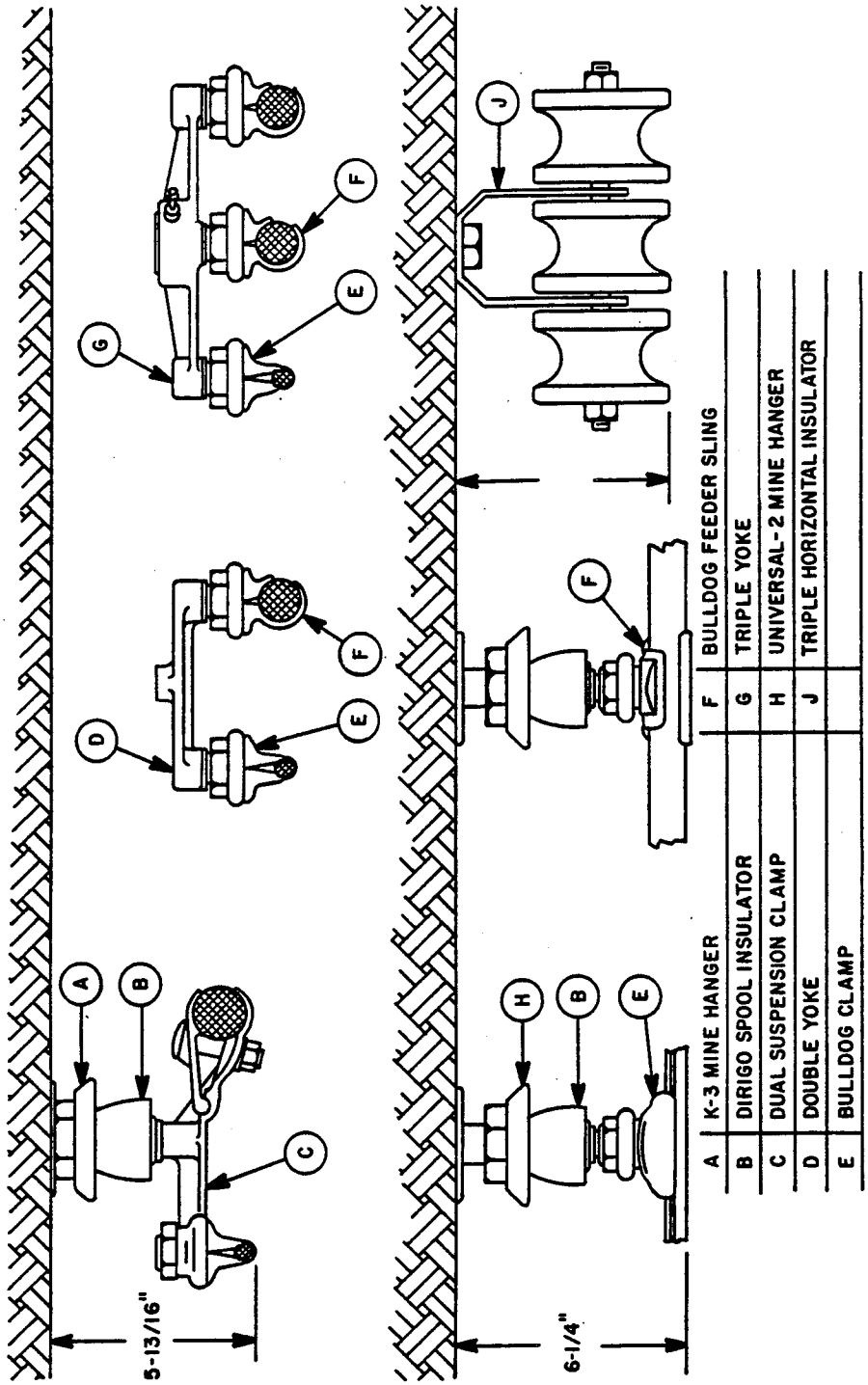
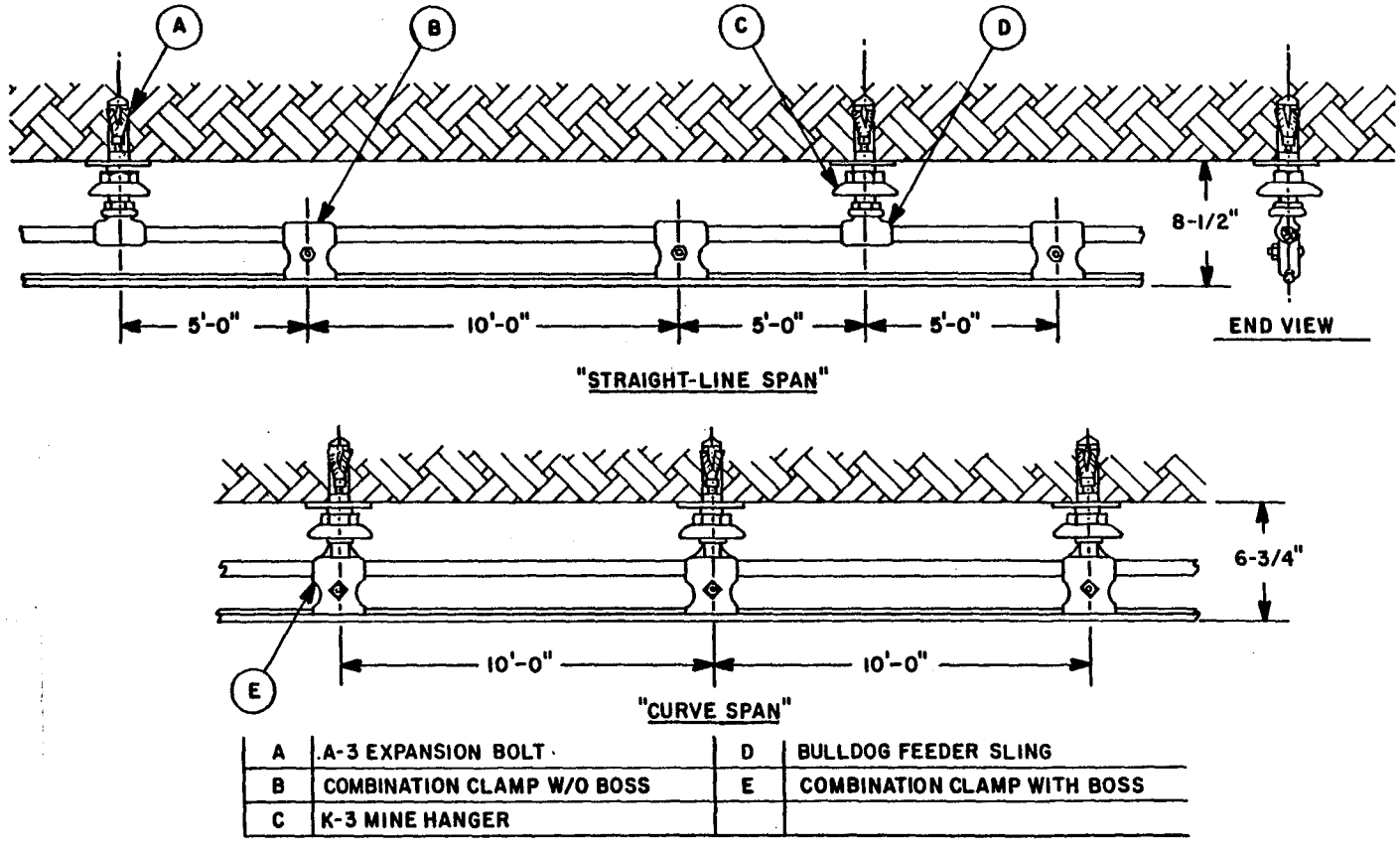


Figure 7.25. Typical Trolley-Wire and Feeder-Cable Supports.



A	A-3 EXPANSION BOLT	D	BULLDOG FEEDER SLING
B	COMBINATION CLAMP W/O BOSS	E	COMBINATION CLAMP WITH BOSS
C	K-3 MINE HANGER		

Figure 7.26. Trolley-Wire Semi-Catenary Suspension.

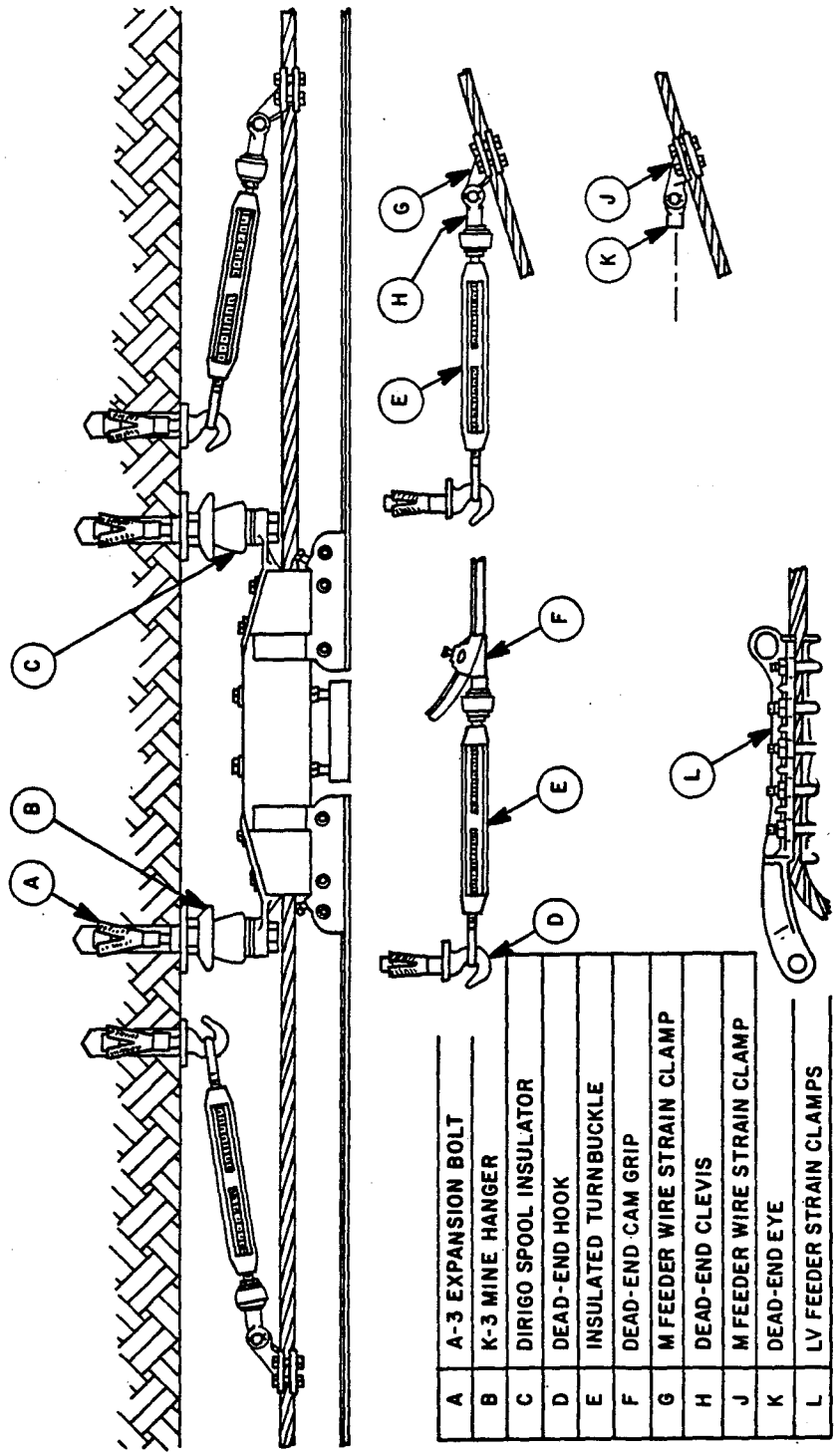


Figure 7.27. Trolley-System Accessories.

Table 7.17 gives support spacings on curves (7). When selecting proper support types and spacings, the weight of trolley guards must be included. Underground coal-mine regulations require guards to be positioned wherever personnel normally work or pass under the uninsulated trolley and feeder wires (3). In addition, when the roof is uneven or too high for the trolley wire, pole-extension brackets can be used either from the roof or from the rib or wall.

For trolley haulage outside the mine, catenary or direct support can be used. Simple catenary (suspending the trolley wire from a messenger) works best for long haulage distances since 100-foot spans are possible on straight track. Compound catenaries, using two messenger wires and subspan catenaries are also used. Semi-catenary or direct-suspension spacing may be increased to 25 or 30 ft on the surface. The previously-mentioned deflection formula (7.7) may be used for more precise calculations.

A properly-installed trolley wire looks level and straight without bends, kinks, or sags. The rubbing surface of the metal should look polished and smooth not scraped or burned bright. A graphite-based lubricant should be used periodically to form a smooth contact surface and maintain the smooth polished-brown appearance. An unlubricated, uneven trolley wire wears out quickly, is unsafe (due to arcing), reduces power efficiency, and also wears out the collector.

At track switches or turnouts, trolley frogs must be installed in the proper location to assure that the collector will pass onto the correct wire. Normally, a standard ten-degree

Table 7.17. Trolley-Wire Support Spacings on Curves.

Radius of Curve (feet)	Max. Spacing (Deflection Angle = 5 degrees) - feet
350 and over	30 *
300	26
250	22
200	17
150	13
120	10
100	9
80	7

* On straight lines, spacing can be increased to 30 feet where wire is 5' or more above rail. If wire is less than 5' above rail, the limit on inside construction is 20'.

Table 7.18. Resistance of Steel Rail.

Rail Weight (lbs/yd)	Resistance @ 20°C Rail (Ω/1000 ft)
40	0.0250
50	0.0200
60	0.0166
70	0.0143
80	0.0124
90	0.0111
100	0.0100

trolley frog is used for any degree of track turnout. The frog must be positioned sufficiently beyond the track turnout so that enough side force will exist on the collector to guide it onto the correct wire. Too much side force will cause the collector to be pulled off the wire. The point at which the frog angle should be located is found by determining the position where the collector pole exerts just enough side force on the collector. This point occurs where the pole angle is equal to the track-frog angle plus ten degrees.

Rails and Bonds. Another important consideration is the resistance of the grounding circuit: the rails and bonds. The specific resistance of high-carbon steel rails is 118 Ω per circular-mil-foot at 20°C. This value is about 12 times that of copper. Using this ratio, Table 7.18 has been constructed to give resistance values for mine track per rail.

Rail-bond cable is soft, stranded copper in sizes from 2/0 to 500 MCM. It is attached with stud terminals or welds across every rail joint. The welded terminal is better for permanent application on main-line haulage. However, the amount of heat that is used must be controlled in order to prevent steel-rail recrystallization. Thermite welds have been successful in this operation. Cross bonds are applied at least every 200 ft along the track so that if a bond breaks along a rail, or the rail breaks, the grounding path can be completed through the other rail. This practice also halves the resistance in the ground circuit by paralleling the two rails. All bonds are subject to damage by the wheels of derailed mine cars so they should be located next to ties and secured to the tie side for protection. If possible, bonds should be placed under the rail-connecting plates.

Bond size is usually determined by voltage drop rather than current-carrying capacity. However, a general rule is that bare conductors will carry one ampere per 5000 circular mils of area without excessive heating. For short periods, five times this amount can be carried and short bonds on heavy rail can carry

150% of the normal load current. Bond-cable resistance is shown in Table 7.19 along with the usual sizes according to rail weights. The terminal resistance is negligible at one microohm, and cross bonds are normally equal in length to the track gage, which is 42 in. Joint bonds are usually 10-in long. The added resistance of joints, expressed in feet of rail, can be found from the chart in Figure 7.28 (11).

7.14 Surface Overhead Lines

On occasion, surface overhead lines must be extended from main substations to mine facilities. In particular, an underground mines's surface plant, such as office buildings, maintenance shops, ventilations fans, haulage, storage, and preparation facilities, require power. In other instances, the need to reach a remote borehole or ventilation fan requires an overhead line, or several small punch mines may also be supplied by an overhead supply from a main distribution point. Surface mines also utilize overhead lines extensively to reach remote areas of the operation without obstructing haulage roads. If these lines are not installed properly, failures from conductor breakage, arcing between phases, and structural collapse can occur. Obviously, serious safety hazards and costly power outages can result; therefore proper design and installation is important.

In-depth treatment of overhead surface-line design is covered by several publications. For example, Fink and Carrol (12) give an excellent detailed summary of design, installation, and repair practices in overhead distribution (also see reference 13). The detailed information that is necessary for an adequate treatment of this subject is voluminous. Consequently, the subject is presented in general introductory terms in the following paragraphs, with a few specifics on the wood-pole structures which are most commonly used in mining applications.

The design of surface overhead lines relies as much on a knowledge of structure and mechanics as it does on electricity. Specifically, the correct placement of structure to support the power and grounding conductors is that which limits the sag between structures to a value which protects the conductors from damage. Additional vertical loading can be supplied by ice accumulation. Obviously, the vertical weight of several single-conductor or one multi-conductor cable(s) must be supported. The structure height, considering sag between structures must be adequate to give the required ground clearance. Also, the structure must be planted firmly enough to avoid being displaced by uplift from the conductors on a steep slope.

In order to install the conductors with the proper amount of sag, tension is applied and will result in stretch. Over a period of time, conductors (especially aluminum) "creep" or elongate which has to be accounted for in the design. Tempera-

Table 7.19. Rail-Bond Cable Data.

Rail-Bond Size	Resistance 1 ft @ 20°C, Ω	Used with Rail Size, lb./yd.
2/0	79.35×10^{-6}	20 to 40
4/0	49.97×10^{-6}	20 to 80
300 MCM	35.31×10^{-6}	80 to 100
500 MCM	21.16×10^{-6}	80 to 100

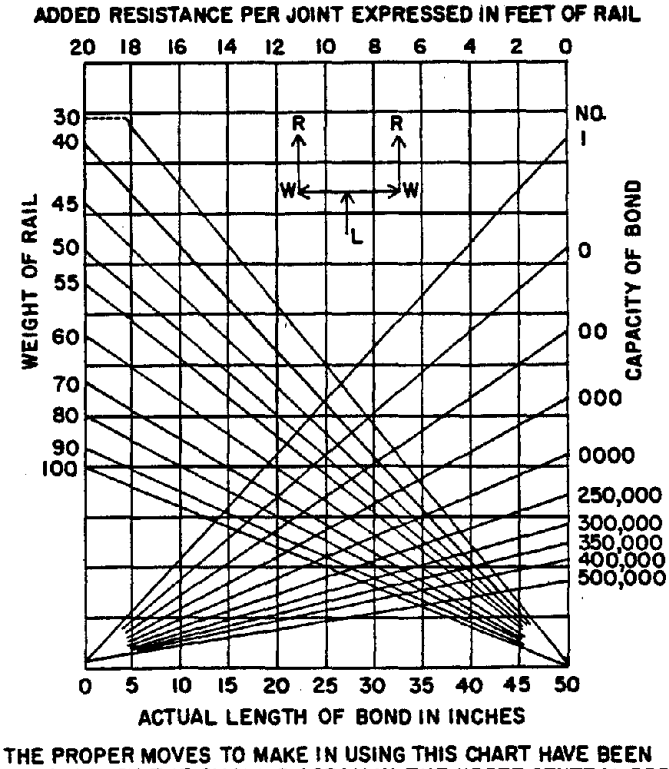


Figure 7.28. Theoretical Resistance of a Bonded Joint.

ture expansion and contraction also affect the amount of deflection and must be considered. In addition, winds cause the conductors to vibrate vertically, and they impart a horizontal force to the structure. Horizontal forces are also a design consideration for angle points in the line. Furthermore, large horizontal forces that exist when one or more conductors break is a necessary consideration. In addition, the conductors must be spaced far enough apart so winds will not force the conductors close enough to allow arcing. Vertical spacing between conductors must be adequate to prevent arcing when the line jumps after a large accumulation of ice falls off it.

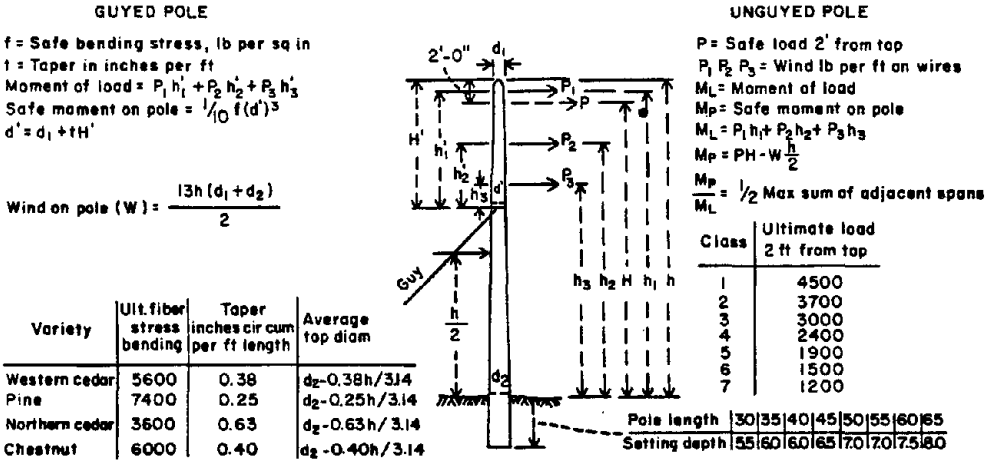
Extremely tedious calculations for catenary spans can result from attempting to take all of these factors into account. Fink and Carrol explain graphic solutions and describe "Thomas" charts that assist the computation process (12). The National Electrical Safety Code (14) gives design information for ice loadings, temperature variations, and wind velocities for different areas in the United States.

Several different types of structures are used to support the conductors. Selection of a type depends on the terrain, accessibility requirements, right-of-way availability, distribution voltage, span length, number of circuits, conductor size, weather, life of installation, availability of material, and economics. The types commonly used are self-supporting and guyed-steel or aluminum towers, steel or aluminum poles, concrete poles, wood H-frames, and wood poles. Steel and aluminum structures are used for high-voltage distribution where long service life and long spans are necessary. Wooden poles and H-frames are usually used below 69 kV, although H-frames have carried conductors for 345-kV circuits. Wood poles are the most prevalent mining-industry support so a few details of their design will be presented.

Wood poles are usually constructed from fully-treated pine or butt-treated cedar. They are classified according to the American Standards Association by their circumferential dimension measured at a point six feet from the butt. Consequently, the nominal ultimate strength is the same for all length and species of the same class. Wood poles, classed 1 through 7 with this system, have the capability of withstanding the ultimate loads shown in Figure 7.29 (12).

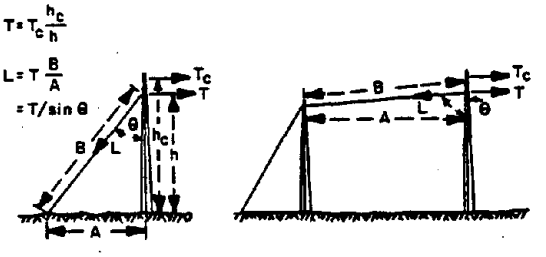
The proper setting depth is important to prevent butt "kick-out," since the pole is primarily a cantilever column.

Guy wires are used where necessary to assist in supporting the horizontal loads. Usually 3/8-in. galvanized-steel wire tied to a long-anchored rod is used as shown in Figure 7.30 (12). The ratio of the guy load (L) to the conductor tension (T) is the same as the ratio of guy length (B) to the distance away from the pole base (A).



Variety	Ult. fiber stress bending	Taper inches circum per ft length	Average top diam
Western cedar	5600	0.38	$d_2 = 0.38h/3.14$
Pine	7400	0.25	$d_2 = 0.25h/3.14$
Northern cedar	3600	0.63	$d_2 = 0.63h/3.14$
Chestnut	6000	0.40	$d_2 = 0.40h/3.14$

Figure 7.29. Pole-Strength Calculations.



DESIGN DATA FOR GUYS

Guy	Ultimate strength, lb	Rod	Net area, sq in	Ultimate strength, lb
3/8 in s.m.	6950	5/8 in.	0.202	11,000
3/8 in h.s.	10,800	3/4 in.	0.302	16,500
7/16 in s.m.	9,350	1 in.	0.551	30,500
7/16 in h.s.	14,500			

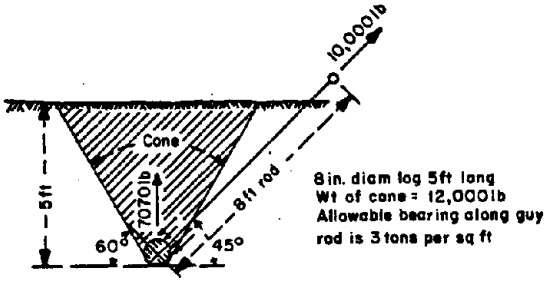


Figure 7.30. Guy and Log-Anchor Calculations.

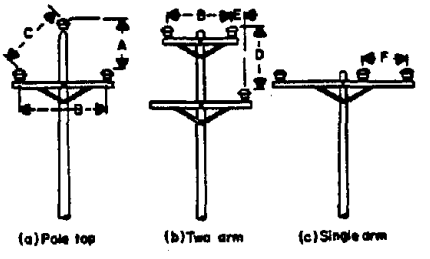
Both wooden and steel cross arms are used on wood poles. Steel cross arms give better protection from lightning strokes, but they are more expensive than equivalent-strength wood arms. Treated yellow pine or untreated Douglas fir are commonly used for cross arms. Their length ranges from 10 to 25 ft depending on the required conductor spacing. In size they vary from five-by-six inches to six-by-ten inches. Two planks, three-by-eight inches, can be mounted on either side of the poles to form a crossarm for heavy conductors.

Typical conductor arrangements and spacings for pin insulators are shown in Figure 7.31. The dimension B is often determined by the span length and calculated according to the method given by Fink and Carroll. Because of sleet-jump failure experience, the dimension E should be at least one foot. Swing-type insulators require additional spacing to give a clearance for the swing. The clearance between the conductor and any grounded structure must be at least 0.75 times the dry-flashover distance of the insulator or the "tight-string" distance under an 8-lb wind at 60°F.

In addition to the conductors positioned at the insulators, overhead ground conductors or static wires are strung above the conductors to give lightning protection, but Chapter 10 discusses this subject.

7.15 Summary

The components that carry electric current throughout the mine and their associated accessories have been described in detail in this chapter. The cables that extend from the substation to the borehole, down the borehole, and into the sections of an underground mine have been described. The portable cables that supply power to the machines and the trolley wire that feeds the haulage was discussed. Furthermore, surface-mine distribution and portable cables were included. In summary,



Voltage	Spacing			
	A	B	D	F
23 kv	3'-0"	4'-0"	2'-6"	3'-0"
34.5 kv	3'-4"	5'-0"	3'-0"	3'-4"
46 kv	4'-0"	7'-0"	3'-0"	5'-0"
69 kv	6'-0"	8'-0"	6'-0"	

Figure 7.31. Typical Arrangements and Pin-insulator Spacings on Wood Poles.

these cables are the veins and arteries of the mine-power-system body, and they must be designed, installed, and cared for properly to achieve a safe, economical operating life. Splices, couplers, terminations, and supports can become the weak links in this complex system if they do not receive the care and attention that their importance demands.

7.16 References

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