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ELECTRICAL-SHOCK PREVENTION

VOLUME II – GROUND-FAULT INTERRUPTING DEVICES

Contract J0113009
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L.A. Morley, F. C. Trutt, and D. J. Rufft

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Department of Mineral Engineering and
Electrical Engineering
The Pennsylvania State University
University Park, PA 16802

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16. Abstract (Limit: 200 words)

Volume II of the final report concerns the application of sensitive ground-fault interrupters (GFIs) to ac utilization circuits in U.S. mines. The main concepts examined are shock prevention and methods for reducing nuisance tripping. The research involved a literature search, input from previous Bureau of Mines contracts, and contacts with electrical manufacturers and mining personnel. Following this background work, several devices that showed promise were obtained and tested. Results of testing indicate the existence of GFIs that may be modified to perform adequately on U.S. mining systems. A recommended set of guidelines is included in the report, covering design, construction specifications, and performance tests.

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FOREWORD

This report was prepared by The Pennsylvania State University, Departments of Mineral Engineering and Electrical Engineering, University Park, Pennsylvania, under Bureau of Mines Contract Number J0113009 administered under the technical direction of the Pittsburgh Research Center with Mr. D. Ambrose and Mr. M. Yenchek acting as technical project officers. Mr. Frank Naughton was the contracting officer for the Bureau of Mines. This report is a summary of the work recently completed as part of this contract during the period April 1, 1981 through December 8, 1982. This report was submitted by the authors in December 1982. This technical report has been reviewed and approved.

No inventions have been developed from Contract J0113009, and no patents are pending.

Project personnel are grateful to outside individuals and companies who provided valuable inputs through discussion.

This report contains test data obtained in the course of this investigation and is provided for the purpose of disseminating information that might help improve mine-power-system safety and performance. Reference to specific brands, equipment, or trade names is made to facilitate understanding and does not imply endorsement by the Bureau of Mines nor The Pennsylvania State University.

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CHAPTER 1

INTRODUCTION

General

A ground-fault interrupter (GFI) is an electrical protective device that interrupts load current at a ground-fault current value less than that which would be interrupted by the overcurrent protective device of the supply circuit [1]. Overcurrent protective devices do not respond to current levels less than 1.5 times the continuous-current rating or tap setting of the device. Consequently, the current interruption (or pickup) level of a GFI may range from zero to 1.5 times the circuit current rating.

A sensitive GFI may be defined as an electrical protective device that interrupts circuit current at a ground-fault current value less than that which might be expected to cause electrocution. Electrocution can be caused by chest current values as low as 50 mA for sustained current flow [2]. The operating range of a sensitive GFI is therefore smaller.

Ground-fault interrupters presently used on ac mine utilization circuits are not sensitive GFIs. In fact, according to the above definition, they are not even GFIs. In all cases in mining application, the GFI acts as a relay to send trip signals to a circuit interrupting device. Mining GFIs should not be called GFIs but ground-fault relays (GFRs). However, the GFI nomenclature has been widely accepted and will be followed in this report. As for pickup levels, mine utilization systems strive for four- to six-ampere levels while distribution GFIs are generally greater than 12 A. In a report by Ketron, Inc., Kohler [3] found that nearly all mining GFIs pickup at greater than 12 A.

This high level of pickup is deemed necessary to avoid interruption of power to machinery by spurious signals. Termed "nuisance tripping," the phenomenon may be caused by motor startups, cable charging capacitance, common-mode currents, and other normal system currents. The current may also be caused by leakage to ground; in which case, it is not spurious and power should definitely be interrupted. Distinguishing between harmful and safe current changes has always been a problem. The usual solution has been to raise the trip level of GFIs above the level of most spurious current. This reduces the number of false trips but increases the level of ground current allowed before power is interrupted.

Sensitive ground-fault interrupters are available for three-phase industrial systems that will interrupt ground current at levels designed to prevent electrocutions. These devices seek to identify the true ground-current signal and ignore any spurious signals. This added intelligence comes from operational-amplifier technology, external-flux rejection, and flux alignment, to name a few innovations.

The application of sensitive-GFI technology to industrial power systems has roots in the irrigation industry and United Kingdom mining practice. These power systems have some similarities that may account for the ease of application of sensitive GFIs. First, both systems operate in a wet environment where shock hazards are high. Second, both systems have concentrated loads with interconnected grounds. The load for the irrigation industry is a single pump motor that operates continuously. The longwall system, while cyclic in nature, generally has only one circuit for each gate-end box (power center). The shearer, conveyor, and shields are powered through a single shielded cable, and all frame grounds are interconnected.

While U.S. mining is usually a very wet job at best, most systems in use cannot claim a concentrated load with interconnected grounds. For example, room-and-pillar mining systems involve individual mining machines, separately powered and grounded through unshielded trailing cables which are subjected to harsh physical treatment. These differences in operating conditions may present a problem to the prospective user or designer of sensitive GFIs.

Statement of the Problem

Volume I of this final report on U.S. Bureau of Mines Contract J0113009 has shown the desire to use sensitive GFIs on U.S. mine utilization systems [4]. However, standards along which the acceptance or rejection criteria for a sensitive GFI in U.S. mining applications are needed. These standards will provide guidelines for the prospective designer of sensitive GFIs and inform the prospective purchaser what exactly the device should do. The standards should be clear and define exactly what is desired of sensitive GFIs for U.S. mining. Acceptable GFIs must be practical for mine duty as well as effective at shock prevention. Further, standards must be written so as not to inhibit sensitive-GFI development totally. In other words, the standard should be within the grasp of present-day technology. This latter point is included to insure that a practical standard be devised.

Scope of Research

The first step in developing standards for sensitive GFIs should be a justification of the need for the device. The mining industry is not a flexible field and change comes slowly even for the most obvious advances. The hazardous environment involved with mineral production demands such caution.

Once the benefits of sensitive GFIs have been acknowledged, a literature search should be undertaken to determine what work has already been done by others. Of special importance here is the research performed under U.S. Bureau of Mines Contract J0199106 on the U.K. sensitive earth-leakage system [5]. This information may be combined to form a background chapter and starting point for further research. At this point in the research, the problem must be clearly delineated.

Following delineation of the problem, industry personnel should be contacted to get a grasp of what is practical for U.S. mining. Both mining and electronics personnel should be contacted, as standards for a mine electrical device will involve both industries.

GFIs should be obtained that show promise for adaptation to U.S. mining. By examining these devices and compiling the knowledge of printed and oral communication, it will be possible to arrive at criteria for GFI standard development. The obvious criteria for a sensitive GFI is a time-versus-current characteristic. Not so obvious might be the device size, noise immunity, or control voltage. Once these criteria have been outlined, physical limitations should set acceptance levels. For instance, the current transformer of the GFI must be able to accommodate three of the largest anticipated phase conductors. All established criteria and acceptance levels can then be formalized, and the resulting standards should be a concise statement of what is desired. Test methods for device conformance should indicate if the tested GFI will be an added safety feature or a drain on production.

Presently, it is appropriate to limit the discussion of sensitive-GFI application solely to mine utilization systems only. There are several reasons for this limitation. First, the utilization portion of a mine electrical system is more frequently handled by mine personnel than distribution. For instance, trailing cables in underground mines are handled routinely by mine personnel and are a major cause of electrocutions [6]. Second, most worst-case situations will be encountered with sensitive GFI application at utilization. Here, high motor startup currents, transients, and electromagnetic interference are found in most any power center. Finally, sensitive-GFI application must be applied at the most downstream point to insure proper coordination with upstream relaying. Subsequent application of sensitive-GFI technology to switchhouses and substations within the distribution portion should be considered as the next research step.

Report Format

A research investigation moves through the steps of problem identification, concept formation, analysis, synthesis, and evaluation. Chapter I has presented a statement of the problem: no standards for sensitive GFIs in U.S. mines. Chapter II reviews the current practice of GFI operation. Chapter III, concept formation, presents electrocution information and desired device trip levels as well as the problems with achieving these levels. Chapter IV is the analysis section of report thesis where specific tests for GFI acceptance are detailed. The synthesis and evaluation portions of the research are given in Chapter V, including a presentation of test results. Chapter VI concludes the report with suggestions for future research. A summary of suggested standards is presented as Appendix III.

CHAPTER II

GROUND-FAULT PROTECTION IN UNITED STATES MINES

General

This chapter presents a chronological review of the use of ground-fault relaying in U.S. mines. Afterwards, the different kinds of protection and their principles of operation are outlined. The following paragraphs only contain short descriptions of the protection techniques; a thorough discussion in terms of the safety implications can be found in Volume I of this final report [4].

History

The earliest ac utilization circuit arrangement employed a completely ungrounded system, with no intentional connection to earth. As such, the instance of a single phase-to-earth fault does not induce current flow (see Figure 1). The second phase-to-earth fault, however, results in an apparent phase-to-phase fault with only the conductor, fault, and transformer impedance to limit current flow. The protection afforded this circuit was by means of fuses in line with the phase conductors. The design provided overload protection and allowed large currents to flow before interrupting power. With this system little protection was afforded to either personnel or circuitry.

The ungrounded system was largely superseded by the solidly grounded system which was first referenced in the United Kingdom Coal Mines Act 1911, "General Regulation of Circuits" [7]. In the solidly grounded system, no intentional impedance connection is made between the source-transformer neutral and earth. At the instance of single line-to-ground fault, large currents will flow as indicated in Figure 2.

The advantage of a solidly grounded neutral lies in the introduction of ground-fault protection as explained in the following passage from the 1911 Act. "Because a leakage protection device can be set to operate with relatively small fault current, it is a much better safegard against fire risk than a fuse or other overload device which is usually adjusted to pass indefinitely a current considerably in excess of the normal full load current." Typical ground-fault relaying is illustrated in Figure 2, where fault current flows through the ground and neutral impedance back to the transformer neutral. A current transformer (CT) surrounding the neutral conductor can be used to sense the initiation of a phase-to-ground fault.

Although solidly grounded systems are a considerable improvement over ungrounded systems, they have several disadvantages. One problem is that the grounding conductor may become open such that the system reverts to an ungrounded system. A neutral-sensing CT cannot see the loss of ground continuity, and protection will be offered only by overload devices.

A solution to this difficulty was first introduced in the 1930s as a core-balance transformer (CBT) [7]. This device is simply a CT that surrounds only (but all) the phase conductors. Along with an associated relay, the CBT compares the flux generated by current in the outgoing phase conductors with that in any return circuit. For a balanced condition, the two should be equal. Its application for ground-fault protection was universal in equipment supplied by the end of that decade. Now it is commonly referred to as zero-sequence ground-fault relaying.

The CBT worked well for ground-fault protection regardless of the continuity of the grounding conductors. However, a remaining problem was the possibility for large ground-fault currents due to the low impedance of the faulted ground loop. The problem was solved with the introduction of a neutral grounding impedance inserted between the transformer neutral connection and ground (Figure 3). The size of the impedance determines the maximum ground-fault current. This resistance grounded system was first introduced to the mining industry in the 1940s although it had been previously applied elsewhere for some years [7].

The maximum ground current chosen depends on the level necessary to activate the protective-relaying devices, any accepted level of ground-current flow, and the ability to reclose on nuisance trips. In the United Kingdom, ground-current limits are set to less that 1.0 A due to the use of solid-state relaying and reclosing circuit breakers. (Automatic reclosing on utilization circuits is not allowed in U.S. coal mines.) For low- and medium-voltage circuits serving portable or mobile equipment, Title 30, Code of Federal Regulations, Paragraph 75.901, requires resistance grounding and limits ground-fault current to 25 A or less [8]. The usual coal-mine design limit is 15 A [9]. This high level is deemed necessary to operate electromechanical relays and avoid nuisance trips which require manual reclosing of circuit breakers. The present practice in U.S. coal mining is, therefore, a combination of high-resistance grounding with ground-fault relaying. This system has proven itself dependable and adaptable to changing mining conditions. At present, there is no resistance-grounding nor ground-current-limit requirement for metal/nonmetal mines in the United States.

Principles of Operation

The majority of mine power systems employs a form of radial distribution. The supply power is branched out through switchhouses and terminates at centers of utilization in the mine. Utilization systems involve power centers, rectifiers, cables, motors, and their associated protective devices and are the most troublesome area in terms of safety and continual power delivery. This is due to temporary nature of the utilization system arrangement. As mining advances, the utilization system is stretched to its limit and then repositioned and protective devices dedicated to this most downstream system portion must adapt to constantly changing conditions. Ground-fault relaying is one such protective device that is normally employed at the utilization level.

An examination of the reasons for ground-fault protection will aid in the understanding of the methods and levels of protection afforded by different utilization systems. The most visible portions of the utilization system are the flexible trailing cables. These cables connect power centers and rectifiers with the motors that power mobile mining machinery. In the

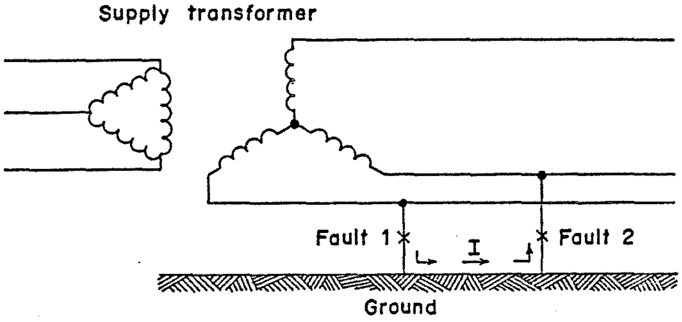

Figure 1. Ungrounded power system.

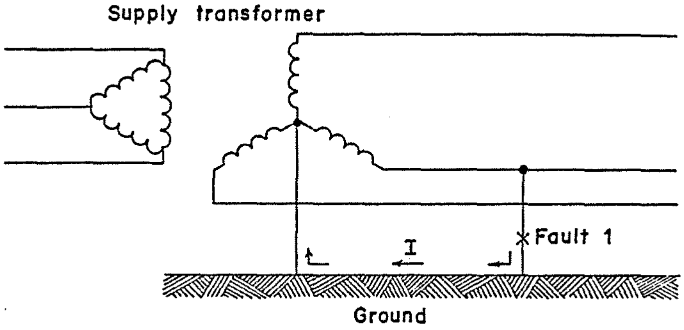

Figure 2. Solidly grounded power system.

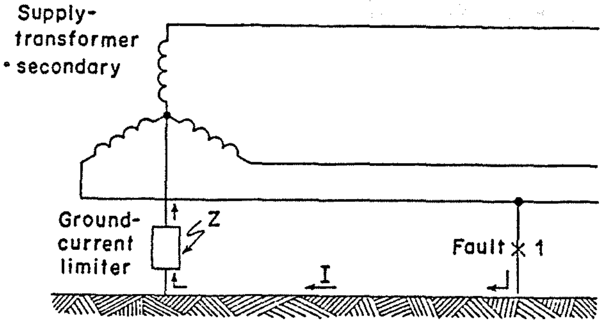

Figure 3. Impedance-grounded power system.

longwall system most prevalent in the United Kingdom, cables can be expected to be well-protected and maintained. Such is not always the case in U.S. mining. For instance in the room-and pillar mining, mobile machinery will drag or reel cables, subjecting them to harsh treatment. Also, the larger number of cables present reduces the amount of maintenance time available per cable. Because of the vulnerability of these trailing cables, this portion of the system needs the protection of ground-fault interrupters (GFIs).

The main hazards of ground faults can be classed into three groups [10]:

1. the ignition of flammable material or gas due to current arcing from phase to ground;

2. the destruction of electrical equipment due to the dissipation of energy, i.e. melting cables or deterioration of motor windings; and

3. the electrical shock, sometimes lethal, to personnel coming into contact with enclosures raised to abnormal potentials above earth.

The methods of ground-fault protection available to reduce these hazards are discussed in the following paragraphs.

Typical ground-fault protection in mining is provided by a hybrid system consisting of high-resistance grounding and ground-fault protective relaying. The resistance or reactance inserted between the system neutral and ground limits ground-fault current and thus hazardous energy dissipation. The GFI monitors the circuit and removes power at the indication of hazardous current flow. In present U.S. mining systems, the current allowed and also that required to operate electromechanical relays, can involve a personnel hazard before power is removed.

High-resistance grounding has been defined as: "a system in which a high-value resistor is inserted in the neutral conductor to ground to limit the resistor current under ground-fault conditions to a value not less than the total system charging current" [11]. A system where the current limit is less than capacitive-charging current is essentially ungrounded, and several problems can result. First, an ungrounded system is a prime candidate for restrike transients [12]. These overvoltages are caused by trapped energy between breaker and capacitance. Second, limiting grounding resistor current to values near the capacitive charging current will result in nuisance tripping as distinguishing between charging current and fault current is difficult. A practical lower limit for effective relaying is a pickup level at 40% of the maximum ground current [13]. Lower percentages (20% or 30%) are sometimes used, although they tend to increase nuisance trips as the capacitive-charging lower limit is reached.

There are four methods of ground fault relaying currently used in mining:

- ground-current sensor,
- potential relaying,

- residual relaying,
- zero-sequence relaying

Ground-current sensor relaying is the simplest of the four systems and is shown in Figure 4. A current transformer surrounds the grounding conductor and monitors ground current directly. Although very simple, the technique is rarely used because of its one major disadvantage. In the event of an open grounding resistor or conductor, the relay can never detect ground-current, and the system is essentially ungrounded. Ground-check monitors help avoid this problem, but they are not infallible and increase the complexity of the GFI arrangement.

For monitoring grounding-resistor current, an improvement can be made by replacing the CT with a potential transformer (PT) connected across the grounding resistor (Figure 5). Ground current through the resistor creates a potential which can be used to operate a relay. Even if the resistor fails, protection will be maintained. In utilization systems, the relay is often replaced by a light and used as backup or problem indication for primary relaying.

Residual relaying involves identical CTs surrounding the phase conductors. As shown in Figure 6, these CTs are paralleled and connected in series with an overcurrent relay. A ground fault downstream will allow an unbalance of current flow in the phase conductors which in turn will produce an unbalance or residual current in the three paralleled CTs. With matched CTs, the residual flow is proportional to ground (zero-sequence) current and can actuate the overcurrent relay. The disadvantage of residual relaying lies in the necessity for identical CTs. Unmatched characteristics of similar CTs cause relaying errors; thus, sensitive settings are very difficult for residually connected relays.

Zero-sequence (core-balance or balanced-flux) relaying is the most reliable and most common method of ground-fault relaying and is illustrated in Figure 7. As described previously, the phase conductors pass through the CT window. The sum of the three phase conductor currents combine to form the CT primary current which is proportional to zero-sequence current [14]. In an unfaulted balanced system, there is little or no zero-sequence current, and the CT secondary current is approximately zero. However, when a ground fault occurs, the secondary current is proportional to the zero-sequence current and can be used to trip a relay. Zero-sequence relaying is not affected by CT errors or phase-voltage fluctuations. It monitors only unbalanced current leakage to ground and thus can afford sensitive trip levels.

Summary

The foregoing paragraphs have reviewed the present methods for providing ground-fault protection in U.S. mines. It has been seen that resistance grounding is necessary, and zero-sequence relaying is the most precise method of detecting ground faults.

Zero-sequence relaying is the only present technique that is practical for the high sensitivity required for shock prevention. The required pickup levels, problems in attaining the levels, and possible solutions are the subject of Chapter III.

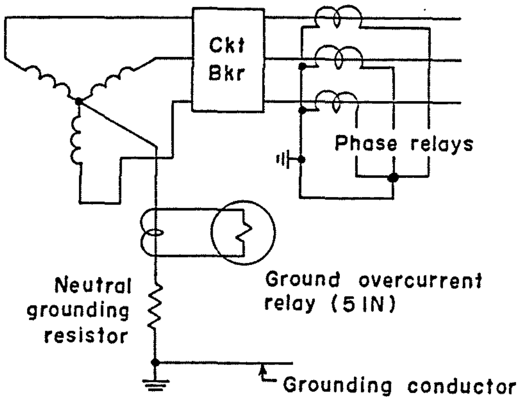

Figure 4. Ground-current relaying.

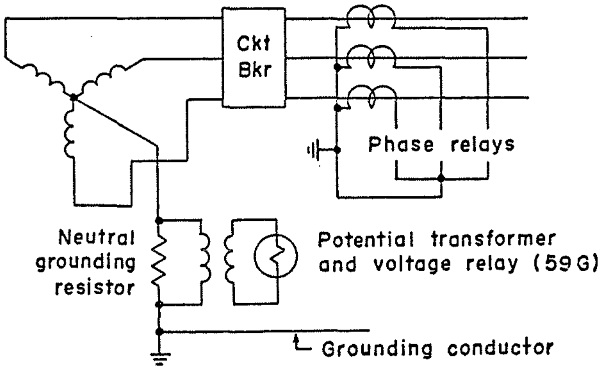

Figure 5. Neutral-resistor potential relaying.

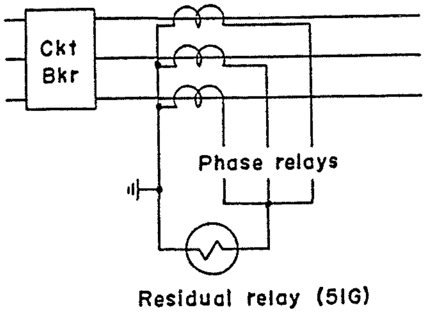

Figure 6. Residual relaying.

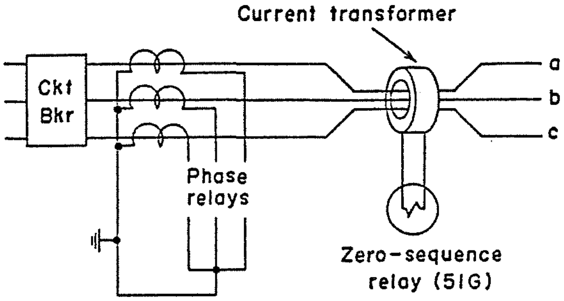

Figure 7. Zero-sequence relaying.

CHAPTER III

SENSITIVE-GROUND-FAULT-INTERRUPTER APPLICATION TO MINING

General

Sensitive-GFI operation involves substantially lowering the pickup levels for circuits that monitor current leakage to earth. The advantages of lower trip levels have been seen as:

1. less energy is available for the destruction of equipment, such as motor windings;
2. fire risk is reduced from the reduction of arcing due to low current trip settings; and
3. the prevention of electrical shock, especially electrocutions, is increased as trip levels may be set below that level necessary to cause ventricular fibrillation.

Sensitive-GFI pickup should be directly related to electrocution levels. The level necessary to cause electrocutions has been the subject of much research, and an extensive analysis of that work is given in Volume I of this final report [4]. Some of that work will be repeated here for completeness. The most widely accepted effort is that of Dalziel [2,15], and the following section will summarize his results.

Electrocution Levels

Dalziel's Level. Electrical shock occurs when an individual becomes some part of a path which permits electrical current to flow. The most common path for electrical current is entering at a limb and exiting from another. However, the most dangerous case is current entering one hand and leaving the opposite leg. In this situation, a majority of the current will pass through the chest cavity. Regardless, the body acts as a volume conductor at power-system frequencies [2]. Hence, any current passing through the human body will likely result in current through the chest cavity and the heart. Current through the heart may cause ventricular fibrillation which is probably the most common cause of death in electrical-shock cases [15].

Ventricular fibrillation is a disruption of the rhythm of the heart [2]. The nerves in the body control the physiological responses through electrical impulses. Impulses from external sources, such as a ground fault, can cause the muscles to override the body's natural signals. The result, in the case of ventricular fibrillation, is a palpatating heart action that continues after the external current source is removed. Death can occur.

The lethal value of current through the chest is not precisely known nor easily determined, as experimentation on humans is hardly possible. Large values of current (>1 A), however, are considered not responsible for ventricular fibrillation. These currents freeze the heart muscle rather than disrupting it, and normal heart beat returns after current is removed. The danger of large current is associated with burns to the entry points. On the other hand, small currents tend to disrupt the heart's pumping action. These currents and their effects on animal subjects have been studied extensively, and the results were various statistical plots of body current versus fibrillation levels for animals. These results were then modified by weight proportioning to arrive at the minimum threshold value of fibrillation for a body weight of 110 pounds. The equation that Dalziel [2,15] found to best fit this curve is:

$$I = \frac{116}{\sqrt{t}} \tag{1}$$

where

I = minimum current (mA, 60 Hz) through the chest
t = duration of the shock with limits between 8.3 ms and 5.0s.

The equation is graphed in Figure 8. Any values to the left of the curve are considered safe.

Underwriters' Laboratories Level. Underwriters' Laboratories (UL) Standard 943 for two-wire ac ground-fault circuit interrupters (GFCIs)

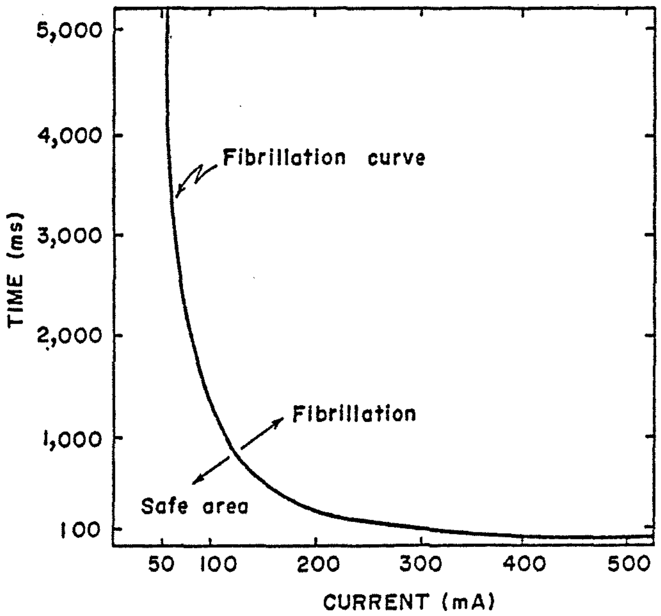

Figure 8. Dalziel's fibrillation curve.

gives the time required to trip a circuit breaker upon occurrence of a specific level of ground-fault current [16]. For Class-A GFCIs, the trip time t for fault currents in the range of 6 to 264 mA is given by:

$$T = (20/I)^{1.43} \tag{2}$$

where T is expressed in seconds and I in milliamperes. Graphs of the UL standard and Dalziel's electrocution equation are presented in Figure 9 on log-log scale to better illustrate the difference between the equations 1 and 2.

The Dalziel curve is much less conservative on the whole. Most low-voltage circuit breakers require approximately 25-ms clearing time which negates the lower time values of Dalziel's curve. Above 25 ms, the UL standard calls for much more stringent time-current values.

The UL Standard has been influenced by the "let-go" current above which a person cannot voluntarily release a charged object. The lower limit of let-go current has been found by experimentation to be 6 mA for 99.5% of those tested [15].

Although the prevention of any sustained electrical shock is an ideal goal for industry, it is usually impractical. Such low level ground-fault current detection would surely be a severe nuisance (and possibly a total impedment) to production. It is the goal of this report to develop standards for GFIs that prevent electrocution, not electrical shock. As such, the levels which cause ventricular fibrillation (the major cause of electrocution) and not those concerning let-go currents should be used as a basis for sensitive-GFI development. Under these conditions, an individual may receive an electrical shock, but will not be exposed to time-current levels capable of causing ventricular fibrillation, according to Dalziel. For this reason, Dalziel's equation remains the basis for defining sensitive-GFI operation.

Past Sensitive-GFI Mining Research

The advantages of sensitive GFIs mentioned earlier cannot be obtained by merely adjusting conventional-relay pickup settings. The sensitive GFI should operate for very low values of ground current (e.g., 50 mA) and therefore must be properly designed. As the output current and voltage of a zero-sequence current transformer is proportional to the ground fault current, a conventional electromagnetic scheme would fail. First, the actuating quantities would be too small and second, false signals would be interpreted as trip signals. A sensitive and sophisticated solid-state device with amplification and filtering capabilities may be needed.

The first known attempt of applying sensitive GFIs to U.S. mine utilization systems was performed in conjunction with U.S. Bureau of Mines Contract J0199106 [5]. Here, the scope of work was to investigate the feasibility of applying the very low ground-current limit, ground-fault protection used in the United Kingdom to underground coal-mining equipment in the United States. A review of that effort will help identify some GFI- application problems.

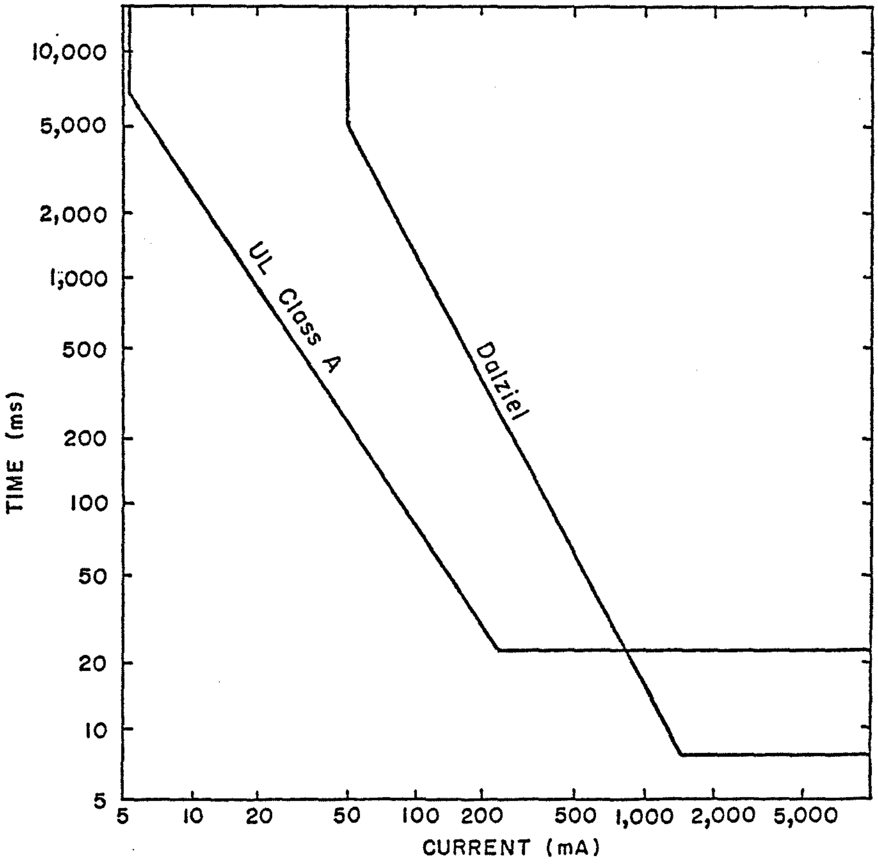

Figure 9. Underwriters' Laboratories and Dalziel shock curves.

United Kingdom Sensitive Ground-Fault Protection. The National Coal Board of the United Kingdom developed two very-low ground-current limit and sensitive ground-fault (GFI) systems: the Sensitive Earth-Leakage (SEL) system and the Multi-point SEL system.

A simplified diagram of the SEL system is shown in Figure 10. The principle of operation is basically the same as zero-sequence relaying. Solid-state relaying and a specially designed current transformer permit improved sensitivity without sacrificing selectivity. For units designed to operate in the United Kingdom, the neutral-grounding impedance limits the maximum ground-fault current to 750 mA, and the solid-state amplifier increases sensitivity to as low as 90 mA. Currents below 90 mA are allowed to flow continuously, but currents up to 750 mA are permitted for about 0.02 s. To provide selectivity, a 0.4-s time delay is introduced at the main circuit breaker. The power factor of the neutral-grounding (earthing) impedance is normally specified from 0.65 to 0.75 lagging to prevent limiting the current to a level that cannot be detected due to system capacitance.

To prohibit the circuit from being reset until a ground fault is cleared, this SEL system has an auxiliary circuit connected to a second winding on the CT. Upon ground-fault pickup, an auxiliary contact is closed by the relay and causes the auxiliary CT winding to be energized. This induces a voltage on the other CT winding which creates a lockout.

A diagram of the Multi-point SEL system is shown in Figure 11. Here, a "false-neutral transformer," which is impedance grounded, replaces the zero-sequence transformer. The source-transformer secondary is isolated from ground across a spark gap. When a ground fault occurs, a potential is developed across the wye-connected impedances (false-neutral transformer), and current flows through the grounding impedance. The voltage developed across the impedance is amplified, causing the relay to pick up. The sensitivity of the multi-point system is excellent. Pickup is about 3 mA and 6 mA on 550-V and 1100-V systems, respectively. As with the preceding system, an auxiliary "change-over" contact provides lockout until the fault is cleared.

The multi-point system has several disadvantages. The technique limits the number of units which can be utilized at a gate-box end (utilization power center) and is not selective. Ground-fault current is again limited to 750 mA, but all relays see the fault current produced and will pick up. Even though the unfaulted units may be reset at once, the faulted unit will be locked out. To offset the production nuisance, the United Kingdom allows automatic circuit-breaker reclosing on this system to restore operation to the unaffected portion.

It was concluded by the personnel on Contract J0199106 that the selectivity problem of the multi-point system, which requires automatic circuit-breaker resetting to implement it on a mine power system, negated its use in U.S. underground coal mines. However, the SEL system appeared feasible for adaptation to low- and medium-voltage trailing-cable protection.

Originally, this research was to be only a feasibility study but, because of an arrangement between the parent company of the SEL manufacturer

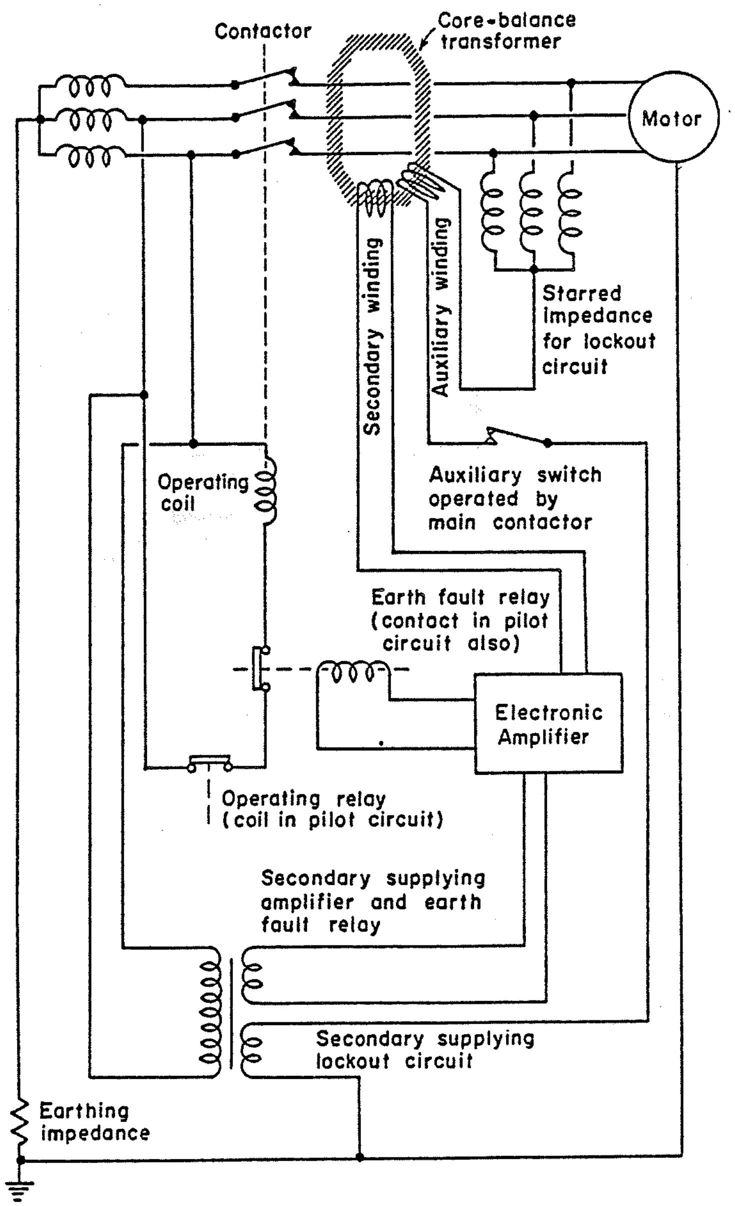

Figure 10. Simplified sketch of the SEL system.

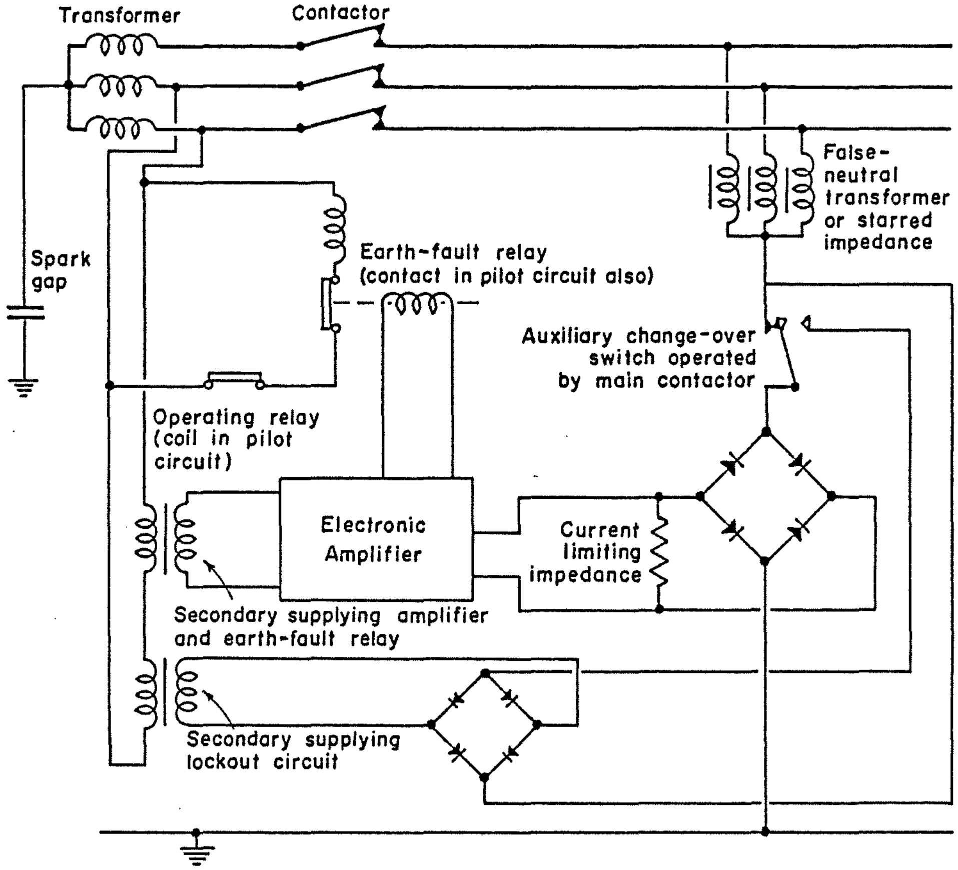

Figure 11. Simplified sketch of the multi-point SEL system.

and the Lee Engineering (now the Maintenance) Division of the Consolidation Coal Company (CONSOL), the research was extended to include monitoring of actual in-mine trials. CONSOL performed the installations, supplied project personnel with the results and also published a paper on their conclusions about the findings [20]. The next section presents the project's interpretation of the in-mine trials and the results.

In-Mine SEL Trials. The first installations used SEL devices similar to those employed in United Kingdom mines but converted for 60-Hz operation. The power-system frequency change caused an increase in pickup current from 90 to 110 mA; the time-current characteristic was definite with a 50-ms delay at 200% of pickup. Two relays were installed in separate underground power centers: one to sense neutral current to a solid-state belt starter, the other to monitor a continuous-miner circuit. For both installations, relay contacts activated trip counters, and the 15-A grounding resistors and the zero-sequence relays were retained for ground-fault protection.

Unfortunately, severe nuisance tripping occurred in both these installations in the first week of operation. Subsequent measurements by Lee Engineering showed that high-frequency neutral current flowed when the belt starter was in the acceleration mode. Furthermore, heavy continuous-miner loading caused induction in the CT used by the SEL, equivalent to a current unbalance much in excess of relay pickup.

To correct these problems the manufacturer further modified the relay amplifiers to filter-out frequencies significantly above 60 Hz, and relay operating time was increased to help discourage possible nuisance tripping caused by inrush currents. The high phase-current problem was believed to be caused by common-mode rejection. That is, high loads causing high phase currents result in enough magnetic unbalance in the CT to cause tripping. To improve flux linking, an iron tube was inserted in the CT window around the phase conductors. These three modifications changed relay characteristics to a 140-mA pickup with a 180-ms delay at 200% of pickup.

The relays were reinstalled in both power centers and were operated for two months. Excellent results were obtained as essentially no nuisance trips occurred. This favorable performance prompted CONSOL to connect the SEL on the continuous-miner circuit to trip its power-center circuit breaker. The counter and 15-A grounding resistor were again retained, and the system was operated for six months. This third trial had only about one unexplained trip per day.

The third trial was considered a success, and CONSOL agreed to proceed with a test on an entire underground continuous-mining section. Ground-fault current was limited to 500 mA by the neutral grounding resistor. This full-face installation was operated for about six months before monitoring by the contract personnel stopped because sufficient information was obtained. The performance of the SEL systems was tremendous. Nuisance tripping was no greater than with conventional zero-sequence (ground-fault) relaying. In fact, no nuisance trips could be ascertained in the first two months of operation.

Problems and Solutions

The previous research on the SEL system encountered certain problems in its use in U.S. mining. During the course of the present research, an extensive literature search and discussions with sensitive GFI manufacturers was undertaken to see if any additional problems might exist. The possible application problems found are as follows:

1. low secondary voltage to operate relays,
2. external-flux rejection,
3. common-mode rejection,
4. transient immunity,
5. harmonic rejection, and
6. capacitive-charging currents.

Each problem will be discussed along with any concepts necessary for complete understanding. Any solution (or solutions) will also be detailed.

Low Secondary Voltage. The numbers of turns on the GFI CT determines the overall turns ratio of the device. This is necessary so since it is impossible to properly wind and distribute as many as three phase conductors around the core. The large conductor size and space requirements in typical mine power equipment prevent the primary from having more than one pass through the CT window. Thus, every turn of the secondary winding further decreases the secondary current according to the ideal current-transformer equation:

$$\frac{I_p}{I_s} = \frac{N_s}{N_p} \tag{3}$$

where

I_p = primary current (A)
I_s = secondary current (A)
N_s = number of secondary turns
N_p = number of primary turns

For a single-turn primary, the equation becomes

$$I_s = I_p \left(\frac{1}{N_s}\right) . \tag{4}$$

With the core size required to accommodate the large primary conductors, a practical lower limit of 20 is required to evenly distribute the windings [17]. Such distribution is also needed for common-mode and external-flux rejection, but these topics will be covered later. Considering a sensitive GFI and substituting 20 for N_s and 50 mA for I_p in equation 4 results in a 2.5-mA secondary pickup level for ideal relay operation. This is indeed a low level, since the best operating mining ground-fault relays with 300/5-ratio CTs pick up at (using a 6-A zero-sequence current):

$$I_s = 6 \left(\frac{5}{300}\right) = 0.1\text{A}.$$

This level is forty times that available for a sensitive GFI.

The most common solution to this problem lies in solid-state devices such as an operational amplifier (op-amp). Figure 12 shows the equivalent circuit for a voltage-inverting op-amp. The usual assumptions made for analyzing this circuit are no current flows into either input terminal, and the differential input voltage is zero [18]. These are the ideal qualities of an operational amplifier but are universally applied. Calculation of voltage gain, E_{in}/E_{out}, is rather simple. Since the differential input voltage is zero, the potential of the inverting (-) input equals that of the non-inverting (+) input (ground) and, therefore, the two currents in the figure are

$$I_1 = \frac{E_{in}}{R_s} \tag{5}$$

$$I_2 = -\frac{E_{out}}{R_f} \tag{6}$$

Since no current flows into the op amp, $I_1 = I_2$ and voltage gain is:

$$\frac{E_{out}}{E_{in}} = -\frac{R_f}{R_s} \quad \text{or} \quad E_{out} = -E_{in}\frac{R_f}{R_s} \tag{7}$$

When the input source (E_{in}) and input resistance (R_s) are replaced by a sensitive-GFI current transformer, Figure 13 results and is a typical practice in solid-state GFIs. In this instance, I_1 equals I_s, and the load impedance for the toroidal coil is virtually zero. (A near zero impedance is an important requirement for correct probe operation [17].) Accordingly, E_{out} becomes:

$$E_{out} = -E_{in}\frac{R_f}{R_s} \tag{8}$$

$$E_{in} = I_s R_s \tag{9}$$

$$E_{out} = -I_s R_s \frac{R_f}{R_s} \tag{10}$$

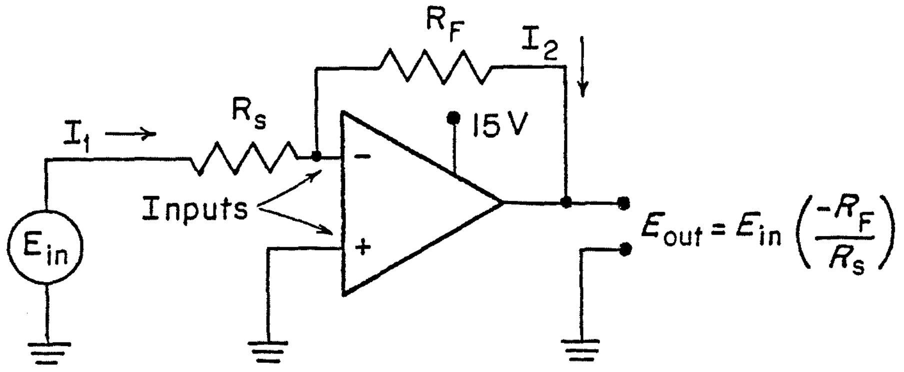

Figure 12. Voltage inverting op-amp.

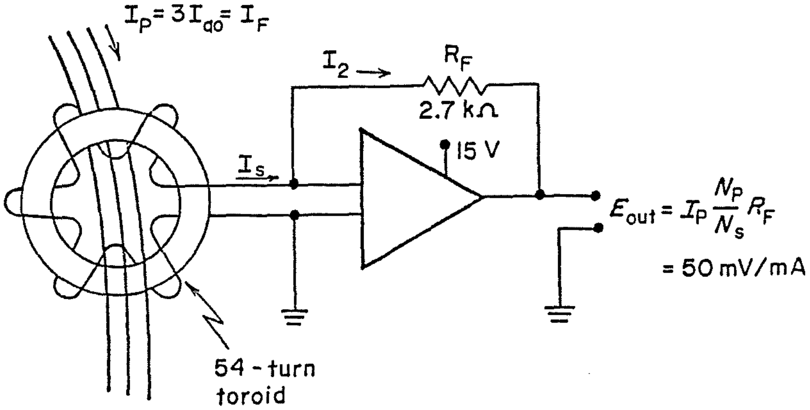

Figure 13. Current probe used by one sensitive GFI.

$$E_{out} = - I_p \frac{N_p}{N_s} R_f \ . \qquad (11)$$

For as 54-turn toroid and 2.7-kΩ feedback resistor, the output voltage per milliampere of CT secondary current is

$$E_{out} = - (1 \text{ mA})(\frac{1}{54})(2700\Omega)$$

$$= 50 \text{ mV/mA}.$$

Thus, the CT-amplifier combination is sensitive to very low current values. In this case the maximum output voltage is 15 V, limited by the 15-V power supply.

In practical GFIs, operational amplifiers may be cascaded for several reasons. First, the input signal range of the op-amp may be increased by lowering R_f, but this results in a lower signal-to-noise (S/N) ratio which is undesirable. By cascading op-amps, the range is increased without decreasing S/N ratios. In fact, an increase of S/N usually accompanies series hookups [19]. Secondly, the first op-amp may be designed to operate as an analog device with the second op amp acting as a digital or trigger device for relay operation. Consequently, very small CT secondary currents can be conditioned into acceptable signals for relay operation through the use of solid-state techniques.

External-Flux Interference. The power centers or distribution boxes used in mining have a typical circuit arrangement. Incoming high voltage is connected to a transformer, the secondary of which is connected to a bus system. The circuit interrupting devices are next in line followed immediately by outgoing cable couplers. Between the breaker and the coupler, the power cables pass through the ground-fault CT. This arrangement results in the CT being placed near the power transformer and in an area which may have a significant magnetic field.

The magnetic field is due to incomplete coupling of flux lines from the primary to the secondary coils of the power transformer, and the "coefficient of coupling" describes the extent of flux linkage between the two cores. For power transformers with iron cores and orientation to provide maximum flux linkage, the coefficient of coupling ranges from 0.9 to 0.98 [12]. The remaining ten to two percent of the transformer flux appears as leakage flux, is not confined to the transformer core, and may link the core of a current transformer.

Figure 14a shows a typical 360-degree winding. Here, uniform external magnetic field will induce equal-but-opposite self-cancelling voltages in either side of the toroid, resulting in zero current flow. However, a magnetic field with an appreciable grandient will induce greater volts-per-turn in one side than the other, thus generating current flow. Such a current could cause false tripping of a sensitive GFI.

Fortunately, one solution to the problem, known as a supertoroid, lies in simply altering the standard winding of the CT [20]. Figure 14b shows the technique. The turns ratio is maintained as the number of 360-degree loops around the core. Each turn is series, adding with respect to inner-core flux, but each pair of turns is self-cancelling to external flux. This seems intuitive by comparing the alignment of the interior of the core with cross-hatching of the exterior. Consequently, any gradient across the major dimension of the CT will have "zero" effect as each pair of x-turns cancels the effects of the external magnetic field.

Common-Mode Currents. Once the effects of external magnetic fields have been neutralized, magnetic effects within the core are the sole source of secondary current. For the standard instrument CT, a single wire passes through the CT window, and alternating current causes a flux-induced voltage on the secondary coil.

Zero-sequence CTs operate on the unbalance in current between two or more phases. The flux lines generated by each phase conductor must couple to exactly zero for a balanced unfaulted system. Unfortunately, the conductors are not concentric and may cause local core saturation as illustrated in Figure 15a. This local saturation will result in a net induced voltage in the secondary for normal balanced-system operation. The voltage will not cause enough current flow to cause nuisance tripping for regular GFIs and rated current. However, the lower trip sensitivities for GFIs can cause difficulties. Just reducing the trip level for GFIs from 4 A to 50 mA may cause problems to occur. Compounding the problem are the demands of motor startups (up to 8 times rated current). These large common-mode (all phases) currents are normally encountered in mining and should not cause tripping of a sensitive GFI.

A simple solution to common-mode-current nuisance tripping is shown Figure 15b. By splitting each phase conductor, the effects of local core saturation are balanced from opposing sides of the toroid. Although significantly reducing the induced voltage in the CT, it may be impractical to split phase conductors on the hundreds of circuits where sensitive GFIs may be employed.

A recent development in eliminating common-mode currents was mentioned earlier in this chapter and demonstrated during a meeting at the Lee Engineering Division [21]. By placing a concentric ferro-magnetic liner between the three phase conductors and the toroid, the common-mode current discrepancies were eliminated. The device, sometimes called a shield, reduces the effective flux penetration of common-mode currents into the current transformer. Currents produced in the shield tend to generate flux that opposes the flux produced by the common-mode currents [22]. A more appropriate term for this shield is "fluxaliner" as it tends to reduce common-mode flux but has little or no effect on the differential or zero- sequence flux that the current transformer perceives.

When designing shields purely for a reduction in electromagnetic coupling as in the case of transient shielding, a high permeability metal suits the purpose best. In the case of a fluxaliner, it has been found that a low-permeability buffer shield wrapped inside a high-permeability metal, such as Permalloy, provides the best results [22]. A cross section of a

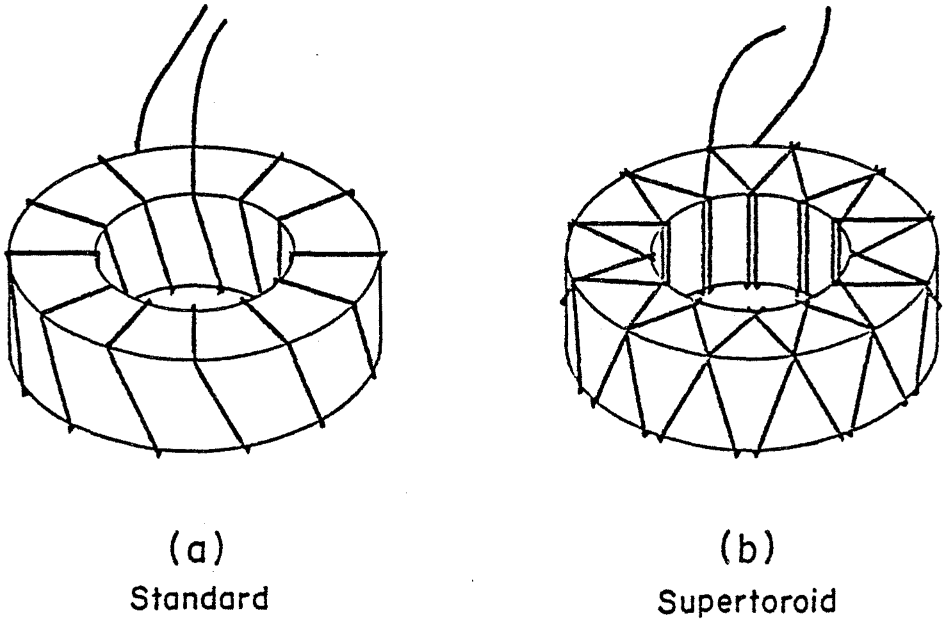

Figure 14. Standard toroid and supertoroid.

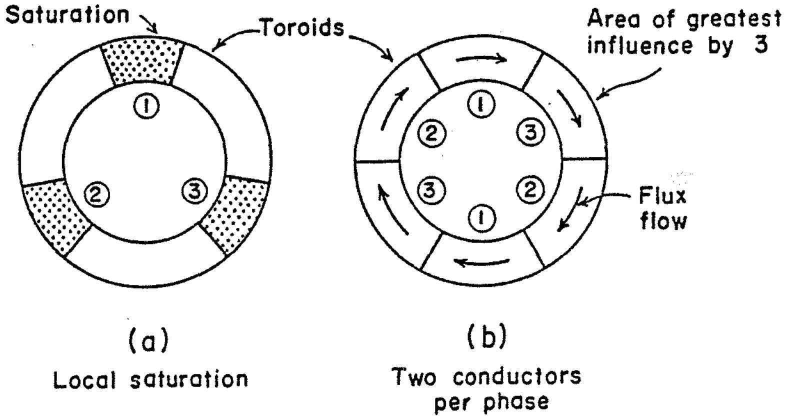

Figure 15. Zero-sequence relaying cable arrangements.

current transformer equipped with the desirable fluxaliner is shown in Figure 16. The fluxaliner should fit tightly inside the current transformer as the window should be as small as possible to retain zero-sequence sensitivity.

Summarizing, there are presently two methods for rejecting common-mode flux, phase-conductor splitting and fluxalining. The first is considered impractical for mining adaptation, but the second method involves a novel technique that has proven adequate as well as practical. By using the fluxaliner, it is likely that a sensitive-GFI CT can directly replace conventional ground-fault CTs with no power-conductor modifications.

Transient Interference. Transients are caused by a sudden change in circuit conditions, and common sources are lightning strokes and switching operations. Although the time involved is very short (usually milliseconds at most), it is during these periods that the greatest electrical stresses can occur.

The best way to reduce transients is through the proper design of the electrical power system [23]. With design and protection, the magnitude of transients can be held within safe limits for power-system components. Unfortunately, solid-state devices are often much more susceptible to damage [24]. Consequently, sensitive GFIs should be designed to withstand any transients that they might see.

The sensitive GFI has no direct connection to the power-system conductors. The only two possible avenues for transient introduction to its solid-state circuitry are through the current-transformer input signal and the control power supply. Here, four possible types of protection are available: filters, transient suppressors, inductors, and diode-resistor combinations. These methods will be briefly discussed in light of application to sensitive GFIs.

The filter as a protection device blocks frequencies above a cutoff value. Thus, high-frequency transients can be blocked, and the power signal passes undisturbed. The simplest form of filter is a capacitor placed across the line. This approach may have undesirable side effects such as resonance and has resulted in the popular use of RC snubber circuits, consisting of a series resistor and parallel capacitor [24].

Transient suppressors divert the incoming transient and two common types are voltage-clamping and "crowbar" devices [24]. A voltage-clamping suppressor has a variable impedance depending on the voltage across its terminals, and Figure 17 illustrates the voltage-current characteristics. For rated voltage, the device presents a high impedance approaching open- circuit conditions but, at high transient voltages, the impedance drops, and it conducts current. This current, flowing through the upstream impedance of the power system, chops the voltage seen by the circuitry protected by the device (Figure 18). Crowbar devices effectively short-circuit high voltages and operate on the spark-gap principle. A problem with their application to solid-state protection is the time delay, typically microseconds, before operation.

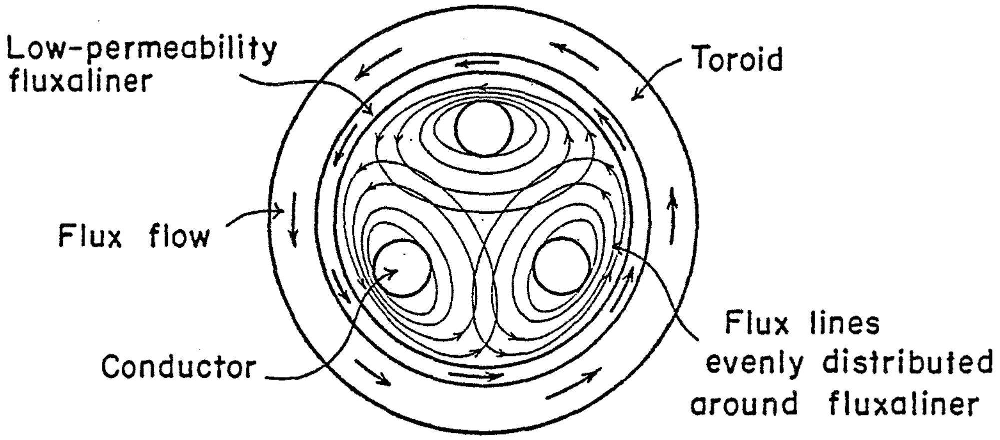

Figure 16. Fluxaliner and magnetic-field alignment.

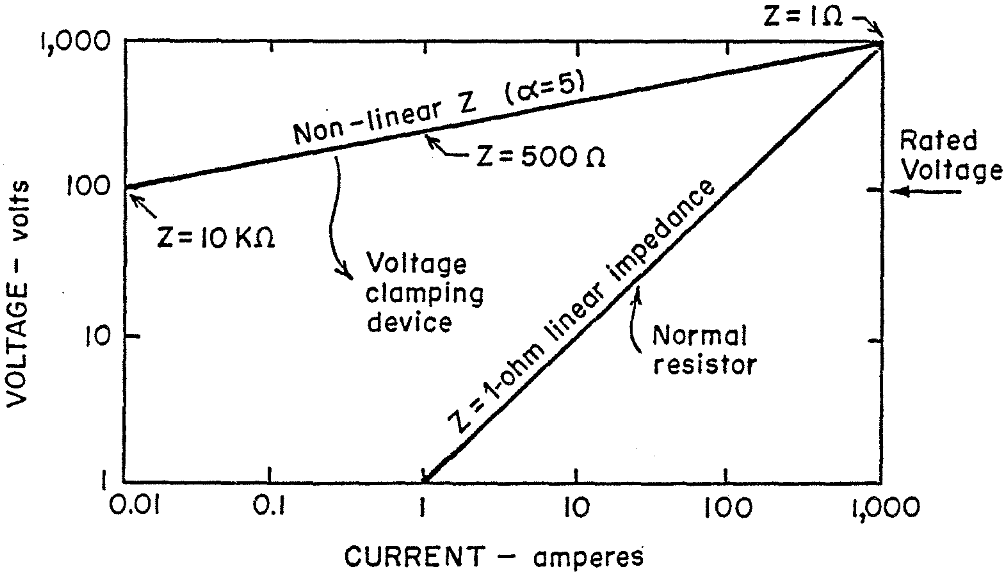

Figure 17. Volt-ampere characteristics of a voltage clamping device.

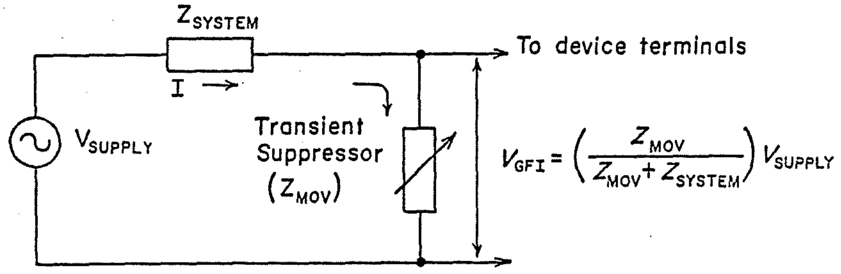

Figure 18. Transient suppressor.

Series inductors can be sized to suppress transients. At power frequencies, they present very little impedance to the flow of current. High-frequency transients, however, will see these inductors as an extremely high impedance.

Another method of transient suppression is a back-to-back diode shunt with associated current-limiting resistors (Figure 19) [25]. The voltage across the diodes reaches a maximum level depending upon the rating of the diode, and current flow is limited by the resistor R_2. R_2 also provides the input impedance for the operational amplifier. (As mentioned earlier, this impedance should be virtually zero.) For typical feedback resistances of the op-amp, R_2 from 1.0 to 2.0 Ω will not attenuate the input signal significantly. R_1 acts as a voltage divider with the toroid impedance to ultimately restrict current flow thus protecting the two diodes.

Protection of the GFI from transients through the control power supply should be routine. A similar situation is ground-check monitors, where filters and metal-oxide varistors (MOVs) are commonly used. The large number of transients found on mining systems suggest the application of MOVs.

Protection of the GFI from transient coupling through the current transformer raises other questions. First, is it really necessary to provide protection? The coupling of a short-lived current transient traveling along the primary conductors is unknown, but available literature [23,26] gives no indication of such coupling. Gross [25], however, does recommend protection and mentions the possible need for electrostatic shielding.

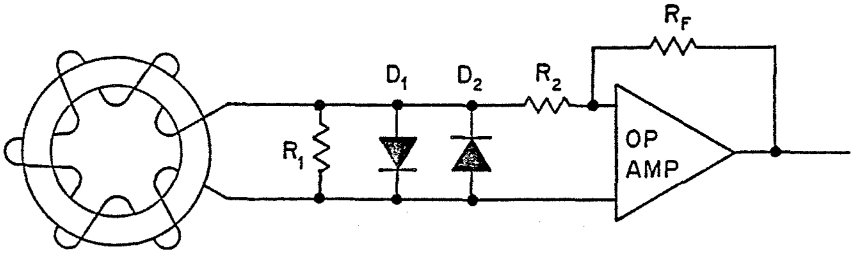

Figure 19. Diode-resistor transient suppression.

Another question concerning input-signal transient suppression is the introduction of attenuation or delay of the signal causing relay operation. The use of inductors can cause substantial current attenuation, and filters can introduce a charging delay. A MOV is not applicable as the voltage of the input signal is approximately zero under balanced conditions, and MOVs are always designed with a nonzero rating [24]. Therefore, if supression is required, the only acceptable solution appears to be the back-to-back diodes with resistors.

Harmonics Generated by Semiconductors. Mine-site testing of the SEL system by the Lee Engineering Division revealed an anomalous amount of false trips with the sensitive GFI monitoring a static belt starter. They reported that the CT would record an unbalance of 400 mA whenever the belt starter was in the acceleration mode [27]. The ground-fault current measured is illustrated in Figure 20. From this information and a knowledge of thyristor harmonic generation, they concluded that the static belt starter produced high-frequency harmonics while the thyristors were accelerating the ac conveyor motor. It was further concluded that these harmonics were the cause of the ground-current unbalance. For this reason, cause and control of harmonics and their possible influence on sensitive GFIs will be presented.

Harmonics are waveforms (voltage or current) with frequencies an integral multiple of some fundamental waveform. A 60-Hz signal, for example, has harmonics of 120 Hz, 180 Hz, ..., 60n Hz for n equals 2 to infinity. By combining harmonics of the proper order and amplitude, any periodic waveform can be generated. When load resistance, capacitance, and inductance are independent of system voltage and current, the load is said to be linear.

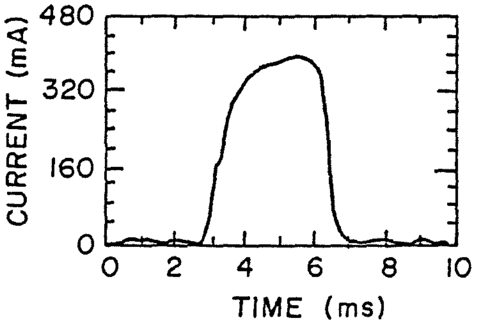

Figure 20. Ground-fault current with the belt starter in acceleration mode.

The current waveform produced will be sinusoidal and described by simply varying the amplitude and phase of the fundamental. When semiconductor devices such as thyristors are involved, the load current may be supplied only during part of the voltage cycle, and the system is nonlinear [28]. Figure 21 shows an elementary thyristor current waveform. The gating signal of the thyristor causes a delay in current resulting in a nonlinear flow. For example, a standard three-phase bridge rectifier with a six-pulse gating signal produces the current square wave shown in Figure 22. The wave can be described by a summation of sine waves of different frequencies (orders) and amplitudes.

The equivalent circuit for a typical ac static belt starter (Figure 23) is basically a three-phase delta-connected ac voltage controller. By thyristor control of the voltage supplied to the conveyor motor, the torque of the motor is varied, and smooth acceleration of the motor is achieved. The rate of acceleration is determined by the gating signals to the thyristors and may be changed either manually or by a feedback loop involving speed or motor current [29].

The same thyristors which provide the benefits of controlled motor starting are a cause of harmonics on ac distribution. The question is whether these harmonics can cause nuisance tripping of the GFIs. Fortunately, research in this area was done by W. Shepard in the United Kingdom [30]. He used Fourier transforms to describe the voltage waveforms of a line-controlled delta-connected or ungrounded-wye load and the expected harmonic content of load current. The resulting equations

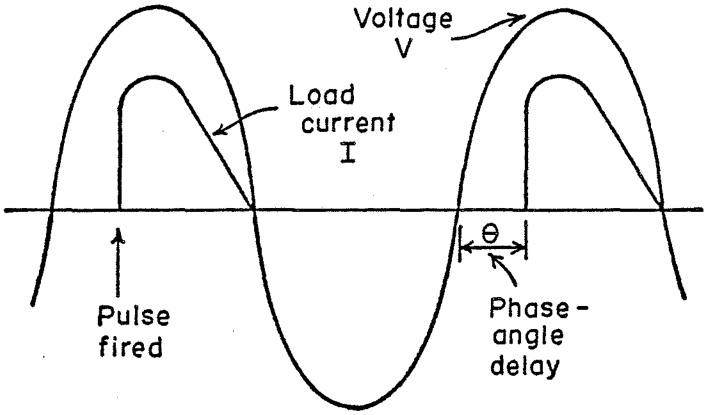

Figure 21. Elementary thyristor circuit waveforms.

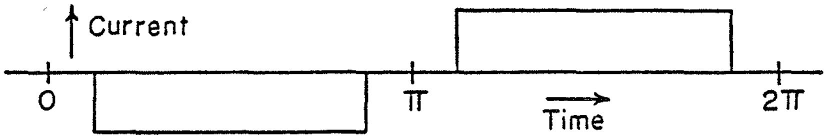

Figure 22. Square wave from bridge rectifier.

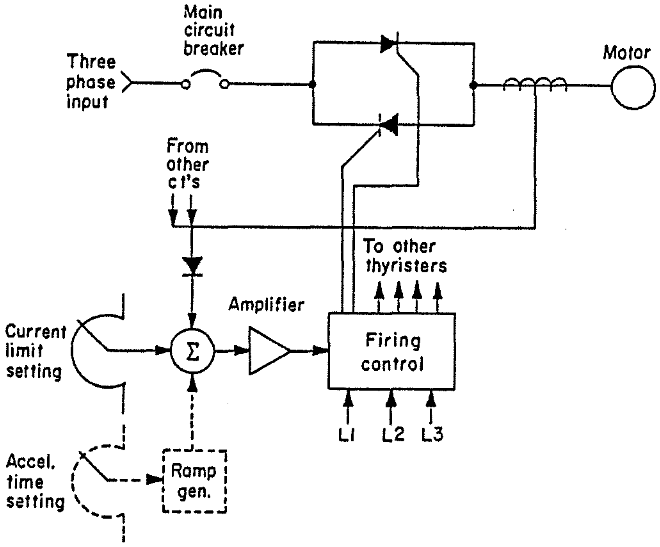

Figure 23. Static belt starter circuit.

indicated a lack of any triplen harmonic current waveforms. Triplens are the waveforms of the order

$$h = 3k \qquad (12)$$

where

h = harmonic order
k = any positive integer.

The actual values of current harmonics are shown in Table 1.

The lack of triplen harmonics does not seem significant until the relationship between system harmonics and symmetrical-component sequence networks is considered. As indicated in Table 2, the triplen harmonics are the only source of zero-sequence current flow. Therefore, for harmonics generated by the static belt starter, the zero-sequence CT of the sensitive GFI should detect no current unbalance. The same situation holds true for the harmonics generated by any static line controlled power converter, such as bridge rectifiers and dc motor controllers connected in delta or ungrounded wye.

The question still remains then as to what did cause tripping of the sensitive GFI during acceleration of the conveyor belt. Returning to the in-mine SEL test, subsequent modification of the GFI involved adding both harmonic filtering to the relayand a fluxaliner to the current transformer. The fluxaliner eliminated the common-mode-current problem, which was probably the only problem with this sensitive GFI. Harmonic filtering was not required to avoid false tripping as no zero-sequence producing triplen harmonics were present.

Further support of this argument is given by an examination of the strip-chart recording in Figure 24 of the secondary current generated by the

Table 1. Belt starter current-harmonic amplitude.

H	F(Hz)	A (% of F)
Fundamental	60	100
5th	300	20
7th	420	14
11th	660	9.1
13th	780	7.7
17th	1020	5.9
19th	1140	5.3
23rd	1380	4.3
25th	1500	4.0

Table 2. Sequence of harmonics.

HARMONIC	SEQUENCE NETWORK
Fundamental	Positive (+)
2nd	Negative (-)
3rd	zero (0)
4th	(+)
5th	(-)
6th	(0)
7th	(+)
etc	etc

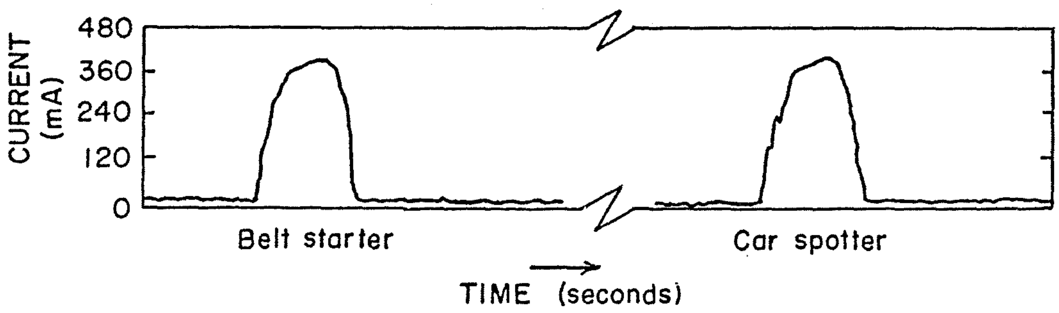

Figure 24. Strip-chart record of belt starter and car spotter.

unmodified CT of the sensitive GFI [21]. The first noticeable information is the 400-mA unbalance caused by acceleration of the conveyor motor. Further down the strip chart is a nearly identical unbalance caused by the operation of the car spotter, which is a hydraulically powered mechanism with an ac pump motor. There is no static control of this motor startup, and the unbalance is apparently caused by common-mode-current saturation in the GFI current transformer.

It should be noted that the addition of filtering may allow possible lethal currents to be ignored by the GFI. The effects of frequency on lethal current levels and the allowable high-frequency current attenuation by filtering will be discussed in Chapter IV.

Effect of System Capacitance. The unwanted effects of system capacitance have already been discussed briefly when defining high-resistance grounding systems. This section will highlight the nature of possible capacitive problems, quantify a typical U.S. case, and suggest solutions.

Any two conductors separated by a dielectric exhibit a capacitive effect. For stable charged conductors, the capacitance is defined as

$$C = \frac{Q}{V} \tag{13}$$

where

C = capacitance (F)
Q = charge (C)
V = voltage (V).

The capacitance also depends on the size of the conductors, their relative positions, and the insulating material between them. For shielded trailing cables, the proximity of the shield to the phase conductor can cause high capacitance.

In an alternating-current system, the capacitive effect between conductor and ground establishes a capacitive circuit. This circuit can conduct current of magnitude

$$I_c = j\omega C V_{cn} \tag{14}$$

where

I_c = capacitive current (A)
$\omega = 2\pi f$ = angular frequency (rad/s)
C = capacitance (F)
V_{cn} = voltage, line to neutral (V)

For example, a National Coal Board (NCB) Type-16 trailing cable exhibits 0.044 μF per 100 yards (0.0402 μF per 100 meters) [5]. For a 1000-V system, the current would equal

$$I_c = j\omega c V_{cn} = j(377)(0.044\mathrm{x}10^{-6})(\frac{1000}{\sqrt{3}})$$

$$I_c = 10 \text{ mA per 100 yards (91.4 m).}$$

This capacitive current is of sufficient magnitude to have an appreciable effect on the level of fault currents and the performance of the GFI. Although the capacitance is distributed along the entire length of the cable, a lumped capacitance model has been shown to agree with field observation [5]. Figure 25 illustrates the circuit representation of a GFI protected circuit with its associated lumped capacitance. For a ground fault with negligible resistance, the relationships for the currents shown in the figure are:

$$I_n = I_t = V/Z \tag{15}$$

$$I_c = V\ (3j\omega C) = \text{total capacitive current} \tag{16}$$

$$I_f = V\ (1/Z + 3j\omega C) = I_c + I_n = \text{fault current.} \tag{17}$$

The capacitive current increases the fault current limit by I_c (equation 17) and, as cable capacitance increases, the amount of fault current available will increase.

Cable capacitance is increased by increasing the length of cable. Figure 26 [7] illustrates the change of fault current which does not appear as GFI trip current when NCB Type-16 trailing cable is added. Curve 1 indicates the fault current increase of a purely resistive grounding system, while curve 2 illustrates a popular solution to the problem. In curve 2, an inductive grounding impedance replaces the standard grounding resistor. The inductance has the effect of lowering fault current as cable is added up to a length of 2,743 m (9,000 ft.).

The ordinate of Figure 26 may provide a clue as to possible problems with parallel capacitive circuits in U.K. mines. Cable lengths in longwall panels in their mines are extremely long, and the average system contains an equivalent of 2,743sm (9000 ft.) of cable per circuit. Also, all cables are shielded making for the largest capacitive effects.

In comparison, unshielded cables are usually used in U.S. room-and-pillar systems. For example, a typical unshielded trailing cable exhibits 0.02 μf per 1000 ft [31]. As trailing-cable lengths seldom exceed 500 ft, an average value of capacitive charging current is:

$$I_c = j(377)(0.2\mathrm{x}10^{-6})(\frac{1000}{\sqrt{3}})(\frac{500}{1000}) = 2.2 \text{ mA}$$

This small current flow should not appreciably affect the performance of a sensitive GFI or the fault current limit.

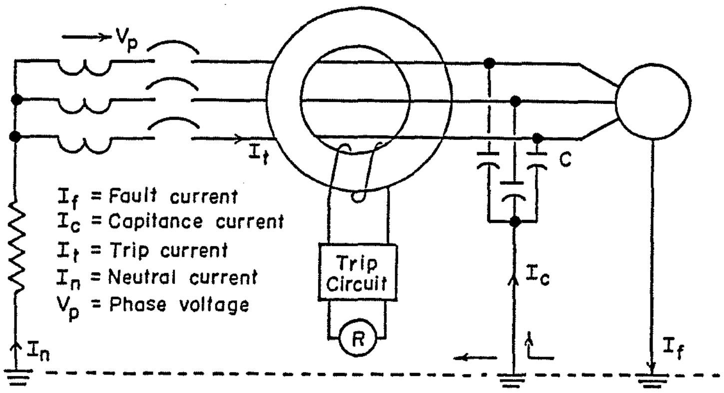

Figure 25. Typical GFI circuit with associated lumped cable capacitance.

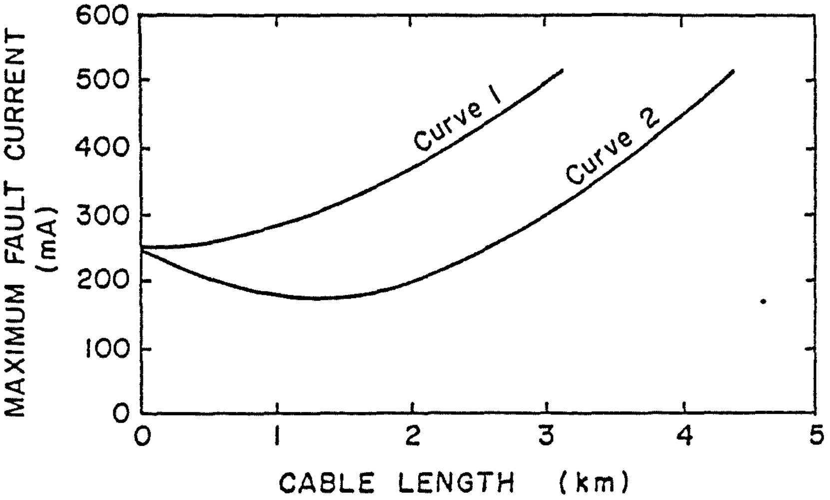

Figure 26. Cable capacitance versus cable length.

To consider the effect of parallel capacitive circuit, the situation of a fault downstream a 14-circuit power center will be examined. (Power centers seldom have more than 14 circuits for a single grounding system.) Figure 27 shows a simplified circuit of a power center, grounding system, and motor loads common in U.S. mining [10]. Only three circuits are illustrated for clarity. Phase A of circuit 2 contains a ground fault with negligible fault impedance. Fault current enters the ground system and returns by several paths depending on the path impedance.

There are three distinct paths that fault current can take. The first and most desirable path is through the grounding system. This path will cause current unbalance and correct relay operation in circuit 2. The second path is through the capacitance of the faulted circuit which will increase available fault levels. The third path is via the parallel feeder circuits 1 through 14. These two paths are undesirable as they may cause incorrect relay operation of GFIs 1 and 3 through 14.

For correct relay-operation, two possible methods are available: correct selection of neutral impedance and capacitive neutralization of CT secondaries. Each method has merit and will be explained.

When selecting a neutral impedance, two previously mentioned aspects are important. First, the maximum ground current must not be limited to less than the capacitive charging current. Second, relays must be set to pickup at less than 40% or less of the ground-current limit for reliable relay operation.

To substantially reduce the possibility of electrocutions, it is recommended in Volume I of this final report that ground current be limited to 500 mA [4]. Here, the ohmic value of the grounding resistor would be:

$$R_g = \frac{V_{c-n}}{I_{f(max)}} = \frac{600/\sqrt{3}}{0.5} = 693\ \Omega.$$

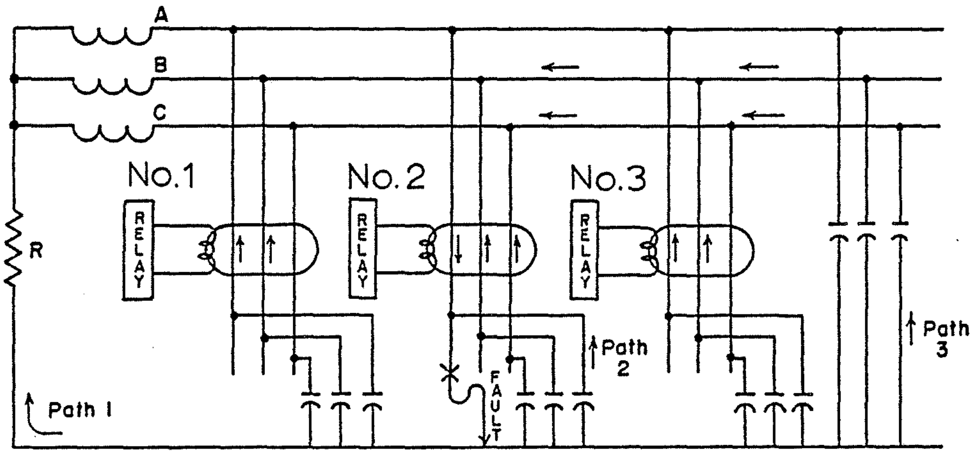

Figure 27. Distribution of capacitance current in parallel feeders during ground fault in a high-resistance grounded system.

The worst-case situation for capacitance would be where the capacitive reactance ($X_c/3$) equals the neutral grounding resistance (Rg), or

$$\frac{X_c}{3} = R_g \tag{18}$$

solving for capacitance,

$$X_c = \frac{1}{j\omega C} = 3R_g \tag{19}$$

$$C = \frac{1}{3j\omega Rg} = \frac{1}{3(377)693} = 1.28 \ \mu F. \tag{20}$$

If typical trailing-cable capacitance for the fourteen circuits are added in series, the result is

$$C_{cables} = 14 \ (0.02 \ \mu f) \ (\frac{500}{1000}) = 0.14 \ \mu F.$$

This leaves a large safety factor and insures that the majority of current will flow through the grounding system. Therefore, for short individually powered circuits, no problems are anticipated from capacitance.

The second aspect concerning neutral-impedance selection was that relays be set to pickup at less then 40% of the ground-current limit. For the 500-mA limit, the maximum value of relay pickup is 200 mA. If the 50-mA level is used as recommended from Dalziel's work, relays will pick up below the 40% level.

As the United States turns towards more longwall mining with its possible longer cable lengths and higher capacitance, it may become necessary to neutralize the effect of capacitance. Two techniques have been developed for removing the capacitive signal from the GFI prior to signal level assessment: phase-sensitive ground-fault protection and capacitance neutralization. Each will be briefly described.

Phase-sensitive ground-fault protection is illustrated in Figure 28 [32]. The method is applicable for single-phase systems only. The current sensor sends its signal to the synchronous demodulator which compares the current phase angle with that of a reference voltage. Only that part of the line current which is in phase with the voltage waveform is sent for signal amplification. Since capacitive current is 90° out of phase with the voltage waveform, its presence is totally ignored. However, resistive current flow, indicating a fault, is in phase and causes circuit breaker operation.

The application of phase-sensitive ground-fault protection to three-phase circuits does not appear feasible [33]. When a capacitive current is in one phase, the synchronous demodulator would not be able to distinguish this from a resistive fault on another phase. The reference voltage needs to correspond to the phase on which the fault appears. Consequently, the technique of capacitive neutralization was devised, and the main features are shown in Figure 29 [34]. Here, the reactive current introduced by cable capacitance is counteracted by an artificially introduced adjustable capacitance of opposing polarity. This artificial capacitance reduces the reactive-current level seen by the CT and allows for increased GFI sensitivity to resistive ground faults.

Summary

This chapter has introduced the development of sensitive GFIs and the possible problems and solutions in their application to U.S. mining. The use of sensitive GFIs is not new to all mining sectors but is particularly novel to U.S. mining.

In order to encourage the application of sensitive-GFI technology, it is desirable that information concerning their correct application be available. In Chapter IV, standards were developed by which the implementation of sensitive GFIs can be done safely, economically, and without troublesome nuisance tripping. These standards will be based on the desired qualities of such a device, with test levels extracted from field and laboratory measurements.

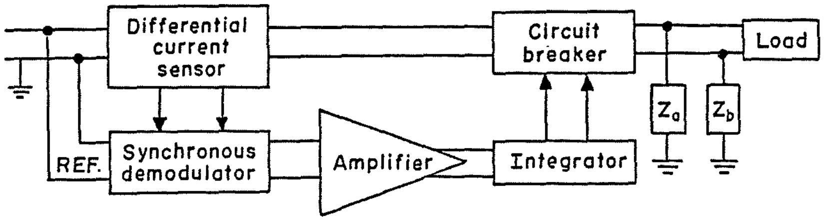

Figure 28. Phase-sensitive ground-fault protection.

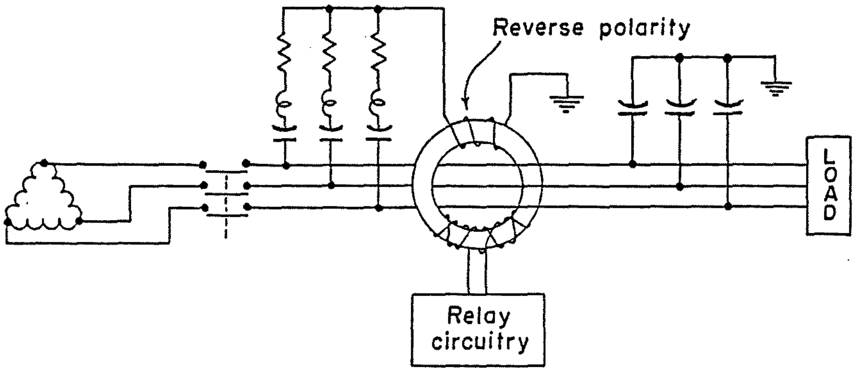

Figure 29. Capacitance neutralization.

CHAPTER IV

TEST DEVELOPMENT

General

This chapter will present the desired qualities for an acceptable GFI, recommended test levels, and test procedures. A systems engineering approach has been used to arrive at the desired qualities of a device.

Systems Approach to Device Evaluation

Before device testing, an overall view of the purpose for testing helps avoid either inadequate or extraneous data collecting. First, at the conclusion of testing, the characteristics of the device should be known. Testing should determine the performance of device. Second, the evaluation should ascertain whether or not device performance fits the desired characteristics of the "ideal" device.

A systematic approach suitable for the evaluation of any device is presented in Figure 30 and is a block diagram of the program plan. The first step involves development of ideal device qualities. These attributes are influenced by the desired operating requirements only. To a practical limit, only "what is needed" and not "what is possible" should be input.

Next, a series of tests based on the ideal characteristics of the device are developed. These tests should insure that any acceptable device does indeed satisfy the required operating conditions. Also, further tests should take into account all possible forms of device abuse that could result in malfunctions. Whenever possible, specific limits for each test should be determined according to established test procedures (Mine Safety & Health Administration, American National Standards Institute, Underwriters' Laboratory, Military Standards, etc.). An example of a test limit would be a requirement that the device operate correctly at 60% of rated control voltage.

During the development of these tests, limits that were not considered when developing ideal qualities can be incorporated. This input may take the form of calculations, device specifications, or field testing. Examples are symmetrical-component modeling, breaker operating times, and zero-sequence current monitoring, respectively.

Once these limits are established, the actual testing of each device can be performed. Results of tests are then compared to the desired characteristics, and a decision is made. Three alternatives are possible. First, if the device conforms to every established limit, it is accepted. Second, design modifications may be performed, and the device retested. Third, if no device can be obtained that satisfies the testing limits, it must be assumed that the desired ideal qualities are presently not attainable. Some modification of design concepts must then be undertaken.

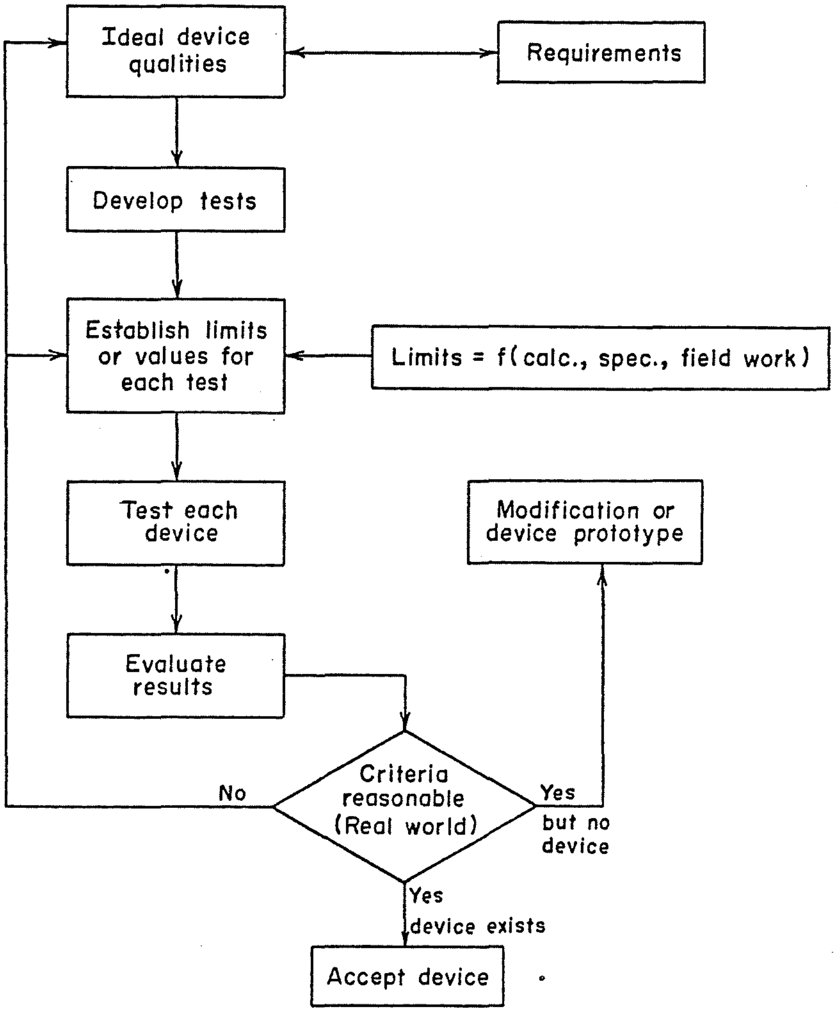

Figure 30. Systems approach for device evaluations.

Under such a systems approach, any device can be tested. The format is general and allows a measure of flexibility. The remainder of the chapter applies the approach to the evaluation of sensitive ground-fault interrupters.

Sensitive-GFI Desired Qualities and Rationale

The first step in developing criteria for sensitive GFIs involves listing the desired qualities. These characteristics are derived from the requirements of the device and are listed below along with a rationale for each item.

Proper Design and Construction. Proper design and construction will reduce the amount of downtime caused by GFI failures, resulting in its acceptance as a useful safety item. Many safety devices fail to be accepted by industry simply because they are too complex or cannot be easily repaired.

Proper Dimensions. The sizing of CTs used on GFIs affects their performance; also space is limited in typical mine power equipment. As up to 14 GFIs may be used in a single power center, they must not be much larger than the present GFIs. Conversely, the CT window must be large enough to accommodate the phase conductors for the equipment to be protected.

Electrocution Prevention. The reason for sensitive-GFI application lies in a reduction of electrocutions of mine personnel. Shock prevention is the primary function of sensitive GFIs.

Minimal Nuisance Trips. It is extremely important that the device operate only in the event of actual faults. Instances of mine maintenance personnel shorting-out problem safety devices are well documented. As in the case of ground-check monitors, any device that causes excessive nuisance tripping may be circumvented, resulting in no protection from ground faults.

Reliable Operation. As a safety device, the sensitive GFI will tend to provide a sense of security. As such, personnel handling cables will rely on the GFI for protection. Such a sense of security should be backed up by a device that will operate reliably to remove power from any ground fault. In the case of a section power center, 14 or possibly more may be separately employed. Each device must be in working order, and some test of the operating mechanism should be conducted at intervals to insure reliable operation.

Fail to Safety. In the event of a GFI failure, the protection it affords would be lost. A false sense of security is much less desirable than no security at all. Thus, a malfunctioning GFI should act to remove power and indicate its malfunction.

Mine-Duty Rated. The GFI will be expected to operate under harsh conditions not normally encountered by relay equipment in other industries. All components of the GFI should be of rugged construction to withstand occasional environmental hazards or electrical overloads.

The above has outlined seven required attributes of sensitive GFIs for mining. The following section will establish tests and test levels. In some cases, the test will consist of merely observing that a requirement is satisfied, but other tests will involve precise quantification of device parameters. Simple or standardized tests procedures will not be discussed in detail. However, those tests developed during the course of the research will be presented completely in Section 4.5.

Tests and Test Levels by Desired Quality

Tests developed to insure device conformance with the desired operating characteristics of sensitive GFIs are provided in the following. These are grouped according to the quality they examine. Tests 1, 2, and 3 cover proper design and construction. Test 4 looks at proper dimensioning, while Test 5 covers electrocution prevention. Tests 6, 7, and 8 verify minimal nuisance trips, and reliable operation is examined by Tests 9 and 10. The last two tests, 11 and 12, cover the fail-to-safety and mine-duty qualities, respectively.

Test 1. Federal-Regulations Compliance. The GFI must conform to all regulations in Title 30, Code of Federal Regulations (CFR), especially Parts 75 and 77 [8]. These regulations shall take precedence in the event of a conflict with any of the following tests.

An examination of the 1979 Coal Mine Safety Electrical Inspection Manual [36] was undertaken to help determine interpretation of specific regulations. This manual details the statutory regulations and contains the quantitative specifics.

It is notable that only three regulations concern ground-fault relaying, these apply to the GFI. Section 75.900 requires that low- and medium-voltage three-phase circuits be protected against a grounded phase. The Manual specifies that phase-to-ground faults must cause circuit-breaker tripping preferably at not more than 50% of the current rating of the neutral grounding resistor. Section 75.800 requires grounded-phase protection for high-voltage distribution, and the Manual specifies that 50% trip setting as an absolute requirement. Finally, Section 75.905 requires that single-phase loads be connected phase-to- phase. The control power of the GFI must be so connected. For most circuits, this requires the use of a control transformer which is standard for most control circuitry. Although the above regulations are redundent with respect to other test requirements that follow, the legal conformance test is still a necessary part of GFI-testing criteria.

Test 2. Military Standard 454 Compliance. Standards for electronic instruments exist in the military as MIL STD-454 [36]. In a study of environmental-test levels for electronic instruments in mining, Dayton T. Brown Inc [37] considered that the following military requirements are applicable.

Requirement 1: Safety,
Requirement 2: Soldering,
Requirement 7: Interchangeability,

Requirement 9:	Workmanship,
Requirement 10:	Electrical Connections,
Requirement 16:	Dissimiliar Metals,
Requirement 31:	Moisture,
Requirement 36:	Accessibility,
Requirement 62:	Human Engineering.

However, much of the information contained in these specifications does not apply to sensitive GFIs. Those portions that do apply are presented on Appendix I.

Test 3. Current Withstand. The GFI current transformer senses only zero-sequence current. The magnitude of this current is presently limited on low- and medium-voltage coal-mine circuits to less than 25 A. Yet, there are instances where the monitored level can be considerably higher; a shorted neutral-grounding resistor, single-phase conductor mistakenly passed through the GFI current transformer, and lightning strokes are examples. The most severe case of a lightning stroke is 20 kA [12]. However, in order to provide for the worst-case situation, the maximum interrupting ability of protective switchgear will be employed for GFI current-withstand levels, because the maximum available fault current must be less than the current-interrupting rating of the switchgear. The highest known level is that of the recently introduced Westinghouse* Model HPBM 1000-VAC mining circuit breaker, which has a rating of 24 kA [38]. This value will be used as the test current level, and the time for withstand is established by the circuit-breaker clearing time of 2 cycles or 33 ms.

Test 4. CT and Relay Sizing - For best control of leakage flux, the CT (and inner fluxaliner) should just accommodate the mine cable passing through the window. The largest cable in common use for trailing-cable applications is a three-phase 4/0 size, as problems of cable handling restrict the use of larger sizes.

Information on conductor diameters was obtained from the Anaconda Mining Cable Engineering Handbook [39]. For a 4/0, 15-kV, single-conductor cable, the copper conductor diameter is 11.68 mm. The insulation thickness is 4.4 mm, giving an overall diameter of 20.56 mm and a cable radius of 10.28 mm. Figure 31 shows the relation between cable radius, r, and CT inside diameter, D. The unknown dimension, X, can be obtained from:

$$x = r/\sin 60^\circ = 1.155r = 11.87 \text{ mm}.$$

Thus, the inside diameter of the CT should be:

$$D = zR = 2(r + x) = 2(10.28 + 11.87)\text{mm} = 44.3 \text{ mm}.$$

A GFI current transformer with this inside diameter would just accommodate three single-conductor 4/0 cable. For ease of installation for cables with attached terminals, the minimum should be increased by 20% and results in a desired inside diameter:

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*Reference to specific brands, equipment, or trade names in this report is made to facilitate understanding and does not imply endorsement by the Bureau of Mines.

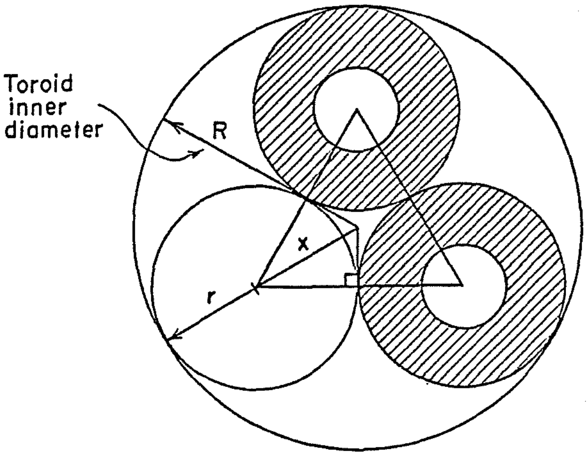

Figure 31. Current-transformer inside-diameter formulation.

44.3 mm (1.2) = 53 mm (2.1 in.).

The outside diameter of the CT should be as small as practical to reduce its space requirements inside crowded power equipment. The typical mine CT for ground-fault protection has an outside diameter of less than 4 in., and can be considered as a goal. The width of the CT should also be minimized as space is often limited between breaker and coupler connection. A maximum of 3 in. is indicated for this dimension.

The GFI relay and components package might be mounted on an interchangeable panel. For this reason, it should also be as compact as possible, but a maximum size of 3 in. by 6 in. by 6 in. should be adequate.

Test 5. Circuit Interruption Time versus Current. The main cause of electrocution, ventricular fibrillation, has already been discussed in Chapter III, where Dalziel's equation was introduced. The curve defined by this equation will be used as the desired test limit, including circuit-breaker operating time, for a time-versus-current test of an ideal GFI. Table 3 is a listing of some points on the curve to provide an idea of the actual times and currents involved.

Table 3. Time and current values from Dalziel's fibrillation equation.

8.3 m	1.27 A
50 m	500 mA
5	51 mA

Two important questions arise from the selection of such sensitive trip values. First, at what value should the maximum ground current be limited? Second, will stray or ambient ground current make low pickup levels impractical for mining? Both points deserve consideration.

A ground-current limit of 500 mA has been suggested in Volume I of this final report [4]. The level is practical for several reasons. It was used during the final in-mine SEL research, with no difficulties. Next, the 500-mA limit conforms to the two guidelines for neutral grounding-resistor design.

1. It is above the capacitive-charging current of a typical power center.
2. The recommended 50-mA pickup is only 10% of the maximum ground current, such that the 40% requirement for relay current levels is observed.

Most importantly, this low value (500 mA as opposed to typically 15 A) will greatly decrease the chance of electrocution due to ground faults.

One concern associated with such a low pickup value is that ground leakage current is often above 50 mA due to wet, worn cables such that constant false tripping will occur. This argument has been successfully used in the past, resulting in the present pickup levels above 4 A. However, both symmetrical-component modeling and field measurements dispute this argument.

The symmetrical-component model for a line-to-ground fault of a typical three-phase power system is shown in Figure 32 where

E_T = line-to-neutral voltage (V)
Z_1 = positive-sequence impedance (Ω)
Z_2 = negative-sequence impedance (Ω)
Z_o = zero-sequence impedance (Ω)
Z_f = fault impedance (or in this case, per-phase cable leakage impedance to ground) (Ω)

An old cable in a wet section may have conductor insulation with a leakage impedance as low as 5 kΩ. Neglecting other impedances and calculating the leakage current:

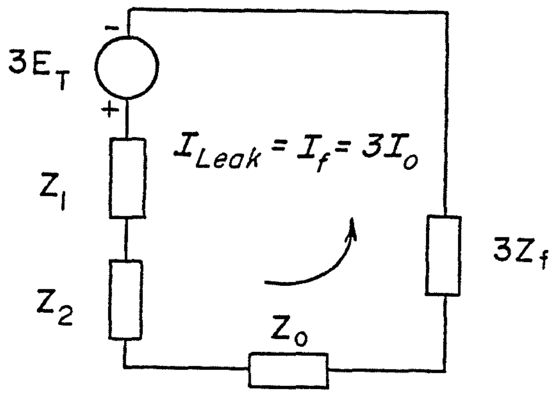

Figure 32. Symmetrical component model for a line-to-ground fault.

$$I_{Leak} = 3E_T/3Z_f$$

$$I_{Leak} = (600/\sqrt{3})/5000 = 6.9 \text{ mA}$$

which is substantially lower than the recommended pickup.

This analytical result can be compared with field measurements taken by the Lee Engineering Division of CONSOL on the power center containing the SELs and a 500-mA ground-current limit [21]. Here, the average value of ground current was found to be 10 mA, and the maximum was 20 mA.

Volume I [4] also contains a detailed analysis of the electrocution situation if the recommended ground-current limit and relay pickup is used. A summary is beneficial here for completeness. Figure 33 is the fibrillation curve with a 50-mA, 100-ms definite-time relay curve superimposed. The logarithmic nature of both the fibrillation and relay curve allow a close match which is desirable for safe nuisance-free operation. For a 100-ms operating time, the relay curve is in the no-fibrillation area up to approximately 400 mA. An analysis of the electrocution current path shows that this level of protection is adequate.

Figure 34(a) is a model of a line-to-ground fault through a human body [4]. For a worst-case condition, the charging current equals the resistor current during a ground fault. In other words, the reactance ($X_c/3$) due to system capacitance equals the resistance (R_G) of the neutral-grounding resistor. For a 1000-V, three-phase system, the grounding resistance for a 500-mA limit is:

$$R_G = \frac{(1000/\sqrt{3})}{0.5} = 1{,}155\ \Omega.$$

The capacitive reactance appears in parallel with the resistance in the symmetrical-component model of Figure 34(b). Assuming a body resistance (R_B) of 1000 Ω [40] results in the total equivalent impedance of Figure 34(c). Thus, the maximum current through the body is approximately 236 mA, less than half the neutral current limit. Locating this point (236 mA, 100 ms) on the fibrillation curve shows that it is inside the safe zone predicted by Dalziel.

Summarizing, Dalziel's fibrillation curve will be used as the desired time-current characteristic for sensitive GFIs, and a 500-mA ground-current limit is recommended for such a sensitive system. This limit is above typical capacitive-charging current and pickup levels are within the 40% requirement. With the recommended system, ambient ground current is low and should not cause nuisance trips. Finally, even under worst-case conditions, the system will provide an adequate margin of safety.

<u>Test 6. Transients</u>. Transients on mine power systems occur frequently. However, with the time-current recommendations, a sensitive GFI can have a several millisecond delay in signal processing and therefore should not experience problems with such short duration events. Nevertheless, it is felt that some voltage-transient testing should be performed to establish that no false tripping occurs from worst-case transients existing on the monitored power conductors, and the relay does not fail from worst-case transients in the control power. Past research has found that the worst-case voltage transients on low-and medium-voltage mine systems are 5 pu of crest [41].

The test procedure found appropriate is in UL STD 943, "Ground Fault Circuit Interrupters" [16]. Using a 1.0-kV utilization voltage, a 20% margin of protection, and the 5-pu crest voltage, 5 kV can be used to simulate worst-case transients for the false-trip test. Likewise, 1-kV pulses can be applied to 120-V control-power inputs. The standard1.2x50 waveform, as shown in Figure 35, can be used as it simulates severe surges and can be easily obtained with a surge generator [42]. Following the UL recommendations, ten random applications of each impulse should be applied to the sensitive GFI. Tripping or a failure should not result. By random applications, it is meant that these applications will be random with respect to the phase of 60-Hz supply voltage.

<u>Test 7. Common Modes</u>. Line currents for 4/0 or larger trailing cables can occur up to 2,500A in coal mining. At this point, present federal regulations require that the instantaneous protection for short circuits trip the circuit breaker [43].

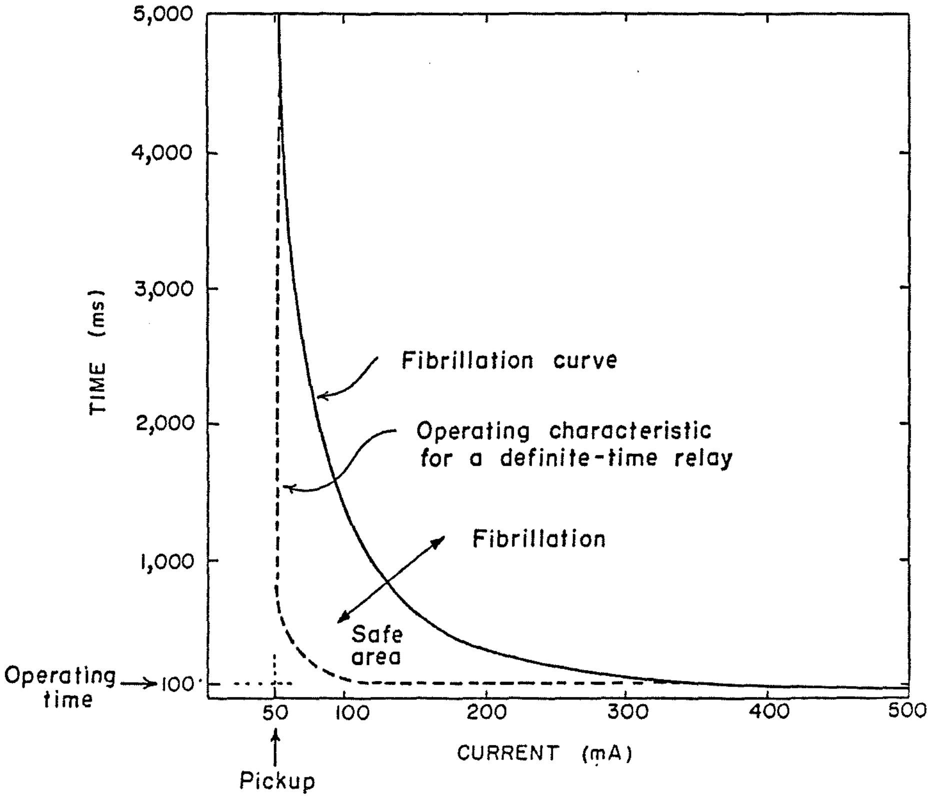

Figure 33. Dalziel's fibrillation curve and relay.

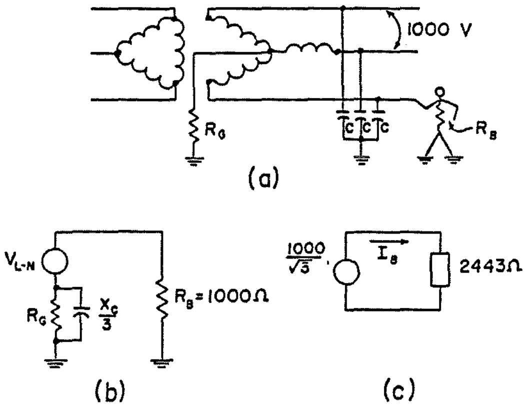

Figure 34. Shock hazard and equivalent circuits.

While such high currents are not expected for continuous duty, they may be generated during motor startups or intermittent motor loading. For example, a continuous miner which normally requires 225 A may temporarily draw 6 times its rated current, and results in a short-time common-mode currents of 1350 A. These high phase currents must not cause false tripping of the sensitive GFI.

Nevertheless, the GFI should be subjected to three-phase common-mode currents up to 2500 A. The level that causes false trips (if any) should be recorded.

Test 8. High Frequency and Harmonics. Harmonics or high frequencies on utilization circuits should not cause false tripping but, in turn, they must also not cause electrocutions. It was pointed out in Chapter III that zero-sequence harmonics are not present in loads common in most mine equipment (i.e., delta-connected or ungrounded-wye- connected motors) such that false tripping should not be a problem. However, frequencies other than the fundamental may be available from other sources, and those possible of causing electrocution should be detected by the GFI.

Dalziel [2] has experimented with the let-go current levels for frequencies from 5 to 10,000 Hz. Figure 36 shows the results of his tests on humans and can be used to check the allowable attenuation of any filtering included in a sensitive GFI. Here, a 50% attenuation of the harmonic or high-frequency waveform could be allowed for a doubling in let-go current. Table 4 has been developed from Figure 36 and indicates the tolerable attenuation for various frequencies.

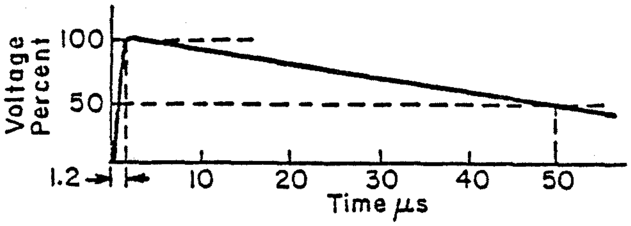

Figure 35. 1.2x50 BIL test waveform.

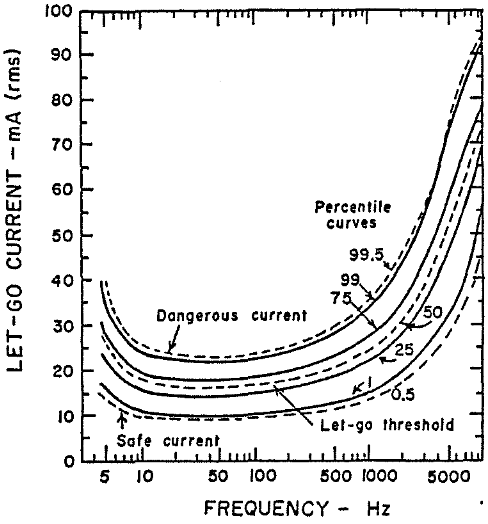

Figure 36. Increase in "let-go" current valves with increasing frequency.

Table 4. Attenuation of GFI from let-go levels.

Let-Go (mA)	Frequency	Factor	Adjusted Pickup
22	60 Hz	1	50 mA
33	600 Hz	1.5	75 mA
44	2000 Hz	2.0	100 mA
66	4000 Hz	3	150 mA
88	8000 Hz	4	200 mA

Figure 37 is a plot of the points in Table 5, and GFI filtering should not exceed this curve.

While Figure 37 is very clear in the amount of current attenuation with frequency, it is not explicit as to filter design levels. By replotting this curve for attenuation in decibels versus frequency (Figure 38), the type of allowable filtering is easier to develop. The slope of the curve in each section denotes a certain filter characteristic, i.e., 0.825 dB/octave from 60 to 600 Hz. By compromising slightly, the dashed lines which indicate a two-stage filter system are obtained. The first stage can attenuate current up to 1.0 dB per octave from 60 to 2000 Hz. The second stage permits attenuation of 3.0 dB per octave from 2000 Hz to infinity.

Test 9. Reliability. If a device looks promising as indicated in the previous tests, five additional devices will be obtained and tested. These devices should operate in the same manner as the first. Any large discrepancy would indicate unreliable construction and hence danger to personnel.

Test 10. Ground-Fault Simulation. Each device should have a test circuit with a pushbutton that simulates a ground fault. A standard test interval should be specified by the manufacturer.

Test 11. Loss of Control Power. In trying to design a fail-to-safety test it was found impractical to remove solid-state components from their connections or in any other way short-out operating mechanisms. Destructive testing was not felt to be a realistic option under this contract. The second best choice is a loss of control power test which can be run by simply removing control power and observing that the sensitive GFI acts to remove power from the protected circuit.

Test 12. Mine Duty Rated. The standards established by Dayton T. Brown, Inc. [37] for environmental testing of mine instrumentation suggest a covering for each instrument. The normal location for sensitive GFIs is inside metal-clad mine power equipment. As such, it should not be required that GFIs undergoo such an enclosure test. However, the suggested features of the GFI relay and CT are as follows.

1. Both devices should have secure, metal mounting lugs that ground any metal casing.

2. The terminal strips of each component should be of rugged construction and sized to handle number 12 AWG wiring.

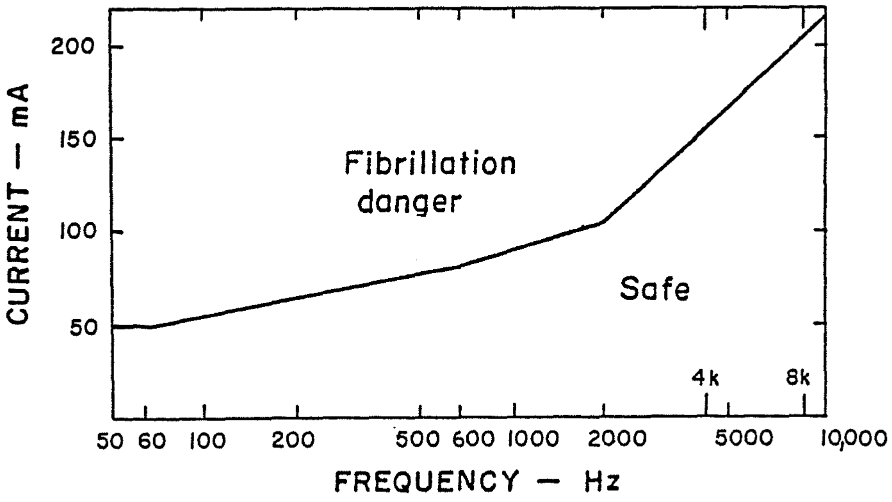

Figure 37. Pickup versus frequency for sensitive GFIs.

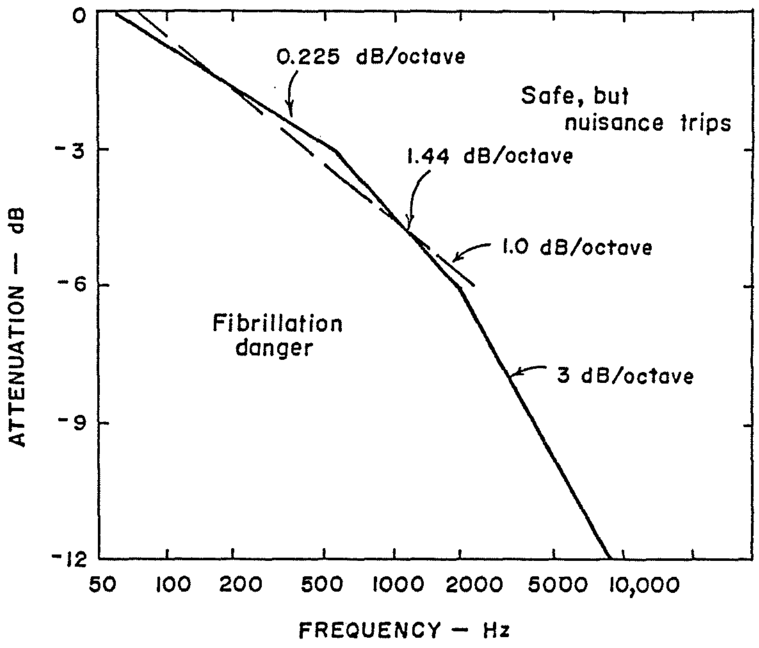

Figure 38. Allowable filter response curve for a GFI.

3. The casing should be moisture and dust resistant, although not necessarily waterproof or dustproof.

These features along with a compact packaging will ensure that the device performs adequately inside mine power equipment.

Test Procedures

In the previous chapter section, the tests and test levels for sensitive GFI operation have been established and justified. The specific tests are as follows:

1. Compliance with Federal Regulations,
2. Compliance with Milatary Standard 454,
*3. Current Withstand,
4. Current-Transformer and Relay Sizing,
*5. Time versus Current,
6. Transients,
*7. Common Mode,
*8. High Frequency,
9. Reliability,
10. Test Circuits,
11. Loss of Control Power, and
12. Mine Duty.

Tests 1, 2, 3, 6, 9, 10, 11, and 12 are felt to be self explanatory by either the remarks of Section 4.4 or the existing test procedure (Test 2 and 6). The tests marked with an asterisk (3, 5, 7, and 8) are somewhat more complicated and will be explained in detail.

Test 5. Time versus Current. The equipment requirements for this test include:

- variable current source, 0-1 A continously adjustable,
- source of control power for the GFI,
- double-pole single-throw switch,
- current probe or ammeter,
- storage oscilloscope (set on triggered single trace), and
- dc triggering source (4 to 5 V).

The first requirement may pose a problem as to continual adjustment. ttempting to use a constant voltage with variable resistance results in poor urrent control in current ranges. This is due to inconsistent resistance riation of most large rheostats at their upper resistance levels. One ution to this is a variable autotransformer in conjunction with a high-tage resistance. A rheostat may also be inserted if more precise control esired.

The circuit is illustrated in Figure 39. As can be seen, primary ion of single-phase current is used to simulate a single line-to-ground The oscilloscope is triggered by the dc battery which is switched at e instant that the ac circuit is excited. This symmetry is obtained the double-pole single-throw switch. As a check of the triggering

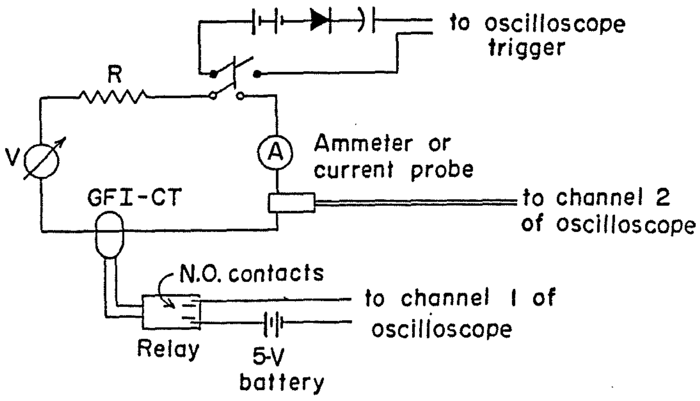

Figure 39. Time versus current test circuit.

circuitry, the ammeter may be supplemented or replaced by a current probe attached to the second channel of the oscilloscope.

The time required to pick up the relay contacts is read directly from one oscilloscope trace (Figure 40); the horizontal axis is set on milliseconds per division. The current level can be read directly from the ammeter or in the case of a current probe from the channel-two trace. This trace must be corrected to rms values.

To perform the test, the current level is first adjusted to the desired test level by adjusting the autotransformer and/or the rheostat. The switch is then opened, and the oscilloscope set to be triggered. Throwing the switch triggers the oscilloscope, and a time and current point for a plot are obtained. Several points are used to construct a time-versus-current graph for comparison to Dalziel's curve.

<u>Test 3. Current Withstand</u>. This test only requires the following equipment:

- a high-level current source, such as the Multi-Amp* Model CB-120-DC-X circuit test set connected to a transformer with low-voltage shorted secondary, and
- an initiate and cutoff switch for proper withstand time.

The minimum withstand rating for a sensitive GFIs has been set at 24,000 A for 32 ms. To generate this large amount of current, several turns on the CT window is required. The maximum current for the Multi-amp* transformer

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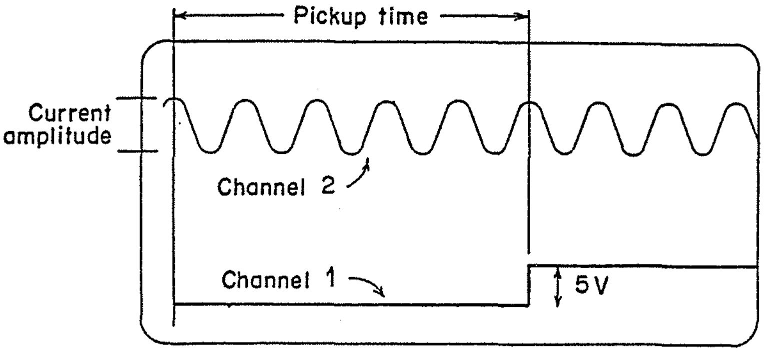

Figure 40. Oscilloscope trace of pickup time and current level.

set is 3500 A. Using 3000 A, 8 turns through the window will be equivalent to the required 24,000 A. The time switch can turn on at a zero point and interrupt power at the second voltage peak, giving about 32 ms. Personnel should be physically protected, as such high currents may cause physical destruction of the current transformer.

Test 7. Common Mode. The equipment requirements here are:

- 2500-A three-phase continuous-current source,
- current probe capable of monitoring 2500 A,
- source of control power for GFI, and
- low-permeability pipe for use as fluxaliner.

Continuous current is provided through a Multi-Amp* Model CB-120-DC-X circuit breaker test set. (This unit was originally designed to be used with a rectifier to provide dc output [44]). An AWL*/180-KV three-phase transformer is used to drop the zero V to 480-V output of the test set to zero V to 12 V for the high-current levels, using a delta-delta connection. The common-mode current is injected through the GFI current transformer using 3.0 m of number 4/0 AWG single-conductor cable. An additional 0.5 m of number 1/0 AWG three-conductor cable is added in series, where the ends of the three conductors are shorted to provide maximum current at low voltage levels.

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Currents are measured using a modified Fluke* Model 80I-600 clamp-on current probe. The probe originally gave a 1.0 mA output for a 1.0 A input. Modification of the probe consisted of placing a resistance across the CT secondary and monitoring the voltage drop across the resistor. The resulting response is 10 mV per ampere of primary current up to 700 A [45]. Above this level, saturation occurs and the problem of measuring 2500 A is solved by observing primary phase current to the AWL* transformer. Here, the transformer turns ratio was found to be 0.29, and 2500 A secondary phase current relates to 73.5 A on the primary.

Considering overload conditions of the Multi-Amp* control unit, the period for each test is limited to 5 s. Fortunately, the on-time is long enough to insure that the GFI was adequately exposed to common-mode current, and the acceleration period of motors and hence the period of current inrush is typically less.

Test 8. High Frequency. The equipment required for this test includes:

- variable frequency generator,
- frequency counter,
- control power source, and
- ammeter.

A Wavetech* Model variable-frequency generator is used to provide frequencies from 60 Hz to the kilohertz range. These are monitored with a Textronics* Model frequency counter connected the synchronous output of the generator. The output leads from the generator run through the GFI- CT window and through a Fluke* Multimeter (as an ammeter). A sketch of the circuit is shown in Figure 41). The frequency is varied from 60 Hz, and the pickup level of the GFI is recorded. From this data, curves can be plotted and compared to the allowable attenuation curve in Figure 38.

The only problem encountered with this test is the low short-circuit current produced by the frequency generator (a maximum of 150 mA). This current is not enough to cause tripping for several devices. The solution is to simply provide more ampere-turns of primary current by increasing the number of primary turns.

Summary

This chapter has presented the tests necessary for sensitive-GFI evaluation. A systems-engineering approach for any device evaluation was applied to the GFI. Desired qualities of the device were justified, and the test levels established. Those test procedures not standardized or easily implemented have been detailed. Actual device testing and evaluation will be described in the next chapter.

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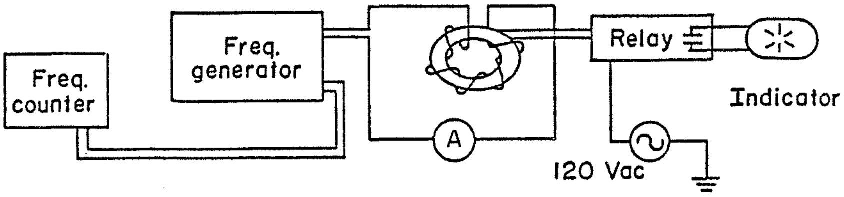

Figure 41. High-frequency test circuit.

CHAPTER V

SENSITIVE-GFI TESTING

General

This chapter will present actual tests on five available devices designed for three-phase sensitive ground-fault detection. Each device and its associated circuitry will be described. Test results are compared with the desired device qualities developed in Chapter IV, and serious design deficiencies will be noted.

GFI Specifications

An extensive survey was made to find commercially available sensitive GFIs intended for three-phase systems. Only five different devices could be located, and the nameplate specifications, estimated price, and manufacturers address are presented in Table 5*.

Device Characteristics and Preliminary Test Results

Monotron* Model 445. The Monotron* Model 445 is a sensitive GFI intended for use with center-pivot irrigation systems. These operate in a necessarily wet environment utilizing electricity for both tower motion and water pumping. This unit is designed to protect against contact with the 480-V power supply for tower motion. As with any sensitive GFI, the Monotron* 445 does not depend on grounds of any type to be effective. Any leakage current, whether from the 480-V power supply current or the 120-V control power, will cause the Monotron* to remove power. Interlocks between 480-V and 120-V circuitry remove 120-V power when a 480-V ground fault occurs.

As received from the manufacturer, the Monotron* 445 is a self-contained sensing and interrupting device. It is packaged in a sturdy metal box with an interlocked "dead-front" inner panel. Inside the box are the sensor, contactor, and test circuitry. Three-phase 480-V power is input to the sensor. The output of the sensor is connected to the adjacent contactor and (from there) exits the metal housing. A separate transformer, provided by the user, supplies 120-V control power and any 120-V power requirements. An example of a 120-V power requirement could be a trip indicating light or floodlights. Light emitting diodes (LEDs) on the sensor board indicate the presence of either a 120-V or 480-V current leakage.

Preliminary testing of this device was undertaken to determine any obvious design flaws. Both the 120-V and 480-V test circuits were wired along with the reset. The interlock system was shorted, and the sensor was removed from its housing. By supplying 120-V control power, it was seen that both test circuits operated correctly, and the associated LEDs indicated a fault. However, primary injection of fault current through the 480-V sensing

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Table 5. Available sensitive ground-fault interrupters.

Monotron* Monotron Model 445 45 A, 480-120 V Sensitivity - 18 mA Response Time - 0.05 s	Redtrol, Inc.* Natick, MA 01760 617/653-0015 Cost: $385.00
Pump Monotron* Monotron Model 3250 250 A, 600 V Sensitivity - 18 mA Response Time - 0.06 s	Redtrol, Inc.* Natick, MA 01760 617/653-0015 Cost: $205.00
Gross Prototype* Prototype Current & Voltage Ratings - None Sensitivity - 15 mA Response Time - UL Class A GFCI	T.A.O. Gross & Assoc.* 230 Concord Road Lincoln, MA 01773 Cost: $250.00
GE Ground Break* Ground-Break Type MC Sensor TMCGS2006T 100 A (single-phase thermal rating) 100,000 A, 1.5 cycles (withstand rating) Sensitivity - 100 mA Response time - 300 ms at 150% trip level Relay TMCGRIS NC contacts - 15 A, 120 Vac, make and break 90 A NO contacts - 3 A, 120 Vac, make 15 A break 3 A	General Electric* Circuit Protective Devices Dept. Plainville, Conn. 06062 Cost: $272.00
SEL GFI Sensitive Ground-Fault Detector (SGFD) 25 A (Ground Current Limit) 120 Vac power supply Sensitivity - 90 mA ± 20% Response Time - 100 ms at 150% trip level Contacts - 5 A, 250 Vac	GBS Harrison Ltd.* Sheffield, England or Minetics Corporation* 150 Plum Industrial Corp. Pittsburgh, PA 15239 412/325-3121 Cost: $495

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system produced no trip at any level. The fact that this device did not respond to this current indicated a malfunction or a serious design problem. This along with the added complexity of a dual-voltage system and lack of a current-transformer toroid eliminated this device from further consideration. The following device, from the same manufacturer, showed better promise.

Pump Monotron* Model 3250. The Pump Monotron* consists of a current transformer and relay combination. The two separate pieces are intended for mounting inside the existing pump control panel of center-pivot irrigation systems. This GFI senses pump-motor ground-fault current and disconnects the pump circuit by energizing an associated shunt-trip circuit. The device uses 120-V control power and is rated for 480-V circuit protection.

Figure 42 is a simplified wiring diagram of the Pump Monotron*. The device uses a clapper-type relay with an adjustable pickup level that creates a potential between terminals 10 and 4 upon pickup.

Preliminary tests pointed out several problems. The first involved resetting of the GFI on an uncleared ground fault. For primary-injection currents of 20 mA to 85 mA, the device picked up to indicate a fault but reset without removing the fault current. This flaw is unacceptable because an actual fault could be interpreted as a nuisance trip. Second, the pickup range was listed 5 to 20 mA by the manufacturer but varied considerably from these values. For primary-injection currents with fast rise time, the pickup level was near 20 mA. However, for a slow rise-time ground fault, simulated by gradually increasing current, the device did not trip until 85 mA.

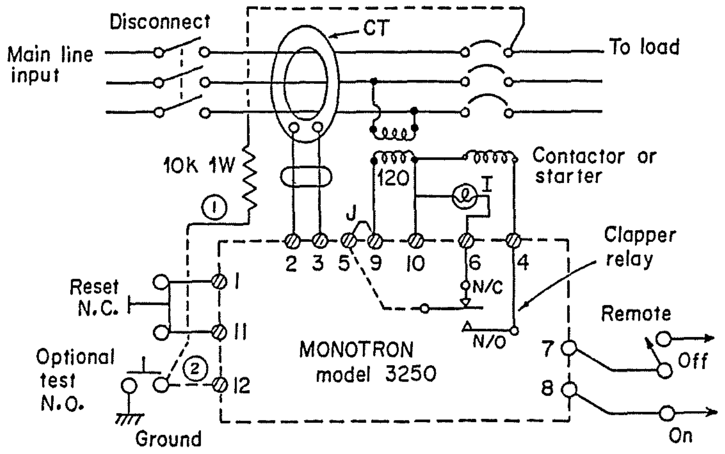

Figure 42. Pump Monotron wiring diagram.

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The final problem involves the use of an apparently inferior clapper relay for trip signaling. Figure 43 is a reproduction of an oscilloscope trace showing contact bounce of the clapper relay. The first jump in the trace indicates that the relay tried to pickup at 100 ms, but the final pickup did not occur until 50 ms later. This contact bounce may introduce serious time delaying. These problems with the Pump Monotron* make it an unlikely candidate for mining application.

Gross Prototype. The sensitive GFI from T.A.O. Gross and Associates* is the most complex but the most schematically detailed device obtained. A block diagram is shown in Figure 44, and the schematic is illustrated in Figure 45. An explanation of the two will aid in understanding the circuitry involved.

The two-stage amplifier of Figure 44 is shown as Block 1 in Figure 45. A diode-resistor transient suppressor is included, capacitor C_4 serves to remove any stray ac input current, and block 2 is an adjustable capacitance neutralizer. Block 3 is a full-wave detector. Block 4 provides for pickup-level adjustment with P_1. Block 5 contains a variable-rate integrator. Here, the three input paths conduct current depending on the size of input signal, and diodes D_5 and D_6 switch into a conduction mode at increasing current levels. Block 6 is a Schmidt-trigger assembly, and block 7 is a rectifier bridge that delivers trip signal. Some control-power transient suppression is provided by capacitor C_8 and zener diodes Z_1 and Z_2, but their main function is dc-supply filtering and regulation, respectively.

Again, this device was designed mainly for use on the center-pivot irrigation systems, but offshore oil rigs have also had some application for an earlier model GFI [22]. The designer has also expressed interest in developing this device for mining use.

The designer, T.A.O. Gross, holds patents on capacitance neutralization, variable-rate integration and full-wave detection. Capacitance neutraliation has been explained in Chapter III. Full-wave detection allows viewing the fault signal from both positive and negative polarity. Variable-rate integration provides precise modeling of time-versus-current curves by electronic equipment. An example of this is shown in Figure 46 where the device characteristic approaches exact modeling of UL Standard 943 for trip time versus fault current [33].

This device utilizes several sensitive monitoring techniques not found on other GFIs. As a result, Gross has set the pickup level in the 5- to 20-mA range. While he may achieve such low levels without nuisance trips in the irrigation industry, it is felt that the pickup is too sensitive for mining application.

Preliminary testing showed that the GFI performed consistently throughout its pickup range. The pickup time varied inversely with current, and no major design flaws were uncovered. However, several other minor problems exist with this GFI. First, the device is still in the prototype stage, and

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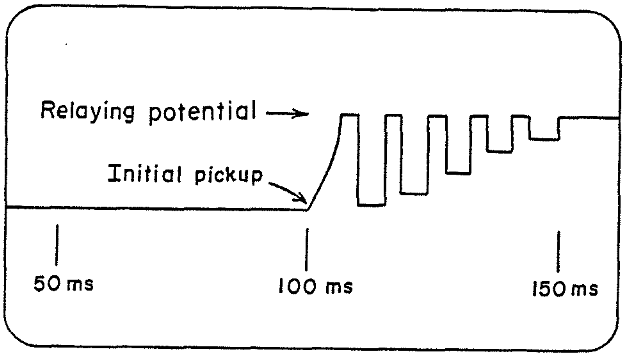

Figure 43. Oscilloscope trace of contact bounce of Pump Monotron relay.

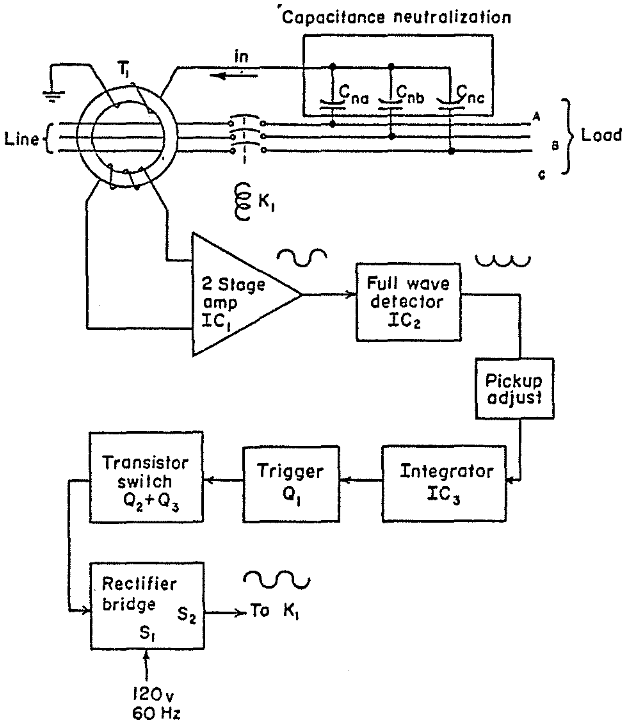

Figure 44. Block diagram of Gross prototype.

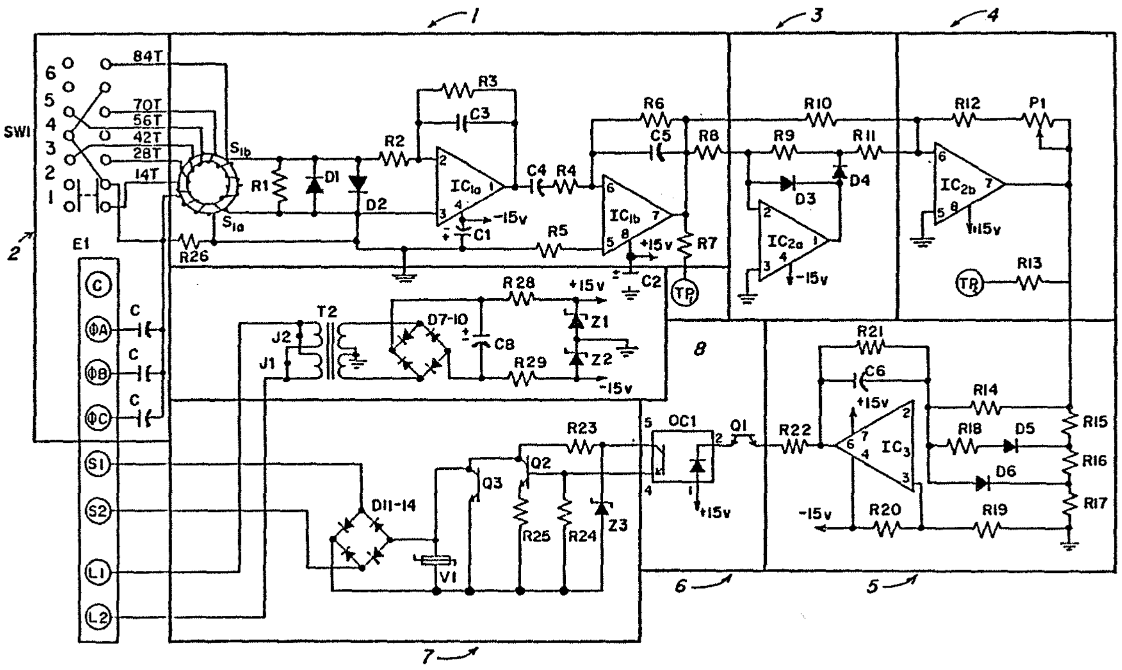

Figure 45. Schematic of Gross prototype.

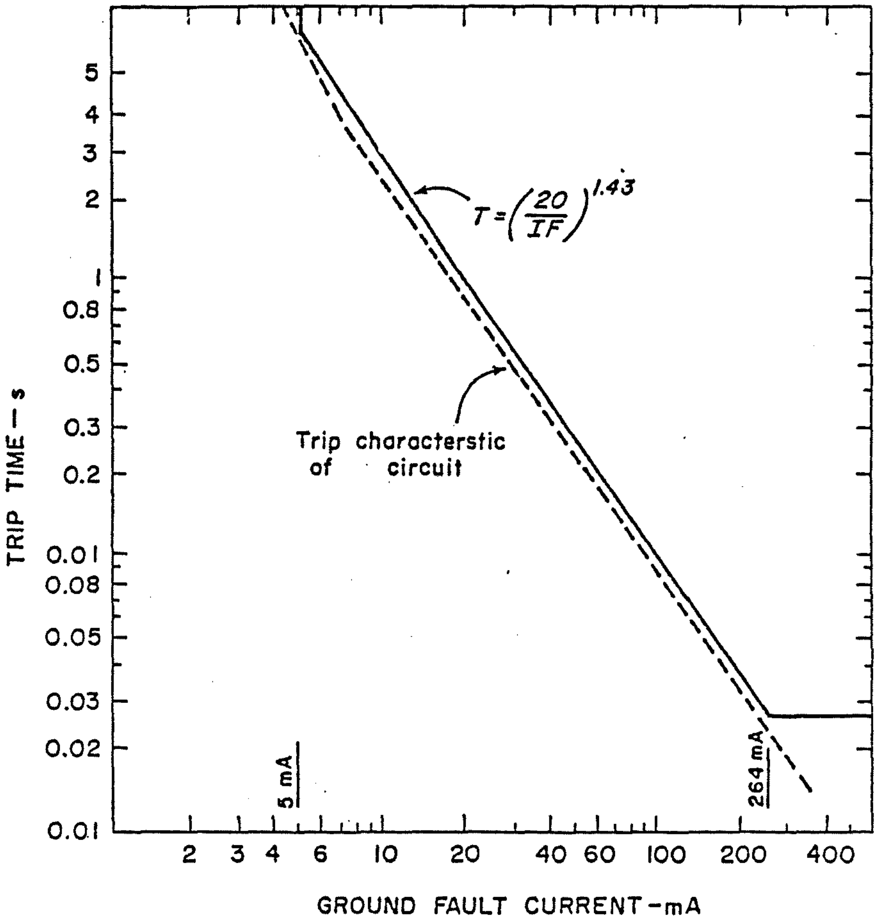

Figure 46. Circuit modeling of UL Standard 943 for ground-fault circuit-interrupter trip characteristics.

as such, no license for manufacture has been granted. Another problem is the trip signal. At pickup, the control voltage is switched from the trip terminals, but some residual voltage remains and may present a problem for some undervoltage-release breakers. Finally, the current transformer of the prototype is too small (less than one-inch inside diameter), but this problem could be easily remedied.

Regardless, by application of standards recommended in this report, it is felt that this sensitive GFI could be modified (perhaps rather easily) to meet the needs of the mining industry.

General Electric* Ground Break. The Ground-Break* system was originally designed for equipment protection only, and the lowest level of pickup was initially 500 mA. During the course of this research, and following a conversation with the head of GE's Circuit Protective Devices Division* [46], a more sensitive current transformer was designed and manufactured. The pickup level of the device was reduced to 100 mA. While not as low as Dalziel's suggested fibrillation level, the GFI performed well under most preliminary test conditions. The advantages and disadvantages of this device will be discussed later.

Sensitive Earth Leakage. The SEL system has already been described in Chapter III. It also performed well during preliminary testing, and the characteristics will be highlighted in the next report section.

Detailed Test Results

Detailed results of the tests run on the four remaining GFIs (the Monotron Model* 445 is excluded) are presented in this section. For each test, all devices will be compared with the desired characteristics outlined in Chapter IV. Not all devices were tested for each characteristic, and reasons for these discrepancies will be explained as each test is outlined.

Test 1. Federal-Regulations Compliance. All four devices tested comply with the applicable federal regulations. The devices perform the function of protection against a grounded phase. For a ground-current limit of 500 mA, MSHA's Inspector's Manual [35] recommends pickup at not less that 250 mA (50% of the limit), and all device pickup levels are lower. Finally, all devices can be powered phase-to-phase through an appropriate control transformer.

Test 2. Military Standard 454 Compliance. The specific regulations applicable to sensitive GFIs are included in Appendix I.

Pump Monotron*. Safety guarding to protect against contact with control power is required but not included on the Pump Monotron*. The electromechanical relay on the circuit board should be interchangeable, which it is not.

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Gross* Prototype. This device is presently unacceptable as is but is still in the design stage and not ready for industrial use. The circuitry must be enclosed and the current transformer removed from the circuit board.

GE* Ground Break. This device conforms to all requirements of Appendix I.

Sensitive Earth Leakage. Safety guarding for control power connections is required. The CT connectors are constructed such that moisture buildup could be a problem.

Test 3. Current Withstand. Because of the possible destructive nature, the current-withstand test was not conducted. Any device with rating greater than 24,000 A should be accepted. The GE* relay is the device that had a specified rating, being at 100,000 A.

Test 4. Proper Dimension, CT and Relay. Relay circuitry was small enough in all cases to be considered properly dimensioned, but current-transformer inside diameters (ID) were usually undersized. The Pump Monotron* has a 1.8 in. ID, a little small for mining application, and the Gross* Prototype uses a 1.0 in. ID which is too small. The General Electric Ground Break* is properly sized at 2.1 in. ID. (However, direct modification for common-mode rejection, to be discussed later, will result in too small of an inner diameter). The SEL is also properly sized (2.1 in. ID).

Test 5. Time versus Current. Results of this test are graphed individually and together for comparison (Figures 47 through 51) and show:

1. actual time versus current points and curve obtained;
2. a parallel curve 32 ms above this curve, indicating the addition of circuit-breaker clearing time (for molded case); and
3. Dalziel's electrocution curve.

Figure 50 actually contains two sets of curves. The first is for the SEL that was obtained from the manufacturer under terms of Bureau of Mines Contract J0199106 with The Pennsylvania State University. The second shows the performance for the SELs procured for this research and relates a substantial increase in sensitivity and decrease in operating time.

Curve values to the right of Dalziel's curve indicate conditions that may lead to ventricular fibrillation and electrocution. It should be noted that for a 500-mA ground-fault current limit, the maximum current through a body resistance of 1000 Ω is less than 250 mA. Therefore, the position of the curve for values above 250 mA, is not significant. The final plot of curves (Figure 51) compares the results with circuit-clearing time added for each GFI, with Dalziel's.

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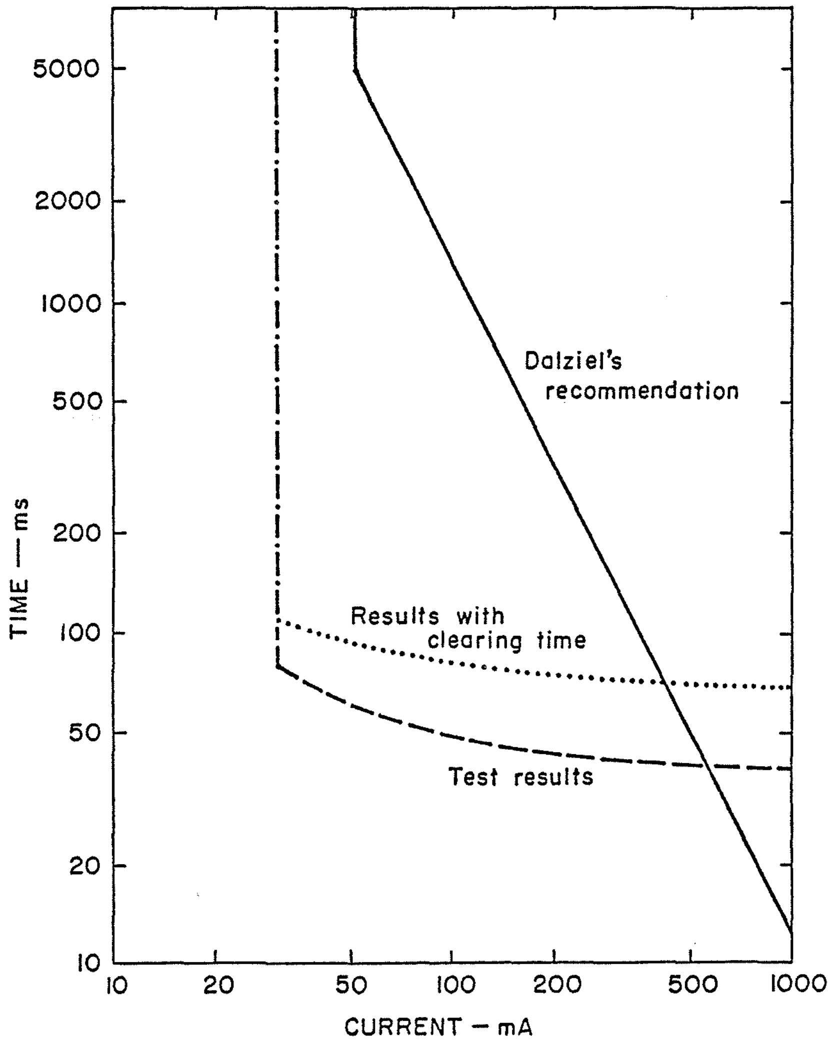

Figure 47. Pump-Monotron time-current characteristic.

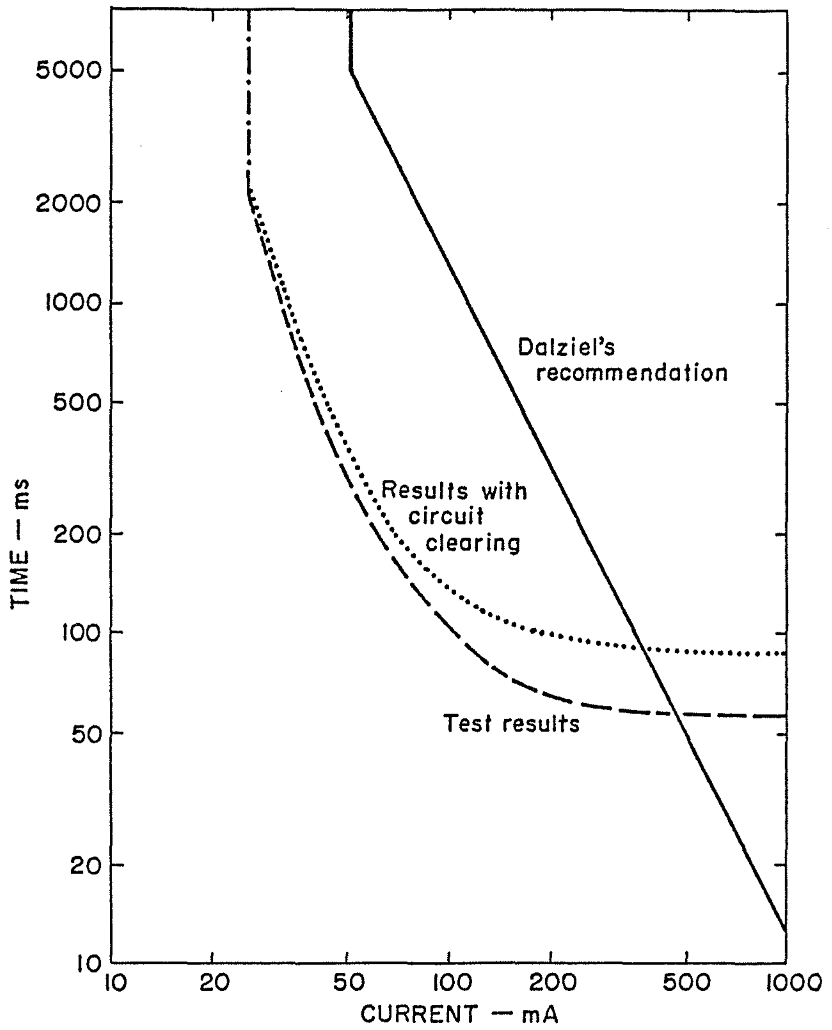

Figure 48. Gross-prototype time-current characteristic.

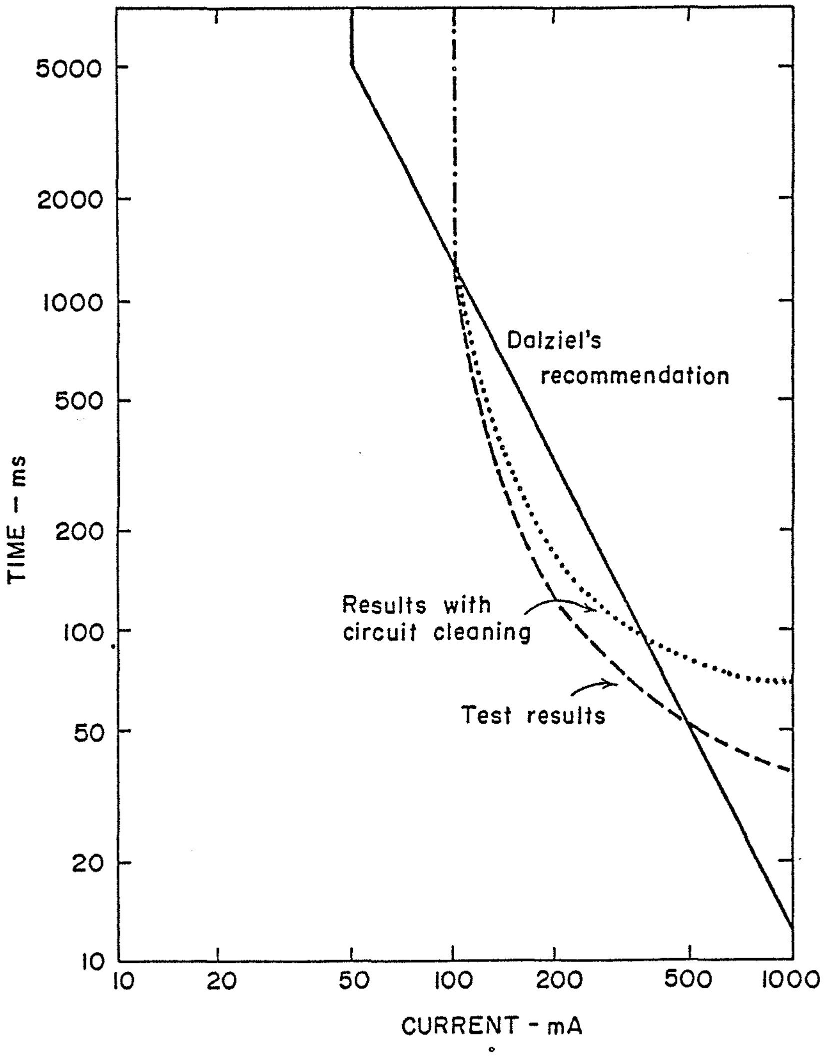

Figure 49. General-Electric Ground Break time-current characteristic.

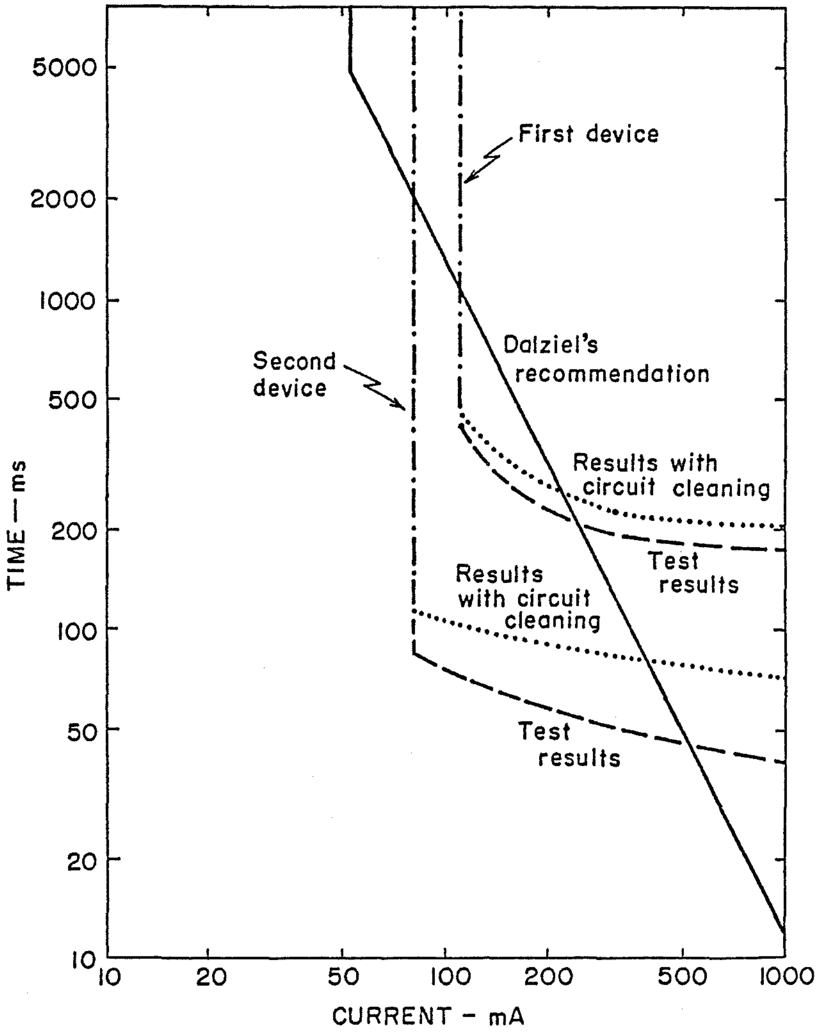

Figure 50. Sensitive-Earth-Leakage time-current characteristic.

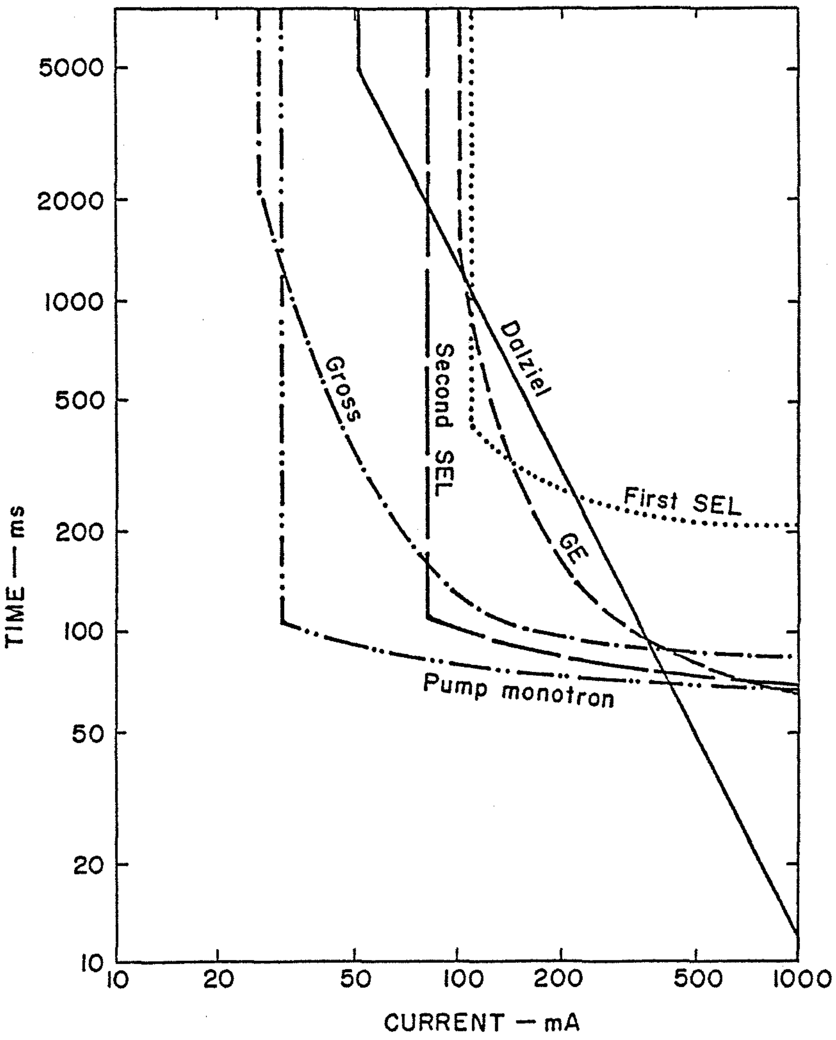

Figure 51. Circuit-interrupt time of each ground-fault interrupter.

Test 6. Transient Immunity. The lack of a properly sized transient generator precluded any transient testing. Also, it was felt unnecessary to perform this test since this report is primarily concerned with shock prevention.

Test 7. Common-Mode Rejection. The trip levels for each device from the common-mode test are shown in Table 6. In the case of an added fluxaliner, the trip level is shown to the right of the original value. Low-permeability steel tubing (12-in. long) was used as a fluxaliner. The Gross* Prototype could not be tested because of its small CT window.

Test 8. High Frequency. The results of this test are graphed together along with the allowable current attenuation with frequency curve in Figure 52. Filtering in the Gross* and SEL devices may allow fibrillation, due to high attenuation of high-frequency fault currents. The GE Ground Break* has no filtering, producing an essentially flat frequency-response curve.

Test 9. Reliability. A research objective was to procure five additional devices for those sensitive GFIs that looked promising for application in the mining industry. Because of previously stated objections, the Pump Monotron* was eliminated. The Gross* Prototype was in development, and additional devices could not be obtained. Only four SELs were found available in the United States, but all GE Ground-Breaks* were purchased. The tests conducted on the five SELs and six General Electric* devices indicated a reasonable degree of reliability. For instance, all devices from GE showed similar dimensions and quality of construction. All visual inspection tests or conformance tests gave the same results. Only tests with some quantification of results indicated any discrepancy. The results of these tests, time-current, high-frequency, and common-mode, are given in Appendix II.

As mentioned earlier, the SEL device obtained under Contract J0199106 performed differently from the additional devices obtained here. The newer devices had lower pickup, shorter operating time, and less attenuation of

Table 6. Common-mode trip currents.

	Common Mode Trip Currents
Pump Monotron	1100 A (>2500 A)**
GE Ground Break	1200 A (>2500 A)
SEL	>2500 A

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** >2500 A means the device did not trip at the maximum limit for trailing-cable currents. Currents above this level were not applied.

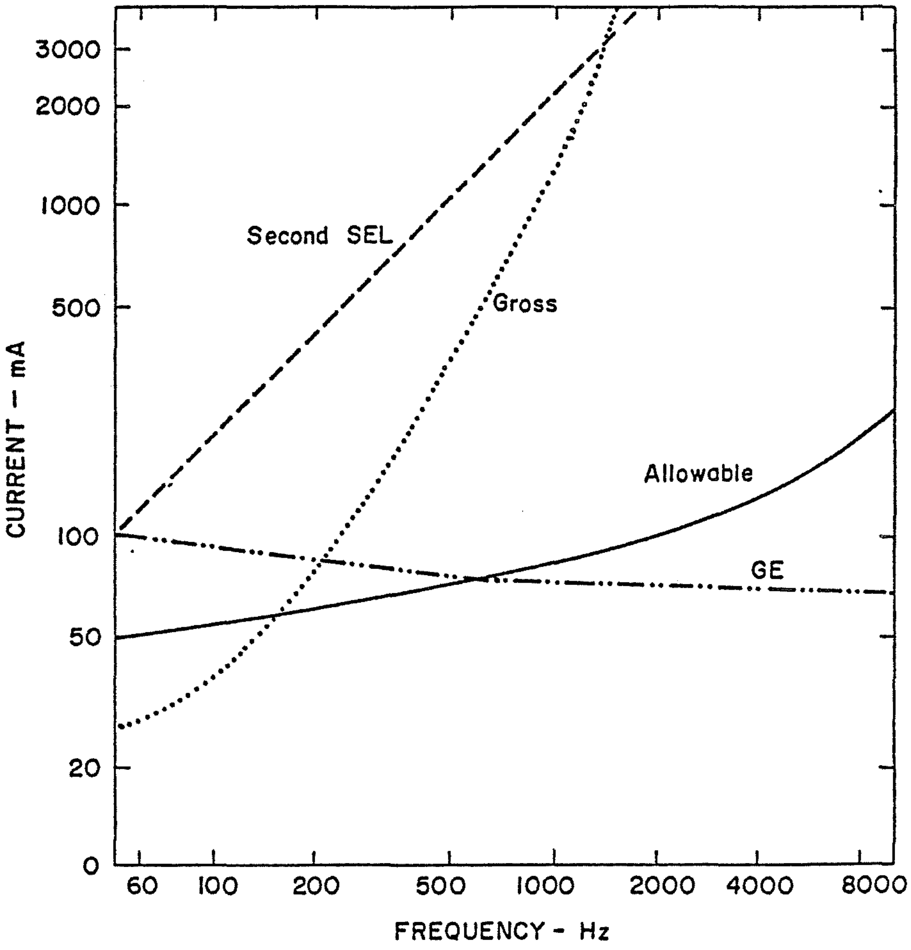

Figure 52. Frequency response of GFIs and allowable response curve.

high frequencies. Furthermore, tests on the four additional units indicated a very high degree of correlation and reliability. The only difference in values was in pickup times at pickup levels less than 150% of rated pickup.

The GE* time-current, high-frequency, and common-mode test results are also shown in Appendix II. Once again, these devices were all identical in terms of visual inspection or tests for conformance. The time-current test gives close results for pickup times when current was in excess of 150% of rated pickup current. Below this value, larger discrepancies existed. The frequency response and reaction to common-mode currents were identical.

The only problem with reliability testing of the GE* devices arose with one device. Here, the contacts stuck, and it would not trip unless tapped or vibrated. Examination of the contacts revealed a likely cause. The normally open contacts are held open by a plastic lip hooked over a restraining edge. Exact tolerances must be maintained in order for the pickup signal to flip the lip over the restraining edge. A more suitable contact arrangement might be considered.

Test 10. Simulated Fault. A test circuit for simulating fault conditions was found on the GE* and SEL devices only. The circuit of the GE* device is internal, while the SEL device requires a momentary contact pushbutton switch. The other two devices lack any test circuit but could easily be modified.

Test 11. Loss of Control Power. When control power is removed from the GFI, the device should act to the circuit interrupting device. Table 7 shows the results of the test. Only the GE* device would not react when control power was removed.

Table 7. Loss of control power test results.

GFI	RELAY PICKUP
Pump Monotron	Yes
Gross Prototype	Yes
GE Ground Break	No
SEL	Yes

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Test 12. Mine-Duty Rated. The GE device is appropriately designed for mine duty. Rugged casing of both CT and relay assure good protection. The mounting plates and wiring terminal are also rugged and sized to handle mine-sized fasteners and tools. The Pump Monotron* is well protected except for the electromagnetic relay. Wiring terminals are correctly sized, but the device lacks any means of mounting to mine power equipment. The SEL device is lightly constructed with very small terminal strips, and the relay casing has no means of attachment. The Gross Prototype is presently inadequate for mine duty as expected.

Summary

The results of testing sensitive GFIs are categorized in Table 8 and show the SEL and GE* devices performing most acceptably according to the test developed. Either one of these two devices may be modified and used as a sensitive GFI in the mining industry.

Modifications to the SEL device are necessary for compliance to Tests 1, 4, 8, and 12. Solid construction of the SEL would enable it to pass Tests 1 and 12. A different filter design would modify the SEL to pass Test 8.

Modifications to the GE* device are necessary to pass Tests 3, 4, 7, and 10. Expanding the CT inner diameter and adding a fluxaliner would result in a compliance with Tests 3 and 7. Modification of relay contacts to allow the device to trip through loss of control power would pass Test 10.

The other two devices, Gross* Prototype and Pump Monotron*, need many modifications before they could be applied as a mining GFI. The Monotron* device is not considered acceptable for mine duty.

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Table 8. Sensitive GFI test results.

Test	No.	Pump Monotron*	Gross* Prototype	GE Ground Break*	SEL
MIL Compliance	1	No Guarding No Interchangeability	No Compliance	Accept	No Guarding Moisture Buildup
CFR Compliance	2	Accept	Accept	Accept	Accept
Sizing	3	Small CT	Small CT	Small CT[1]	Accept
Time Current	4	Too Sensitive[2]	Too Sensitive[2]	Too Sensitive[3]	Close[3]
Common Mode	7	Needs Fluxaliner	No Test	Needs Fluxaliner	Accept
High Frequency	8	----	Too Much Attenuation	Accept	Too Much Attenuation
Reliability	9	----	----	Accept[4]	Varied[5]
Loss of Control Power	10	Accept	Accept	No	Accept
Simulated Fault	11	No	No	Accept	Accept
Mine Duty	12	Modify	No	Accept	Modify

1 - Size is acceptable, but shielding will reduce to unacceptable levels.
2 - Trip levels way below necessary and in ambient stray current range.
3 - Second unit very close to desired levels, pickup needs to be lowered to 50 mA.
4 - One bad device.
5 - The four additional SELs were repetitive
* - See footnote in text.

CHAPTER VI

CONCLUSIONS

This report contains the results of an extensive investigation into the possible use of sensitive GFIs for U.S. mining utilization circuitry. During the course of the research, six problems peculiar to sensitive GFIs were uncovered and solutions recommended. Test development resulted in seven desirable qualities for sensitive GFIs. These desirable qualities led to formulation of 12 tests by which an acceptable GFI may be recognized. A compaction of the tests and test levels is presented in Appendix III as suggested standards for sensitive GFIs.

Several devices that approach sensitive GFI specifications were obtained. The testing indicates that:

1. the recommended guidelines and accompanying tests are feasible as at least one sensitive GFI passed each test, and
2. some available devices come very close to complete conformance with the recommendations, while others could be modified for widespread mine usage.

Recommendations for Future Research

As research progressed, it became apparent that the technology for sensitive-GFI application to mining exists now. The following suggested course of future research could enhance implementation.

1. With consultation from manufacturers, at least one device evaluated under this contract should be modified to meet all recommended guidelines. Otherwise, a new sensitive GFI should be constructed.
2. Upon device assembly and packaging for mine duty, in-mine testing with 500-mA ground-current limiting should be undertaken in several different environments for final confirmation that the suggested standards are practical.
3. Following successful implementation of the modified GFI for ac utilization, research should be undertaken to see if the sensitive-GFI benefits can be extended to high-voltage distribution. One possibility here might be to use sensitive GFIs in conjunction with coordination-free ground-fault protection as developed at The Pennsylvania State University [48].

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APPENDIX I

EXTRACTION OF PORTIONS OF MILITARY STANDARD 454 - GENERAL REQUIREMENTS FOR ELECTRONIC INSTRUMENTATION FOR SENSITIVE GFIs

Requirement 1 - Safety (Personal Hazard)

Purpose. This requirement establishes criteria for the design and development of military electronic equipment to promote maximum safety for personnel and equipment.

General Considerations. The design and development of all military electronic equipment shall provide fail-safe features for safety of personnel during the installation, operation, maintenance, and repair or interchanging of a complete equipment assembly or component parts thereof. Equipment design for personnel safety shall be equal to or better than the appropriate requirements of the Occupational Safety and Health Act (OSHA) as identified in Title 29, Part 1910, of the Code of Federal Regulations.

Electrical. The design shall incorporate methods to protect personnel from accidental contact with voltages in excess of 30-V rms or dc during normal operation of a complete equipment. Means shall be provided so that power may be cut off while installing, replacing, or interchanging a complete equipment, assembly, or part thereof. Personnel shall be protected from capacitor discharges and when changing fuses to tubes. The main power ON-OFF switch located on the equipment (clearly labeled as such) shall cut off all power to the complete equipment. The power input side of the switch and the incoming power line connections shall be given physical protection against accidental contact.

Ground Potential. The design and construction of the equipment shall insure that all external parts, surfaces, and shields, exclusive of antenna and transmission-line terminals, are at ground potential at all times during normal operation. The design shall include consideation of ground faults and voltage limits established on a basis of hazardous location. Any external or interconnecting cable, where a ground is part of the circuit, shall carry a ground wire in the cable terminated at both ends in the same manner as the other conductors. In no case, except with coaxial cables, shall the shield be depended upon for a current-carrying ground potential, except for radio frequency (rf) energy on their external surfaces. Plugs and convenience outlets for use with metal-cased portable tools and equipment shall have provisions for automatically grounding the metal frame or case of tools and equipment when the plug is mated with receptacle, and the grounding pin shall make first, break last.

Grounding. Ground connections to shields, hinges, and other mechanical parts shall not be made to complete electrical circuits. A point on the electrically conductive chassis or equipment frame shall serve as the common tie point for the static ground, power ground and, when applicable, airborne return leads. The path from the tie point to ground shall:

1. be continuous and permanent,
2. have ample carrying capacity to conduct safely and fault currents that may be imposed upon it,
3. have impedance sufficiently low to limit the potential above ground and to facilitate the operation of the overcurrent. devices in the circuits (unused wires installed in lines (conduit or cables) shall be grounded to allow for stray or static electricity discharge), and
4. have sufficient mechanical strength of the material to minimize possibility of ground disconnection.

Grounding to Chassis. Ground connection to an electrically conductive chassis or frame shall be mechanically secured by soldering to a spotwelded terminal lug or to a portion of the chassis or frame that has been formed into a soldering lug, or by use of a terminal on the grounding conductor and then securing the terminal by a screw, nut, and lockwasher. The screw shall fit in a tapped hole in the chassis or frame or it shall be held in a through-hole by a nut. When the chassis or frame is made of steel, the metal around the screw hold shall be plated to tinned to provide a corrosion-resistant connection. When aluminum or aluminum alloys are used, the metal around the grounding screw or bolt hold may be covered with a corrosion-resistant surface film only if the resistance through the film is not more than 0.002 Ω..

Guards and Barriers. All contacts, terminals and like devices having voltages between 70- and 500-V rms or dc with respect to ground shall be guarded from accidental contact by personnel if such points are exposed to contact during direct support or operator maintenance. Test probe holes may be provided in the barriers or guards where maintenance testing is required.

Permanent Terminations. Terminations such as soldered connections to transformers, connectors, splices, etc. which are normally permanent and not used during routine maintenance testing, may be protected by permanent insulation such as shrink sleeving, tubing, insulating shields, etc., provided the material is rated for the potential exposed voltage.

Mechanical Hazards. The design of the equipment shall be such as to provide maximum access and safety to personnel while installing, operating, and maintaining the equipment. Suitable protection shall be provided to prevent contact with moving mechanical parts such as gears, fans, and belts when the equipment is complete and operating. Sharp projections on cabinets, doors, and similar parts shall be avoided. Doors or hinged covers shall be rounded at the corners. Doors, hinged covers, and rack-mounted equipment shall be provided with stops to hold them in each operating and maintenance configuration. Equipment design shall include provisions to prevent accidental pulling out of drawers or rack mounted equipment components which could cause equipment damage and injury to personnel. Equipment power switches shall be so designed and located that accidental contact by personnel will not place equipment in operation.

Signs. Danger, caution, etc., signs shall be used in accordance with ANSI 235.1-1982 to warn of specific hazards such as voltage, current, thermal, physical, etc. The markings shall be as permanent as the normal life expectancy of the equipment on which they are affixed.

Requirement - Soldering

Purpose. This requirement establishes procedures for making soldered electrical and electronic connections, as well as preparation of conductors and terminals.

Stripping Insulation. Sufficient insulation shall be stripped from the wire or leads to provide for insulation clearances as specified in the insulation clearance section of the following page. In stripping insulation, care should be taken to avoid nicking or otherwise damaging the wire or the remaining insulation. The number of damaged or severed strands in a single lead shall not exceed the limits given in Table 9. Insulation discoloration resulting from thermal stripping is permissible.

Wire and Lead Wrap-Around. Leads and conductors shall be mechanically secured to their terminals before soldering. Such mechanical securing shall prevent motion between the parts of a joint during the soldering operation. Leads and conductors shall be wrapped around terminals for a minimum of one-half and not more than one full turn in a single layer only. For AWG 30 or smaller wire, a maximum of 3 turns may be used. Exception is made in the case of those small parts used to terminating conductors and to which such mechanical securing would be impracticable, such as connector solder cups, slotted terminal posts, heat shrinkable solder devices, etc. Lead extension shall be restricted to the limits required by design to prevent equipment malfunction. In no case shall conductors be wrapped on each other.

Table 9. Broken strand limits.

Number of strands	Maximum allowable nicked or broken strands
Less than 7	0
7 - 15	1
16 - 18	2
19 - 25	3
26 - 36	4
37 - 40	5
41 or more	6

Lead bends. The distance between the body of the part or weld and the bent section of a lead shall be at least twice the diameter of the lead but not less than 0.030 in. (Figure 53).

Insulation clearance. Clearance between the end of the insulation and the solder of the connection shall be as follows.

a. Minimum clearance: The insulation shall not be imbedded in the solder joint. The contour of the conductor shall not be obscured at the termination end of the insulation.
b. Maximum clearance: Clearance shall be less than two conductor diameters (including insulation) or 0.060 inch, whichever is larger, but shall not permit shorting between adjacent conductors.

Resoldering. The automatic soldering operation may be repeated once, provided that the reheating and resoldering does not introduce degradation of parts or printed wiring boards.

Flux residue removal. Flux residues shall be removed within one hour after soldering by applying noncorrosive solvents and drying. Mechanical means such as agitation, brushing, etc., may be used in conjunction with the solvents. The cleaning solvents and methods used shall have no deleterious effect on the parts, connections, and materials being cleaned. Ultrasonic cleaning may damage certain parts, particularly transistors, and should generally be avoided.

Workmanship. Workmanship shall be of the level of quality adequate to assure that the processed products meet the performance requirements of the applicable drawings and criteria delineated herein. The soldered connections shall have a smooth bright appearance with metallic luster and shall not have a chalky, gritty or irregular surface, not exhibit protrusions, pits, or voids which expose basis metal or where the bottom of the pit or void is not visible.

Inspection. Visual inspection of all soldered connections and assemblies shall be performed to determine conformance to the requirements specified herein.

Accept/reject criteria. Accept/reject criteria for soldered connections shall be in accordance with Figures 54 through 60.

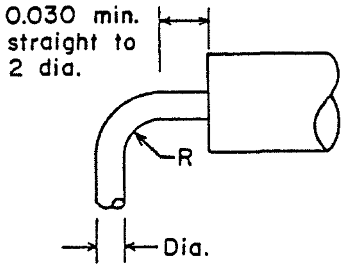


Figure 53. Lead bends.

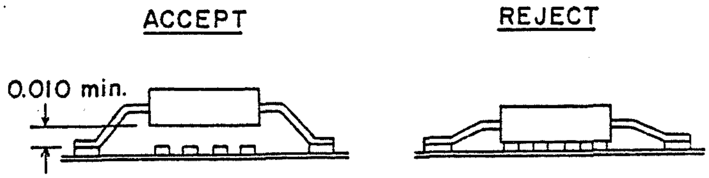


Figure 54. Planar mounted devices - lead forming.

Parts mounted over protected surfaces, or surfaces without exposed circuitry, may be mounted flush. Parts with electrically conducting bodies over exposed circuitry shall have their leads formed to allow a minimum of .010 inch between the bottom of the component body and the exposed circuitry.

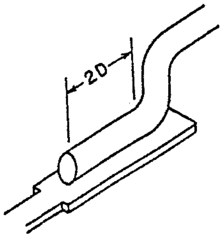


Figure 55. Planar mounted devices - part placement.

Minimum contact length shall be equal to the lead width for flat leads and two times the diameter (2D) for round leads. Heel must be completely over pad area.

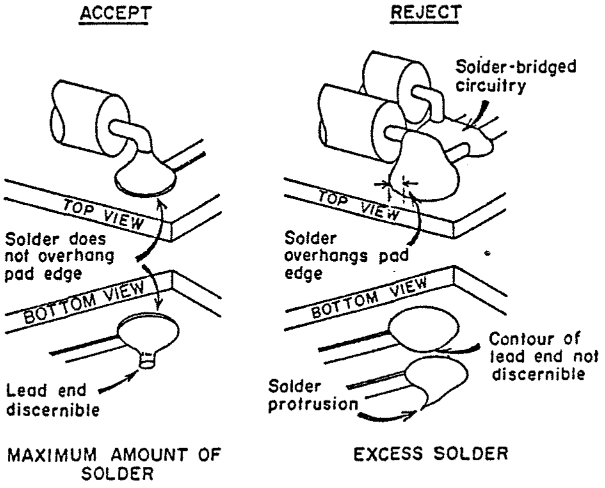
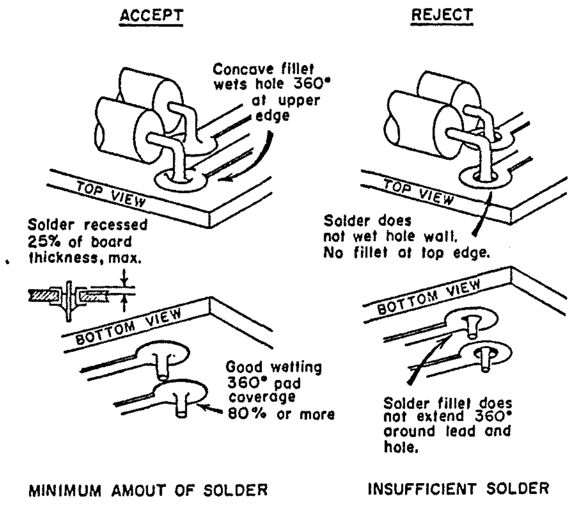


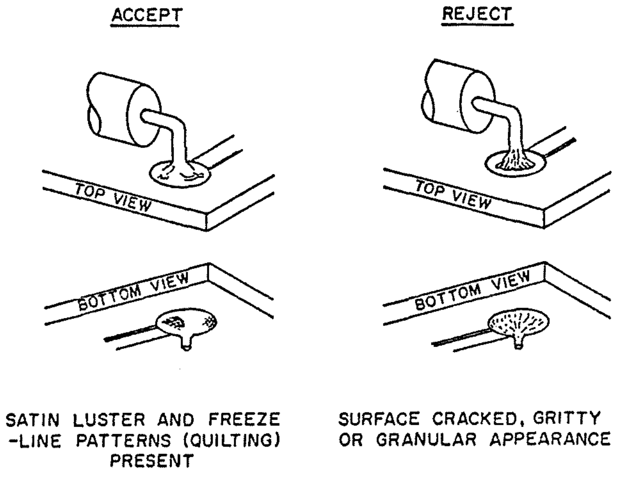
Figure 56. Plated-thru holes - amount of solder on joint.



MINIMUM AMOUT OF SOLDER

INSUFFICIENT SOLDER

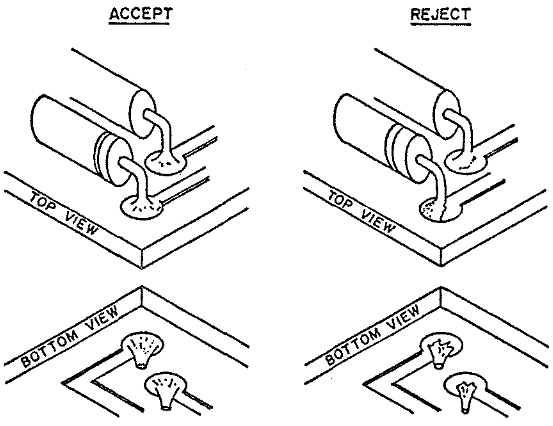
Figure 57. Plated-thru holes - amount of solder of joint.



SATIN LUSTER AND FREEZE -LINE PATTERNS (QUILTING) PRESENT

SURFACE CRACKED, GRITTY OR GRANULAR APPEARANCE

Figure 58. Plated-thru holes - solder surface characteristics.

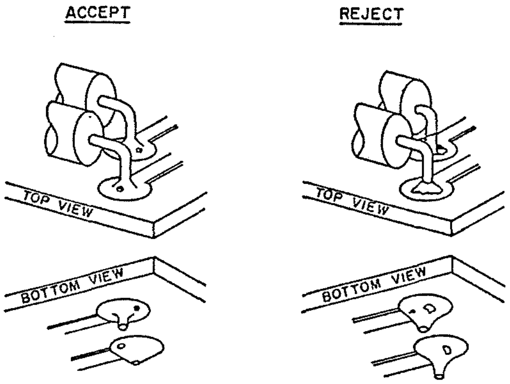


SMALL INCLUSION IN FILLET DOES NOT CONSTITUTE DEWETTING. SURROUNDING AREAS WELL WETTED.

FILLET MAY BE CONCENTRATED ON ONE SIDE OF PAD. NO DEWETTING IS IN EVIDENCE.

SOLDER DOES NOT COMPLETELY COVER SURFACES OR DOES NOT FEATHER TO LEAD OR PAD SURFACES. SOLDER GATHERS INTO DROPLETS OR BALLS.

Figure 59. Plated-thru holes - solder wetting.



BOTTOM OF VOIDS VISIBLE

BOTTOM OF VOIDS NOT VISIBLE

Figure 60. Plated-thru holes - voids

Requirement 9 - Workmanship

Purpose. This requirement establishes the acceptable workmanship criteria for electronic equipment intended for use by the Department of Defense. This requirement will define those workmanship requirements not normally covered in subsidiary specifications or drawings. It is not intended to supersede any of the provisions of the contract or applicable specifications and drawings considered a part of the contract. Where actual conflict exists, the provisions of the contract or application specification of drawing shall take precedence over the requirement herein.

General. Workmanship shall be in accordance with the requirements herein and any requirement of the detail equipment specification applicable to soldering, marking of parts and assemblies, wiring, welding and brazing, plating, riveting, finishes, machine operations, screw assemblies, and freedom of parts from burrs, sharp edges, or any other damage or defect that could make the part (or equipment) unsatisfactory for the purpose intended.

Mounting of Parts. Parts of hardware shall be assembled and secured or mounted in the specified manner to satisfactorily accomplish the purpose for which intended. Electronic equipment having missing, inoperative, defective, bent, broken, or otherwise damaged parts will not be acceptable.

Cleaning. After fabrication, parts and assembled equipment shall be cleaned of smudges; loose, spattered, or excess solder; weld metal; metal chips and mold-release agents or any other foreign material which might detract from the intended operation, function, or appearance of the equipment. (This would include any particles that could loosen or become dislodged during the normal expected life of the equipment.) All corrosive material shall be removed. Whenever possible, this cleaning shall take place before the parts are assembled into the equipment. All assembled equipment shall be cleaned of contaminants such as lubricating oils, mold-release agents, waxes, sand, corrosion products, solder fluxes, finger prints, dust, etc. The nature of the contaminant must be determined to the extent that a suitable cleaning solvent can be selected for item removal. The inertness of the materials of construction to the solvent must be determined to prevent damage to electrical and mechanical properties. After cleaning, moving parts should be relubricated and the assembly allowed to dry to remove trapped or soaked cleaning fluid. Cleaning processes shall have no deleterious effect on the equipment or parts.

Treaded Parts or Devices. Screws, nuts, and bolts shall show no evidence of cross threading, mutilation, or detrimental or hazardous burrs.

Tightness. All screw-type fasteners shall be tight. The word tight means the screw shall be firmly secured and that there shall be no relative movement possible between the attached parts.

Riveting. The riveting operation shall be carefully performed in order to assure that rivets are tight and satisfactorily headed with the rivet heads tightly seated against their bearing surface.

Bearing Assemblies. Bearing assemblies shall be free of rust, discoloration, and imperfections of ground, honed, or lapped surfaces. Contacting surfaces shall be free of tool marks, gouge marks, nicks, or other surface-type defects. There shall be no detrimental interference, binding, or galling.

Wiring. Insulated conductors running between equipment or subassemblies within an equipment, such as between drawers or chassis and module subassemblies, shall be formed into cables or ducted wherever practicable. Conductors and cables shall be positioned or protected to avoid contact with rough or irregular surfaces and sharp edges.

Clearance. The clearance between conductors or cables and heat generating parts, such as electron tubes and resistors, shall be such as to avoid deterioration of the conductors or cables from the heat dissipated by these parts under the specified service conditions of the equipment.

Requirement 10 - Electrical Connections

Purpose. This requirement establishes criteria for the selection and use of electrical connectors.

Connector Wiring. Not more than one conductor shall be routed through any hole in the grommet of an environmentally sealed connector. Multiple conductors may terminate in a contact provided the sum of the circular-mil areas of the conductors does not exceed the maximum circular-mil area for which the contact is rated.

Protective Measures. All unmated connectors shall be protected with metal or plastic caps of otherwise suitably protected during maintenance, storage, and shipment. Protective caps specified by military specifications or military standards and designed for mating with specific connectors shall be used. Unmated connectors which may contain electrically "hot" circuits while in environmentally hazardous areas shall be covered with moisture-proof and vapor-proof caps. Connectors on enclosed cabinet-mounted equipment need not be provided with protective caps unless an environmental hazard exists.

Requirement 16 - Dissimilar Metals

Purpose. This requirement establishes criteria for the selection and protection of dissimilar metal combinations and other significant corrosion behavior factors.

Selection and Application. Where electronic design requirements preclude the insulation of incompatible metal combinations from one another, specific attention should be paid to isolating the combination from exterior environments.

Requirement 31 - Moisture Pockets

Purpose. This requirement establishes criteria for the treatment and drainage of moisture pockets.

Pockets, wells, traps, and the like in which water or condensate could collect when the equipment is in normal position shall be avoided where practicable.

Where moisture pockets are unavoidable and the equipment is not sealed, provision shall be made for drainage of such pockets. Desiccants or moisture-absorbent materials shall not be used within moisture pockets.

Where moisture buildup cannot be tolerated in sealed equipment or assemblies such as waveguides, the use of desiccants or other methods, such as gas purging, should be considered.

Requirement 36 - Accessibility

Purpose. This requirement establishes criteria for accessibility.

Compatibility. Equipment shall be designed for optimum accessibility compatible with operating, maintenance, electromagnetic compatibility, and enclosure requirements.

Access. Each article of equipment and each major subassembly forming a part thereof shall provide for the necessary access to its interior parts, terminals, and wiring for adjustments, required circuit checking, and the removal and replacement of maintenance parts. Accessibility for testing and replacement does not apply to parts located in nonrepairable subassemblies or assemblies. For routine servicing and maintenance, unsoldering of wires, wire harnesses, parts or assemblies shall not be required in order to gain access to terminals, soldered connections, mounting screws, and the like.

Connections. Connections to parts inside a removable container shall be arranged to permit removal of the container without threading connection leads through the container.

Parts. Parts which are identified as replaceable parts for the equipment shall be easily removable and replaceable. These parts shall not be mounted by means of rivets, spot welding, or hard curing compounds. If, in order to check or remove a part, it is necessary to displace some other part, the latter part shall, whenever practicable, be so wired and mounted that it can be moved without being disconnected and without causing circuit detuning or instability. No unsoldering or soldering of connections shall be necessary when the front panel or any subchassis is removed for maintenance purposes. Design shall be such that where plug-in modules or assemblies are used, they can be easily inserted in the proper location when correctly oriented without damage to equipment or parts being engaged. Plug-in modules and assemblies shall be designed to prevent insertion when incorrectly oriented.

APPENDIX II

RELIABILITY-TEST RESULTS

Sensitive-Earth-Leakage GFIs

Table 10. Pickup time versus current.

Current (mA)	Time (ms)				
	First SEL	Additional Devices			
		# 1	# 2	# 3	# 4
80	---	80	150	---	---
90	---	80	125	120	---
100	---	80	100	115	120
120	420	70	100	95	100
150	280	55	80	85	90
170	260	50	80	85	80
200	230	60	85	80	70
250	230	50	70	65	60
300	220	60	60	65	65
400	210	60	70	70	70
600	200	40	60	60	70
1000	175	50	65	70	70
1300	---	45	60	70	70

Table 11. Frequency versus pickup current.

Frequency (Hz)	Current (mA times 15 secondary turns)				
	First SEL	Additional Devices			
		# 1	# 2	# 3	# 4
60	7.2	4.3	4.1	5.3	4.8
80	10.4	7.5	6.3	7.5	6.9
100	13.4	9.3	8.0	9.5	8.9
120	15.6	11.1	9.8	11.7	10.5
160	22.1	15.1	13.8	16.8	15.0
200	27.6	19.3	17.5	22.3	19.2
300	41.6	29.2	26.8	33.8	29.5
500	70.0	49.8	45.9	57	50.9
800	113.5	79.5	72.0	92.0	82.0
1000	142.0	99.0	91.0	116.0	102.0
1.2k	185.6	120.0	113.5	138.0	125.0
1.4k	203.0	142.0	131.0	163.0	147.0

SEL Common-Mode Test - All devices did not trip with 2500 A of common-mode current.

General Electric GFIs*

Table 12. Pickup time versus current.

Current (mA)	Time (ms)					
	1	2	3	4	5	6
100	1300	2500	CONTACTS STICK	600	1600	2000
120	440	800		420	500	450
150	280	800		280	300	300
200	150	400		100	120	140
300	75	100		50	40	40
400	70	75		30	30	40
500	60	75		30	30	40
750	50	40		35	30	30
1000	35	20		25	30	30

Table 13. Frequency versus pickup current.

Frequency (Hz)	Current (mA times 5 secondary turns)					
	1	2	3	4	5	6
40	22	25	CONTACTS STICK	21	20.5	22.0
60	22	22		22	22	20.4
600	14.8	16		13.6	13	14.7
6k	14.2	16		14	14.5	14.9
60k	23	23		23	23	23.5

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* Reference to specific brands, equipment, or trade names in this report is made to facilitate understanding and does not imply endorsement by the Bureau of Mines nor The Pennsylvania State University.

Table 14. Common-mode current-pickup levels.

	Trip Level (A)					
	1	2	3	4	5	6
No Fluxaliner	1200	1050	920	None[2]	1150	500
Fluxaliner[1]	None[2]	None	None	None	None	None

[1] A low-permeability steel pipe was used.

[2] None means that no trip a 2500 A.

APPENDIX III

SUGGESTED STANDARDS FOR SENSITIVE GFIs IN MINING

Scope

Use. These recommendations cover sensitive ground-fault sensing and relaying equipment (GFI) for use in mining utilization circuits. For these recommendations, a mining utilization circuit may be defined as a high-resistance grounded, three-phase, four-wire circuit.

Operation. These devices should operate at predetermined values to cause a disconnecting device to open all three ungrounded conductors. The disconnecting device may be either shunt-trip or undervoltage controlled.

Exceptions. These recommendations do not cover high-voltage (greater that 1000 V), single-phase, or direct-current ground-fault sensing and relaying equipment.

Construction

General. The design, workmanship, and degree of production uniformity should be such that the reliability of the sensitive ground-fault sensing-and-relaying equipment to perform functions evaluated by these recommendations in high.

Frames and Enclosures. The GFI should be formed and assembled to withstand abuses, to which it may be subjected, without affecting spacing, insulation, ground-fault performance, or grounding to the extent that the device fails to comply with these recommendations. Burrs, sharp edges, or any damages or defects that could result in device malfunction of injury to maintenance personnel are unacceptable.

Impact Resistance. The GFI may be dropped prior to its installation in the mine power equipment. The "drop" test of MIL STD 810 [37] recommends a drop height of 36 in. for permanently mounted electronic equipment weighing less than 40 pounds. This height will be used for three drops onto a hardwood surface. The GFI may show minor failure points, such as terminal-strip cracks, but should operate correctly.

Corrosion Resistance. Parts should be suitably protected against corrosion if failure of such parts would likely result in a hazardous condition, including failure to perform during ground faults. Metals should not be used in combination such as to cause galvanic action affecting GFI performance.

Size. The size of the GFI should be such as to facilitate mounting of the complete GFI on the removable modules in use in mine power equipment.

GFI Current Transformer. The outer dimensions of the CT should not exceed a 4-in. diameter and 3-in. width. The inner diameter of the CT sensing window should be at least 2.1 in.

GFI Relay. The outer dimensions of the GFI relay enclosure should not exceed 3 by 6 by 6 inches.

Mounting. Provisions should be made for securely mounting both the GFI current transformer and relay. A bolt or other device used to attach a component should not be used for securing the complete device. Loosening of the attaching means should be prevented by suitable lockwashers.

Grounding. All accessible parts of a GFI that can become energized should be connected together and to the grounding-conductor terminal.

CT Winding Configuration. To prevent external-flux interference, the current-transformer windings should be regressively wound. This means that the inner portion of the windings should be parallel, while the exterior portions are angled as perpendicularly as possible.

Terminals. Terminals should be capable of accommodating No. 12 AWG conductors. Solder lugs should not be used. Terminals should be clearly marked on the device.

Fault-Simulation Circuit. The GFI should be provided with a test circuit that will allow for periodic, convenient testing of the ability of the device to trip due to a ground fault. The results of the test should be made known by visual indication.

Reset. The reset operation of the GFI should be such that (1) the disconnect device cannot be reclosed until the reset operation of the GFI is performed, and (2) the GFI may not reset in the presence of a ground-fault current in excess of the device rating.

Performance

Time versus Current. A sensitive GFI for mining in conjunction with a disconnecting device should be capable of interrupting the electrical circuit when the fault current, I, is within the range of 5 to 1273 mA, within the time interval, t (including disconnect device operating time), according to the relationship.

$$t = \left(\frac{116}{I}\right)^2$$

where t is expressed is seconds and I is expressed in milliamperes. Definite-time relays should have a maximum pickup of 50 mA and a maximum operating time of 100 ms. Procedures for determining compliance with this section are found in Chapter IV.

Current Withstand. A sensitive GFI for mining should have a current-withstand rating greater than 24,000 A for 32 ms. The GFI should comply with the recommendations of this report after being subject to its rated withstand current for its rated withstand time. The test procedures are found in Chapter IV.

Transient Immunity. The GFI should be subjected to the following surges both at the control power and through the current transformer window:

1. Ten random applications of a 5-kV surge impulse at 60-intervals through the CT primary. Trip signals may not result.
2. Ten random applications of a 1-kV surge impulse at the 120-V control-power terminals. Damage to any internal component of the relay is not acceptable.

A random application is a random in phase with the 60-Hz control voltage. A 1.2x50 BIL test waveform should be developed by the surge generator under no-load conditions. The test procedure is as described in Section 19 of Underwriters' Laboratories Standard 943. An exception to this procedure is in GFI connection. The surge will pass through the CT window for the input transient test and be placed in parallel with the supply power for the control transient test.

Common-Mode Currents. The GFI should be subjected to common-mode (all phases) currents up to 2500 A. Trip signals should not be generated. Three-phase, short-circuited cables passed through the CT window should be used. The procedure for this test is detailed in Chapter IV.

High-Frequency Currents. The GFI should not attenuate zero-sequence currents of frequencies greater than specified by the following two-stage filter design. The first stage can attenuate current up to 1.0 dB per octave from 60 to 2000 Hz. The second stage can attenuate up to 3.0 dB per octave from 2000 Hz to infinity. The procedure for this test is described in Chapter IV.

Loss of Control Power. Upon removal of control power supply, the GFI should act to remove power from the protected circuit. A switch on the control-power circuitry will provide an adequate test. A random application is random in phase with the 60 Hz control voltage. A 1.2x50 BIL test waveform should be developed by the surge generator under no-load conditions. The test procedure is as described in Section 19 of Underwriters' Laboratories Standard 943. An exception to this procedure is in GFI connection. The surge should pass through the CT window for the input transient test and be placed in parallel with the supply power for the control transient test.