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The Bureau of Mines Ground-Fault Protection Research Program—A Summary

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

A	ampere	kΩ	kilohm	mV	millivolt
dB	decibel	kV	kilovolt	Ω	ohm
°F	degree Fahrenheit	lb	pound	pct	percent
ft	foot	mA	milliampere	s	second
h	hour	μF	microfarad	V	volt
hp	horsepower	μH	microhenry	V·A	volt-ampere
Hz	hertz	MΩ	megohm	W	watt
in	inch	ms	millisecond	Wb/A-m	weber per ampere-meter
kHz	kilohertz	μs	microsecond	yd^3	cubic yard

THE BUREAU OF MINES GROUND-FAULT PROTECTION RESEARCH PROGRAM–A SUMMARY

By M. R. Yenchek[1] and A. J. Hudson[2]

ABSTRACT

The U.S. Bureau of Mines designed and constructed sensitive and coordination-free ground-fault relays (GFR's) for use on mine power systems. First, a list of GFR attributes for mine ac utilization applications was compiled. These practical guidelines specified design, construction, transient immunity, reliability, and operating criteria. The time-current characteristics of the ac and dc units, subsequently fabricated, were designed to be below the human electrocution threshold. The significant and highly variable capacitance of high-voltage distribution cables was found to preclude the sensing of ground currents in the milliampere range. However, the coordination-free system developed for high-voltage distribution should enhance safety by significantly decreasing response time to ground faults. Implementation of the sensitive GFR technology in the mining industry has the potential to eliminate the majority of injuries and nearly all the deaths resulting from contact with energized components.

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INTRODUCTION

An analysis of U.S. Mine Safety and Health Administration (MSHA) statistics for electrical accidents at underground mines between 1980 and 1985 showed that electricians and mechanics suffered the highest incidence of injury and death. Specifically, there were 595 accidents associated with repair and maintenance of electrical apparatus, 29 of which were fatal. The resultant cost to the public and private sectors was estimated at $28 million (*1*).[3]

These data are not surprising since electricians and mechanics have the greatest exposure to electrical hazards. Space on mining machines is extremely limited, with electrical control boxes crowded with parts. During troubleshooting of energized circuits there is danger that, through either inattention or an inadvertent slip, an elbow or arm will contact an energized component. Under such working conditions electrical safety can be improved through the use of effective protective devices for personnel.

When a worker contacts an energized component, electric current flows through the worker's body and returns to the power source, either through the earth or via a ground wire. In this case the presence of a ground wire does not preclude or mitigate hazardous leakage current. The only available safeguard in such occurrences is a ground-fault detection system.

Most ground-fault protection in use on underground mine power systems is inadequate from a shock prevention standpoint. Typical response levels are in the ampere range, significantly exceeding the electrocution threshold. Increasing device sensitivity results in undesirable nuisance tripping and unscheduled interruptions in production. However, a sensitive ground-fault relay (GFR) not only can identify and act to interrupt the small deadly ground currents that electrocute people, but can ignore spurious signals that may result when motors are started or circuit breakers switched. Recent U.S. Bureau of Mines research, aimed at virtually eliminating electrocutions resulting from direct contact, developed sensitive GFR's for ac and dc utilization circuits. In addition, coordination-free relays were devised for use on high-voltage distribution. Application of this technology in the mining industry could eliminate the majority of injuries and nearly all deaths resulting from contact with energized components.

ELECTRIC-SHOCK ANALYSIS

Although the prevention of sustained electric shock is an ideal goal for industry, it is usually impractical. The detection of such shocks and resultant body currents as low as 10 mA would likely be a complete impediment to production. Consequently, a more realistic goal is to design protection against electrocution, not electric shock.

To devise effective personnel protection, it is first necessary to understand how electrical current can be lethal to humans. Ventricular fibrillation is by far the most common cause of death from accidental electric shock. This condition is induced when sufficient current flows through the chest and disrupts the nervous system impulses, internal to the heart, that synchronize normal heartbeat. The heart no longer acts as an efficient pump to circulate blood, and death is likely to occur within minutes. In light of this, safety can be enhanced if the potential current flow through the body can be minimized.

This risk of electrocution is determined to a large extent by power system configuration. To maximize safety, the recommended arrangement for ac systems features a direct- or derived-neutral point on the source transformer secondary, tied to earth through a grounding resistor. Equipment frames are then grounded by a grounding conductor connection to the grounded side of the resistor. When a grounded worker accidentally contacts an energized conductor, the body current is limited in magnitude by the grounding resistor (fig. 1).

Ventricular fibrillation is a function not only of current magnitude (I), but also of frequency, duration of exposure (t), and weight of the victim. The threshold was

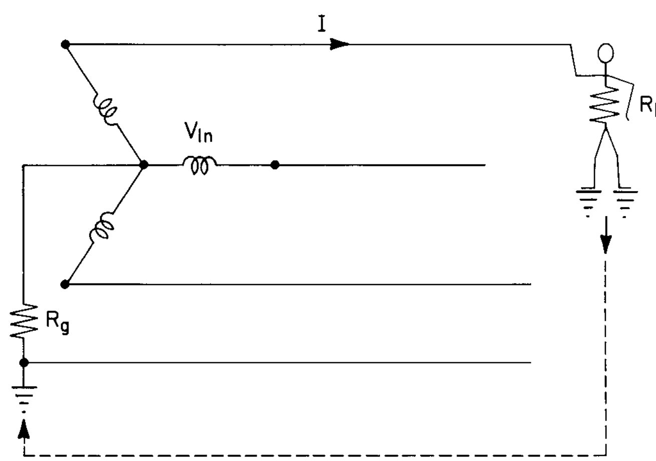

Figure 1.–Resistance-grounded power system with grounded worker.

[3]Italic numbers in parentheses refer to items in the list of references preceding the appendix at the end of this report.

statistically defined by Dalziel and Lee (*2*) as that current through the chest that will cause ventricular fibrillation in 1 out of 200 people. For 110-lb individuals, the 60-Hz threshold was expressed as

$$I = 116/\sqrt{t}, \quad (1)$$

where I = current, mA,

and t = time, s.

This relationship is shown graphically in figure 2. For brief exposures, relatively more current is needed to cause fibrillation. For longer durations, the limit decreases, down to 50 mA, below which fibrillation is unlikely no matter how long the exposure.

Given these constraints, an optimum ohmic value can be determined for the neutral grounding resistor, R_g, shown in figure 3. This value should be high enough to protect against ventricular fibrillation, yet sufficiently low to permit reliable ground-fault detection without nuisance tripping. Ideally, the resistor should limit current below the electrocution threshold for a direct contact shock. In such instances, the body resistance, R_b, may be as low

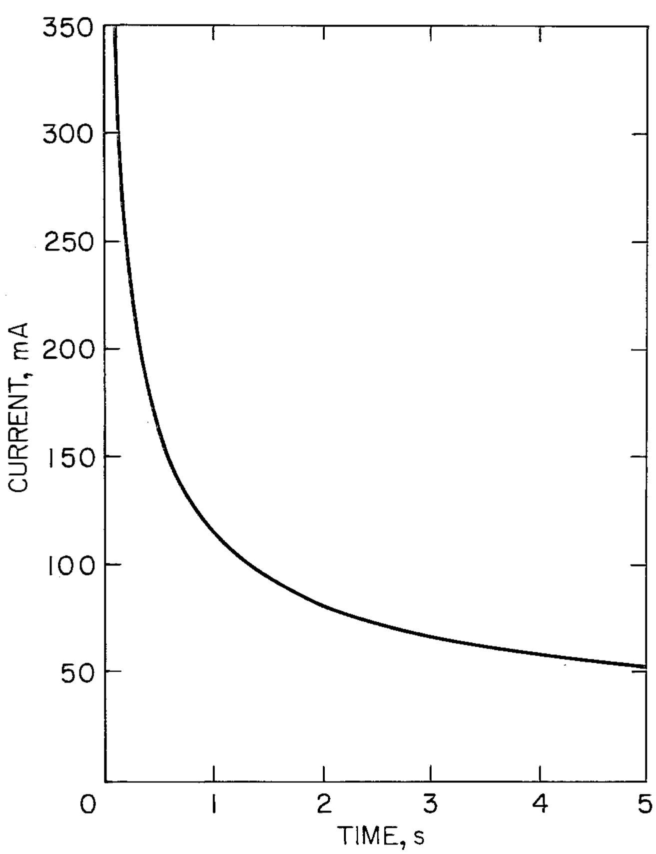

Figure 2.–60-Hz fibrillation threshold for 110-lb individuals.

as 500 Ω (*3*). The equation defining the 60-Hz electrocution threshold may be rewritten to determine the maximum nonfibrillating current for the total circuit clearing time as follows:

$$I = 116/\sqrt{(t_1 + t_2)}, \quad (2)$$

where t_1 = operating time of GFR, s,

and t_2 = operating time of molded-case circuit breaker, s.

A relay operating time of 100 ms provides sufficient time delay to prevent nuisance tripping. A molded-case circuit breaker typically opens its contacts within 34 ms. Given a total operating time of 134 ms, the maximum current that will not result in fibrillation is 317 mA. This can now be used to define the ohmic value of the neutral grounding resistor, R_g (fig. 3):

$$R_g = (V_{in}/I) - R_b, \quad (3)$$

where V_{in} = line-to-neutral system voltage, V,

I = maximum nonfibrillating current, A,

and R_b = human body resistance, Ω.

For example, on a 480-V system, R_g = 374 Ω, and ground faults are limited to a maximum of $(480/\sqrt{3})/374$ = 740 mA.

The human response to currents of varying frequency is shown in figure 4 (*4*). It is an unfortunate fact that humans are most sensitive to 60-Hz signals. The reason for this is that, physiologically, the muscles and the nerves of the body are most easily stimulated by changes in current magnitude. The ac sine wave is characterized by constantly changing magnitude, as opposed to pure dc where the only change occurs the instant the circuit is made or broken. Consequently, about 3.5 times more dc than ac is required to induce ventricular fibrillation (*5*). Conversely, the muscles and nerves do have a finite reaction time, such that with increasing frequency, the

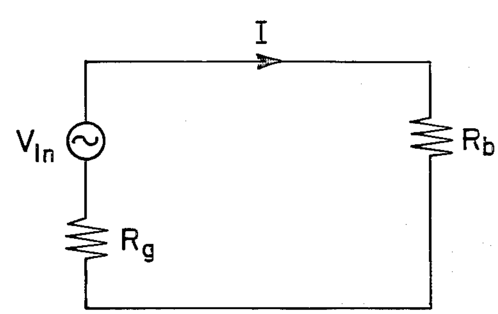

Figure 3.–Electrical accident equivalent circuit.

stimulation of one alternation does not have time to elicit a response before it is annulled by the succeeding alternation.

For dc power systems, a three-phase bridge rectifier arrangement is preferred (fig. 5). Shock hazards are reduced, not only by the presence of the grounding resistor, but also because line-to-ground voltage is one-half the line-to-line dc voltage. When a grounded worker inadvertently contacts an energized positive or negative conductor, the resultant current through the individual is half-wave rectified as shown in figure 6. Research conducted recently by Bernstein (*6*) has established that the presence of an 18-pct ripple in a half-wave-rectified wave tends to reduce the threshold such that the following relationship applies (fig. 7):

$$I = 348/\sqrt{t}, \qquad (4)$$

where I = current, mA,

and t = time, s.

These electrocution threshold characteristics are an important consideration for the design of sensitive GFR's.

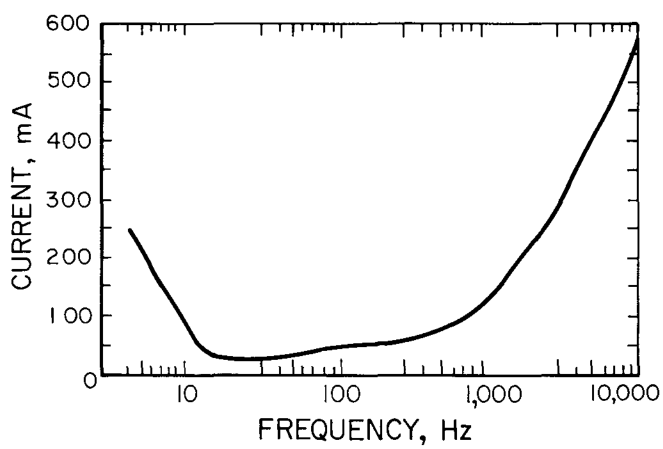

Figure 4.–Fibrillation threshold at currents of varying frequency.

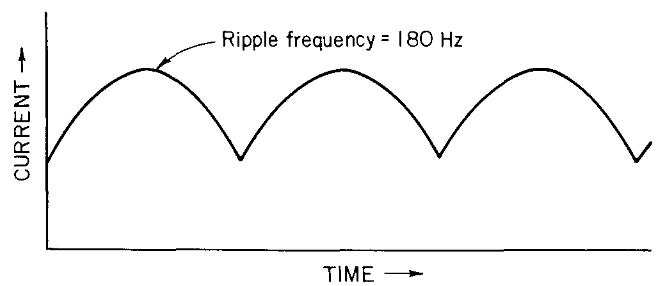

Figure 6.–Half-wave-rectified ground-fault current.

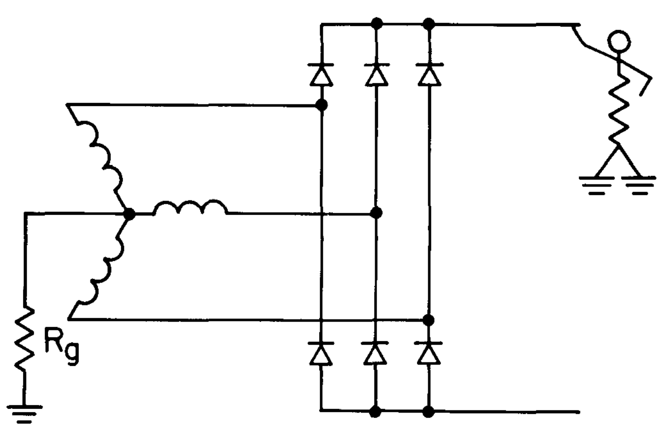

Figure 5.–Three-phase resistance-grounded system feeding full-wave rectifier.

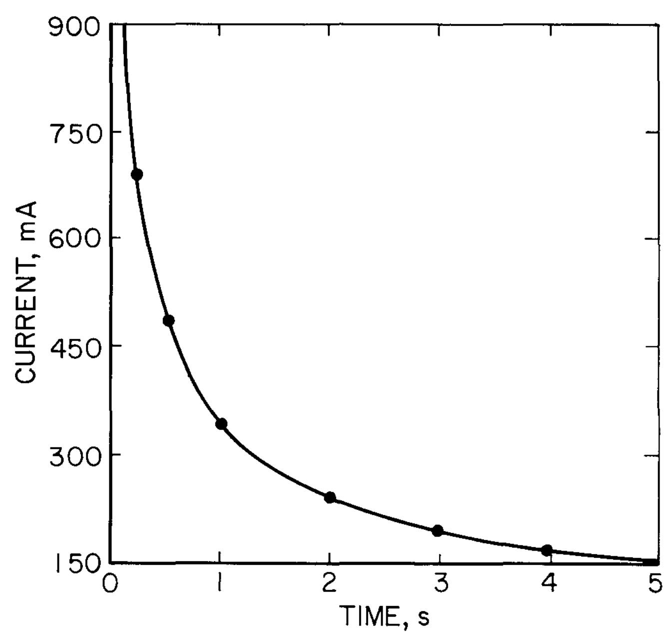

Figure 7.–Half-wave-rectified dc ventricular fibrillation threshold.

ALTERNATING CURRENT UTILIZATION

Initial Bureau research concentrated on providing the ac utilization portion of a mine power system with sensitive ground-fault protection. The utilization system includes portable power cables, power centers, rectifiers, motors, and the associated protective devices. It is the most troublesome part of the power system in terms of safety and reliability because of its temporary nature. As mining progresses, the utilization system is stretched to its limit and repositioned, necessitating frequent handling of trailing cables and equipment repairs, a major source of electrocutions underground (*1*). The presence of large motor loads strains the dependability of protection devices by introducing large voltage and current transients. Consequently, the application of effective personnel protection for utilization circuits would have a major impact on underground safety.

Zero-sequence or balanced-flux relaying (fig. 8) is the most reliable and most common method employed for ground-fault relaying (*7*). As shown in figure 8, the phase conductors pass through the toroidal current transformer (CT) window. The sum of the three phase currents is the CT primary current and is proportional to the zero-sequence current (*8*). An unfaulted balanced system features little or no zero-sequence current, and the CT secondary current is approximately zero. However, when a ground fault occurs, the resultant secondary current is used to trip the relay. Zero-sequence relaying is unaffected by phase voltage fluctuations, and since only ground leakage is monitored, the relay can be made very sensitive. Consequently, it is the only practical technique capable of responding to low-level hazardous ground currents and the method of choice for the Bureau's sensitive GFR research program.

BACKGROUND RESEARCH

As a first step in the design process, a list of GFR attributes for ac mining applications was compiled. Next, test procedures were devised to ensure device compliance with the desired operating characteristics. These practical guidelines (*9*), addressing GFR design and construction, transient immunity, reliability, and time-current characteristics, are summarized below.

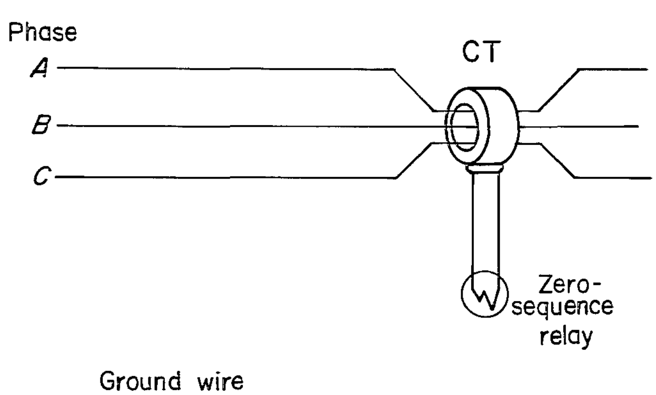

Figure 8.–Zero-sequence relaying.

Proper Design and Construction

A relay system of suitable design and construction does not pose a personnel hazard, reduces the amount of downtime caused by GFR failures, and facilitates acceptance of the GFR as a useful safety device. Electronic instruments designed and constructed for military use must comply with Military Standard 454 (*10*). The key portions of that standard, which can be applied to GFR's in underground mining, are related to safety and accessibility: The design shall incorporate methods to protect personnel from accidental contact with voltages greater than 30 V root-mean-square (RMS) or dc during normal operation. All external surfaces shall be at ground potential during normal operation. All terminals shall be corrosion resistant. Sharp external projections shall be avoided. Suitable access shall be provided for adjustments, testing, and routine maintenance. No unsoldering shall be necessary to remove the front cover for troubleshooting.

Mine Worthiness

Underground, GFR's are located inside metal-clad load centers, so both the relay and CT must have metal mounting lugs. Terminal strips should be sized for No. 12 AWG wire. In addition, the relay case should be moisture and dust resistant.

Size Limitations

Space is typically limited inside mine power equipment compartments. Since several GFR's may be used in a single power center to protect all outgoing circuits, they must not be much larger than present GFR's. Thus, the relay components should be mounted in a compact enclosure not exceeding 3 by 6 by 6 in. To minimize flux leakage, the CT window should only be large enough to accommodate the encircled power conductors. The outside diameter of a 4/0 single-conductor cable is 0.807 in (*11*). Three such cables fit snugly through a 1.750-in-diameter window. For ease of installation of cables with terminals, the window diameter should be increased to 2.100 in. Present ground-fault CT's in use underground have outside diameters smaller than 4 in. Since they are placed between the molded-case circuit breaker and the load-center coupler, they are no more than 3 in wide.

Electrocution Prevention

The primary reason for employing sensitive GFR's in mining is to prevent accidental electrocutions. For 60-Hz circuits, the desired region for GFR operation is below and to the left of the threshold shown in figure 2. To define GFR time-current characteristics, a variable 60-Hz voltage source in series with a 50-Ω, 225-W fixed resistance is used to inject current through the CT primary as shown in figure 9. A double-pole, single-throw switch initiates the test and triggers the storage oscilloscope, which monitors relay contact activity. Test currents are varied from 0 to 1,000 mA.

Power Harmonics

The filtering for GFR's must be designed so as to preclude false tripping by any harmonics superimposed on the power conductors. However, attenuation of these higher frequencies must not be so severe that hazardous currents above the electrocution threshold (fig. 4) are permitted. In testing GFR frequency response (fig. 10), an audio oscillator and power amplifier provide high-frequency currents from 60 Hz to 10 kHz. For each frequency, the voltage is slowly increased until the GFR activates.

Voltage Surge Immunity

Mine power systems frequently experience voltage surges when circuit breakers and switches are opened or closed. Although the duration of these transients is less than 50 ms, past research indicates their magnitude can reach five times the utilization voltage (*12*). These surges, when present on the power conductors encircled by the GFR CT, should not falsely activate the relay. In addition, they should not damage the relay control circuitry.

An impulse generator, constructed in accordance with Underwriters Laboratories (UL) Standard 943 (*13*), is employed to simulate transient overvoltages as they would occur on residential and industrial power systems. The test circuit consists of a relay switch and resonant circuit, shown schematically in figures 11 and 12. The generated waveform exhibits the following characteristics under no load:

1. Initial rise time of 0.5 μs between 10 and 90 pct of peak amplitude;
2. Period of following oscillatory wave, 10 μs; and
3. Amplitude of each successive peak, 60 pct of the preceding peak.

The amplitude of the first peak is fully adjustable from 0 to 9,000 V. In the first part of the test, 10 successive 5-kV surges are imposed on the power conductors encircled by the CT while the relay contacts are observed. Next, ten 1-kV impulses are applied in parallel with the 120-V ac control voltage, and at random with respect to its phase. Afterward, the relay is operated at 60 Hz to detect possible damage to circuitry.

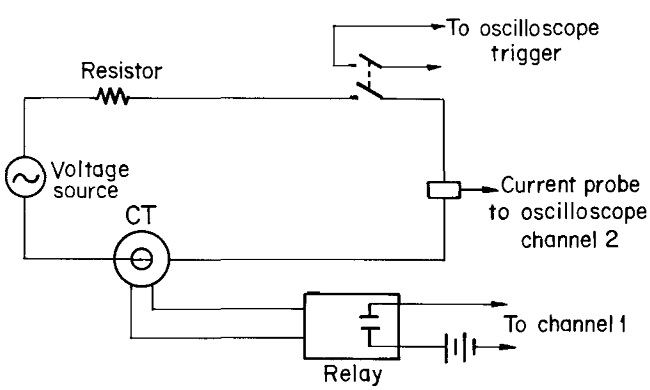

Figure 9.–Test setup to determine 60-Hz tripping characteristics.

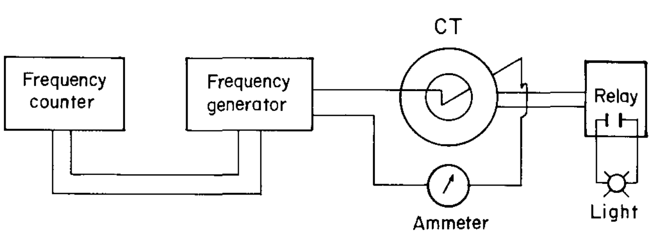

Figure 10.–Frequency response test circuit.

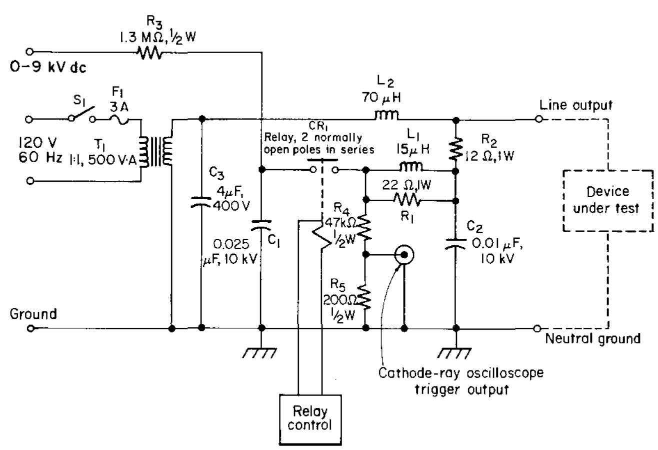

Figure 11.–Impulse generator circuit.

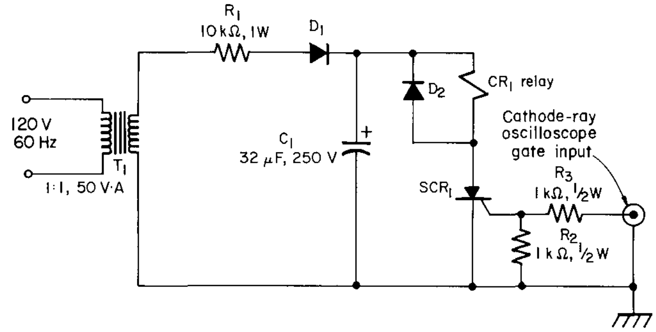

Figure 12.–Relay control circuit for impulse generator.

Common-Mode Transients

Sensitive GFR's must be unaffected by large transient currents occurring simultaneously on all phases of an ac utilization circuit. Such currents may briefly exceed six times full-load motor rating during starting or under heavy intermittent load. The maximum short-circuit settings listed in 30 CFR 75.601 (*14*) effectively limit balanced three-phase loading to 2,500 A. Nevertheless, balanced currents up to 2,500 A should be tolerated for up to 5 s without activation of the GFR. A three-phase high-power source is used to variably supply balanced three-phase currents through a shorted trailing cable encircled by the GFR CT. The voltage is increased until the relay activates or the 2,500-A ceiling is reached. Tripping thresholds are confirmed through repeated tests.

Current Withstand

The molded-case circuit breakers used on low-voltage ac mine power circuits typically have an interrupting rating of 30,000 A. Currents of this magnitude are quite possible during three-phase faults. Since the GFR CT is a part of the power system, it too should withstand up to 30,000 A for the time it takes the breaker to clear (a few hertz). The withstand test is conducted with a high-current circuit breaker tester as shown in figure 13. The tester is equipped with an initiate switch that can be jogged to reasonably control the test duration. Current magnitudes are recorded on a storage oscilloscope connected across a 400-A, 100-mV shunt. The CT secondary is shorted to preclude high secondary voltages. The CT is subjected to 30,000 A for approximately 4 Hz. The 60-Hz current ratio and winding resistance are measured before and after the withstand test to detect any degradation of the CT.

Quality Assurance

For dependability underground, all devices from the same manufacturer should be consistent in electrical and mechanical performance over a reasonable service life. In addition, each GFR should be equipped with a means to test its operation.

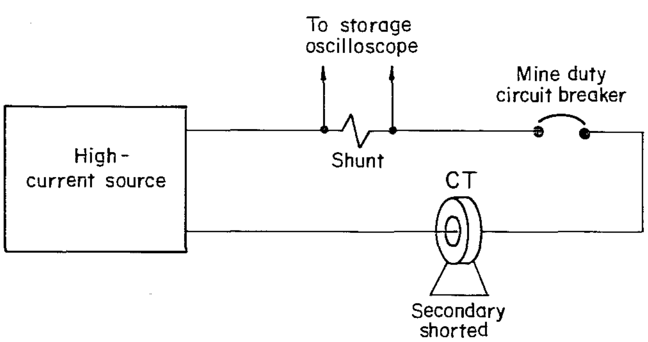

Figure 13.–Current withstand test circuit.

Safe Failure Modes

In the event of failure of the GFR's internal circuitry, it is vital that the unit activate its associated circuit breaker to remove power and prevent a false sense of security. Two common failure modes are the loss of 120-V control power to the GFR and an opening of the CT winding.

PROTOTYPE DESIGN AND CONSTRUCTION

Sensitive GFR's are available commercially for use in British mines and in the U.S. irrigation industry. Three such brands were evaluated in-house for potential applicability to U.S. mining using the above criteria. None was found suitable without design modifications (*15*). However, these tests served as the basis for the development of a mine-worthy sensitive ground-fault protection system consisting of a CT and an electronic relay.

Current Transformer

The CT for a sensitive ground-fault system has the duty of precisely sensing the existence of small ground-fault currents on three-phase line conductors feeding mine machinery. It must be able to distinguish these faults within the complex electromagnetic environment that exists in mine power equipment. Specifically, the CT must not send erroneous signals to the relay circuitry when in the presence of external magnetic fields and when observing high common-mode line currents. This precise device must also be able to physically, electrically, and magnetically withstand the mine environment.

The output of the CT secondary was anticipated to be in the millivolt range when sensed currents were in milliamperes. The following expression is used to predict open-circuit output voltage for a given ground-fault current (*16*):

$$E = hNuf\, I_p \ln(R_o/R_i)\,, \tag{5}$$

where E = RMS output voltage of secondary voltage, V,

h = toroid core width, m,

N = number of turns on secondary winding,

u = core permeability, Wb/A-m-turns,

f = frequency, Hz,

I_p = RMS value of ground-fault current, A,

R_o = outer toroidal radius, m,

and R_i = inner toroidal radius, m.

Equation 5 is valuable in designing a current sensor for a sensitive ground-fault protection system. It shows that CT output voltage may be affected by various electrical and mechanical quantities.

In addition, consideration must also be given the CT burden, or external load impedance on its secondary. The burden impedance cannot be so low as to reduce the secondary voltage to an unusable value. Voltage input to the relay must be sufficiently high so that amplification and noise concerns are minimal. Since core dimensions are limited by available space, voltage output can be maximized by using a high-permeability core and a large number of secondary turns (see equation 5). Also, a high-permeability core minimizes flux leakage inherent with window-type CT's.

Cores are usually constructed of thin laminations to reduce eddy current losses. For the GFR toroid, the core was made by continuously winding a 0.006- by 0.75-in tape of magnetic material starting with a 2.5-in ID. After winding to an outer diameter of 3.5 in, the core was annealed to remove strains and impurities from the tape.

An 80 pct nickel-iron alloy core was able to meet the accuracy requirements of sensitive ground-fault relaying. However, one problem with nickel-iron cores is that their excellent magnetic properties can be degraded by winding stresses and pressures. A nonmetallic or phenolic box (fig. 14) around the core provided protection against mechanical damage as well as insulation for the secondary winding. The effects of vibration and shock are mitigated by cushioning the core in a silicon casing.

The CT must be able to operate within significant magnetic fields generated by nearby power transformers or the monitored power conductors themselves. To minimize any volts-per-turn imbalance requires a regressive winding technique (fig. 15) (*17*). One-half of the 250 secondary turns of No. 22 AWG magnet wire were wound around the core in one direction. The second half were wound around the core in the opposite direction across the first half so that each second-half turn falls between a pair of first-half turns within the window crossing on the CT sides. A separate single turn was wound on the core for primary injection testing.

As stated previously, power conductor common-mode currents can produce local core saturation, noncancelling voltages across the CT secondary, and nuisance tripping of the relay. It was found (*18*) that a 2.1-in-ID, 0.1-in-thick, concentric, low-permeability iron buffer adjacent to the power conductors tended to distribute local flux saturation effects.

The core, windings, and buffer were potted in epoxy and enclosed in a metallic housing that has convenient holes for mounting the assembly inside mine power equipment. The output cable contains the four conductors for the CT secondary and the test winding.

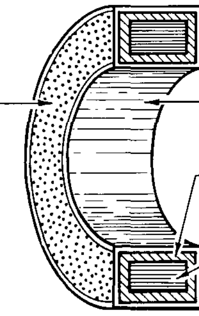

Figure 14.–Nonmetallic core box construction.

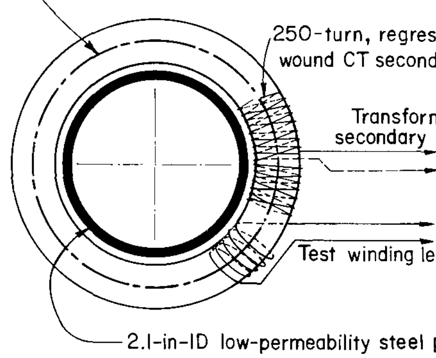

Figure 15.–Sensitive CT design.

Electronic Relay

Solid-state sensitive GFR's were designed to operate with the CT (figs. 16-17). Two versions were conceptualized, one based upon analog techniques, the other using digital (*19*). Both incorporate the same control power supply and electromechanical relay trip circuitry mounted on interchangeable cards.

Analog Version

A block diagram of the analog relay is shown in figure 18 and a schematic is shown in figure 19. Since the sum of the three line currents that form the primary current in the CT is nearly zero under normal operating conditions, normal phase currents should not trip the relay. However, when a ground fault occurs, a voltage will be induced across the secondary in proportion to the fault magnitude. The CT (T_2) secondary was connected across a burden resistor (R_1) and an inverting operational amplifier QA_1 (fig. 19). Diodes D_1 and D_2 were included to limit short-duration transients at the GFR input.

A first-order, low-pass filter was utilized to match the relay frequency response to that of humans (fig. 4). This filter consisted of operational amplifier QA_2, resistors, R_5,

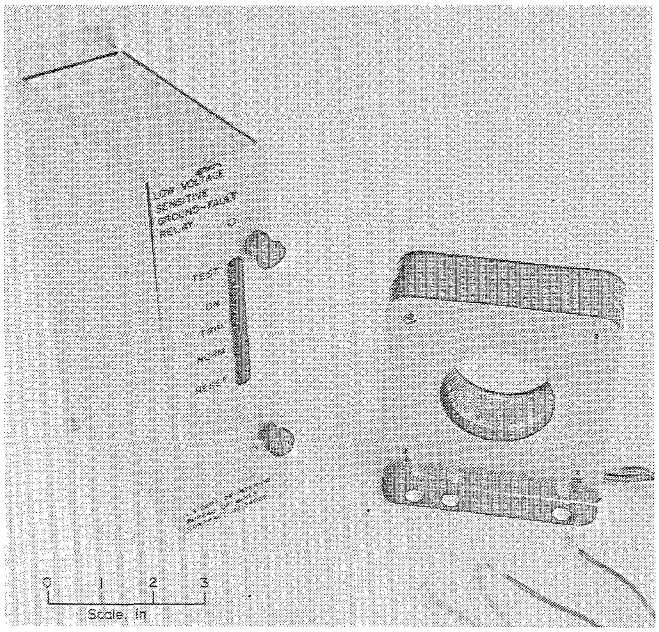

Figure 16.–Electronic relay and CT.

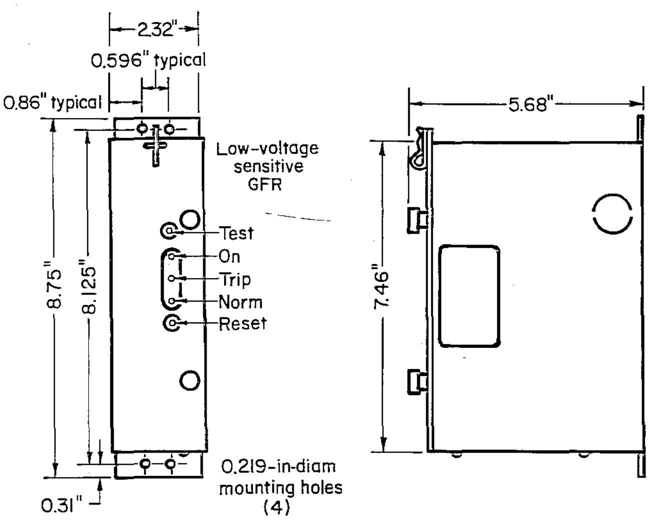

Figure 17.–Prototype sensitive GFR enclosure.

R_6, R_7, and capacitor C_3. It had a 3-dB cutoff frequency of 2 kHz and a gain of 2. Full-wave rectification was accomplished by the combination of the two operational amplifiers QA_3 and QA_4. Diode D_5, resistor R_{14}, and capacitor C_5 provided a smoothed dc output signal comparable to the peak value of the input sinusoidal voltage at QA_3. The smoothed signal was then applied to the noninverting input of the comparator QA_5. This stage was designed such that its output state changes abruptly from zero to a high voltage when the input reaches an adjustable pickup reference voltage.

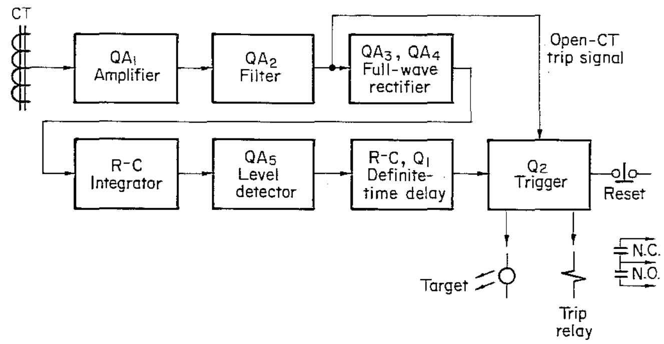

Figure 18.–Block diagram for prototype ac analog relay.

During normal operation, the current from the 24-V supply flows through the coil of the normally closed electromechanical relay K_1, resistor R_{30}, and the green light-emitting diode (LED) D_{14}, because the thyristor, Q_2, is off. When a ground fault occurs above the pickup setting, the voltage signal from the comparator starts to charge capacitor C_6 through the adjustable resistance R_{23} and fixed resistor R_{24}. This continues until the unijunction transistor (UJT) turns on and discharges C_6. The GFR operating time is determined by the time it takes to turn on the UJT. To activate the GFR, a trip signal greater than the trip level setting must still be present after the desired delay has occurred. The output of the UJT initializes the gate of the thyristor, Q_2. Once the thyristor is fired, it latches on. This deenergizes the electromechanical relay and turns on the red LED D_{13}.

Several fail-safe characteristics were incorporated into the relay design. For example, a loss or significant drop of control power deenergizes the electromechanical relay coil. In addition, if the secondary winding of the CT disconnects from the analog circuitry, the relay will initiate a tripping signal.

An internal power supply provides regulated ±15-V power for the relay's active integrated circuits, as well as an unregulated supply of approximately +24 V for the relay K_1 and its associated network. The 120-V primary of the power supply transformer is fuse protected and includes transient suppression.

A test circuit, consisting of a test winding on the CT T_2, momentary switch S_2, and a current-limiting resistor R_{33} is provided on the relay. When the switch is closed, a test current greater than the relay pickup setting is primary injected into the CT, and the relay activates.

Digital Version

A block diagram of the digital prototype is shown in figure 20 and a schematic in figure 21. As with the analog version, the CT T_2 is connected across a 1,000-Ω burden R_2. The ac output voltage of the CT is amplified by the inverting operational amplifier QA_{1B}. The output

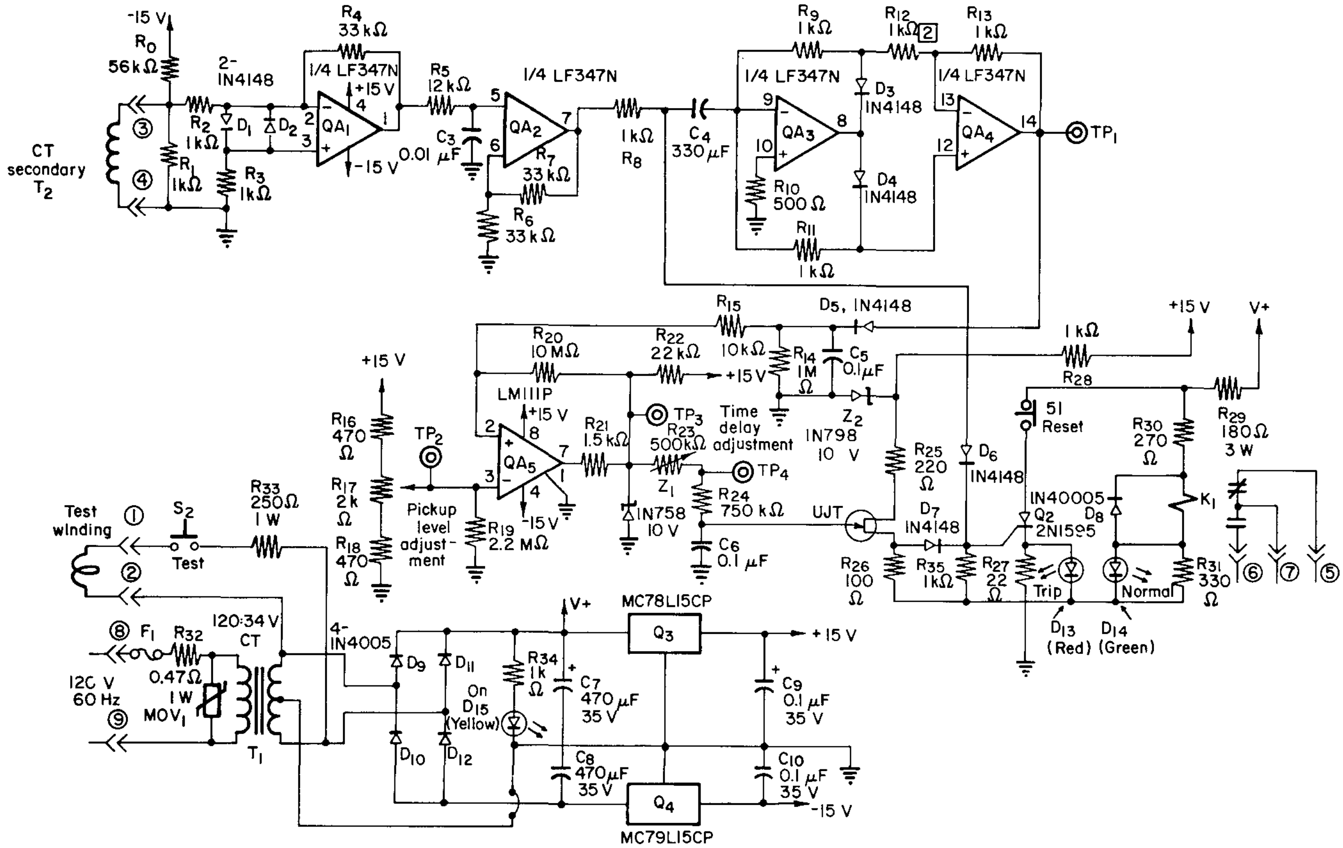

Figure 19.–Schematic diagram for prototype ac analog relay.

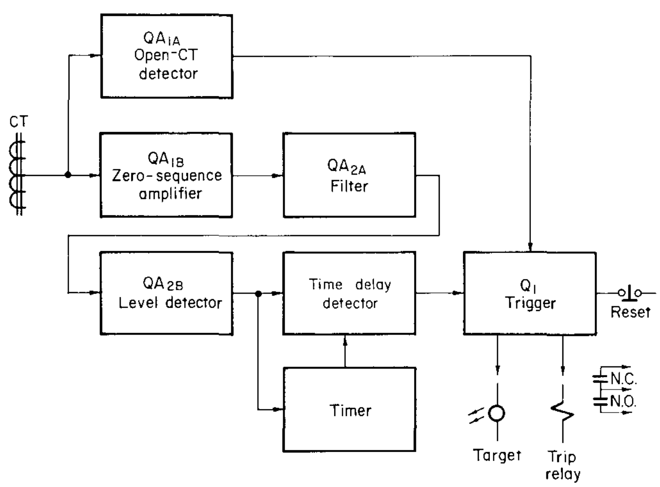

Figure 20.–Block diagram for prototype digital relay.

of QA_{1B} is then fed into a first-order, low-pass filter with a 3-dB cutoff of 1.6 kHz. The purpose of this filter is to attenuate high-frequency signals such that false tripping due to harmonic currents or high-frequency, long-duration transients may be avoided. This attenuation should not be too steep, because high-frequency currents can cause electrical fatalities.

The ac output of the filter network is fed to the comparator QA_{2B} through a dc-blocking network consisting of C_3, R_{12}, and C_4. Consequently, an ac-filtered trip signal will be delivered to the negative input terminal of this differential amplifier. The voltage divider consisting of R_{13} and R_{14} provides a positive reference voltage to the positive input terminal of the differential amplifier. When the sinusoidal trip signal at the negative amplifier input is less than the trip level setting at the positive input terminal, the output of the comparator is at its positive saturation value of about +13 V dc. At any instant when the trip signal is greater than the trip level setting, the comparator output goes to its negative saturation value of -13 V dc. During this time, diode CR_5 clamps the inputs to the CD4528 retriggerable one-shot and the 555 timer to approximately 0 V.

The retriggerable one-shot remains in its stable state of unity logic output as long as a 1-to-0 transition does not occur at its input. However, when such a transition does occur (corresponding to a trip signal), the retriggerable one-shot goes to its unstable state of zero logic output for as long as the trip signal is present. Should the input switch back to a high state before the GFR activates, the one-shot will return to its stable state and GFR operation will be blocked.

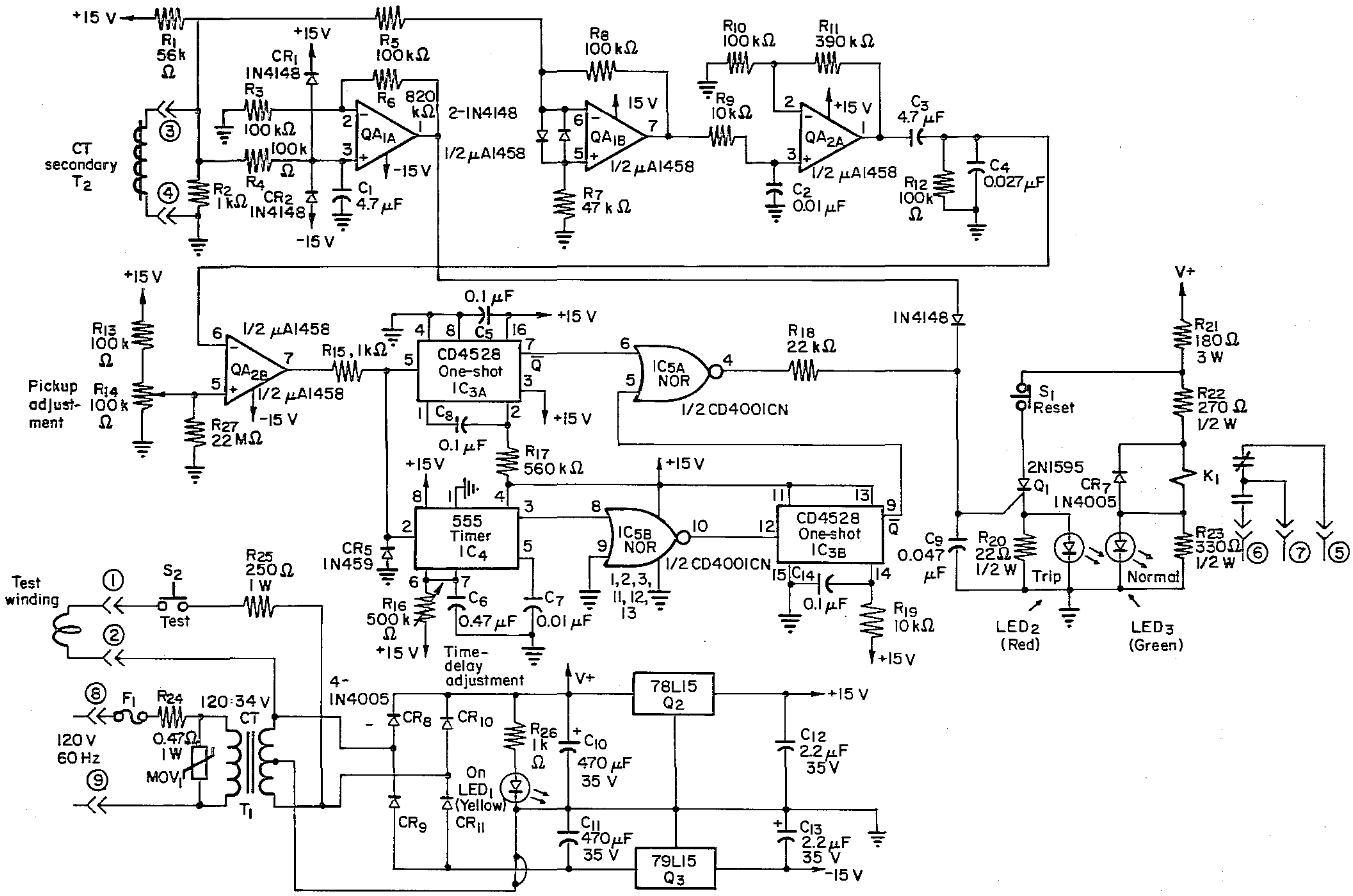

Figure 21.–Schematic diagram for prototype digital relay.

The GFR time delay circuitry includes the 555 timer, the IC_{5B} NOR gate, and the CD4528 retriggerable one-shot. As long as no 1-to-0 transitions occur at the timer input, its output remains in a stable zero state. When a 1-to-0 transition does occur (corresponding to a trip initiation), the 555 timer output becomes unstable (1) for 100 ms, the GFR intentional delay time. The IC_{5B} NOR gate isolates the timer output from the CD4528 one-shot input.

The relay firing circuitry includes the IC_{5A} NOR gate, the 2N1595 thyristor, Q_1, the electromechanical relay K_1, and associated components. The relay tripping signal, a high NOR output, is developed only if the outputs of both CD4528 one-shots are zero. This occurs only if the relay delay time has expired and the trip signal exceeds the trip level setting. The remainder of the firing circuit is similar to the analog version, as are the power supply and test circuit. The digital version also has open-CT and loss-of-control-power safety features.

Four analog and four digital prototypes were constructed under phase 1 of Bureau contract J0134025 (*19*). Their ability to detect low-level faults was confirmed in the laboratory. What remained to be demonstrated was satisfactory operation in an underground mining environment.

FIELD AND LABORATORY EVALUATIONS

To ensure an unbiased evaluation, the Bureau assumed the responsibility of testing the units at a cooperative commercial mine. This demonstration would have a twofold purpose:

1. To expose the prototype GFR's to the transients and anomalies associated with a mine power system to gauge circuit durability.
2. To measure the number of tripping events and determine if false or nuisance tripping is of concern when GFR's are actually providing ground-fault protection.

Bruceton Mine

Initially, the economically depressed coal industry was unresponsive to published solicitations for cooperators. Consequently, the devices were first installed at the

Bureau's Bruceton Mine near Pittsburgh, PA, to establish some performance history.

Bruceton Mine Power System

Electrical power at a potential of 7,200 V is delivered to the mine substation on the surface, as shown in figure 22. The three-phase, 480-V utilization voltage for the mine is derived via a delta-wye configuration. Ground-fault currents are limited to 15 A by an 18.5-Ω resistor connected between the secondary neutral point and the earth grounding bed. From the substation, power feeds into the surface control building (building 07) where it divides to supply both the Experimental Mine and the Safety Research Coal Mine (SRCM). Overcurrent, short-circuit, undervoltage, and grounded-phase protection are provided at the beginning of these branch circuits, located within a wall panel in building 07. The sole ground-fault protective device (GFR 2) for the Experimental Mine is in this panel. From building 07, power for the SRCM is transmitted underground through a borehole. A 480-V, three-phase service disconnect is situated underground at the bottom of this borehole. From this disconnect, power is fed into A-Butt, where three-phase auxiliary and single-phase lighting power is tapped (fig. 23). The auxiliary circuits, infrequently used to maneuver equipment in and out of the mine, are equipped with grounded-phase protection (GFR's 7 and 8). In 12-Room, the 480-V power connects to a load center (fig. 24) for the portable mining equipment. Grounded-phase protection is incorporated on each of the four outgoing circuits.

In summary, as shown in figure 22, ground-fault protection is provided at eight locations within the Bruceton Mine power system. Toroidal transformers encircling the power conductors are connected to small socket-type relays with sensitivities of 6 A.

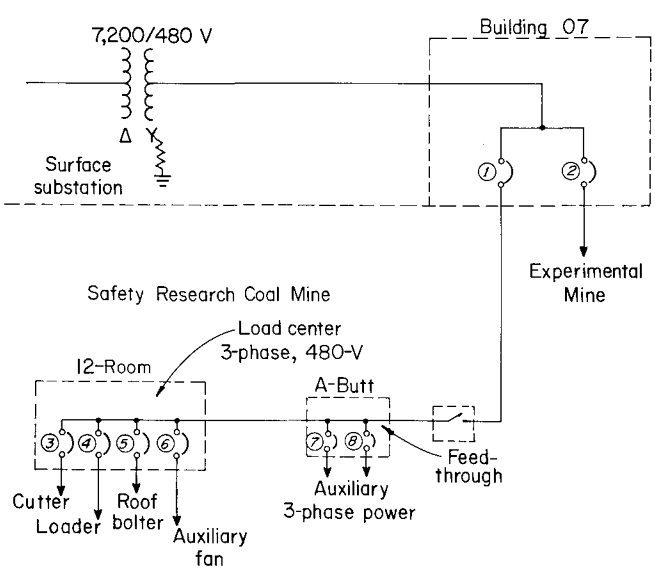

Figure 22.–Bruceton Mine power system. Circled numbers indicate GFR's.

Ground-Fault Relay Installation

To preclude extensive tripping of the power, it was intended that the prototype sensitive GFR's operate event counters in lieu of activating the circuit breakers each time leakage current exceeded 50 mA. The existing ground-fault protection and grounding resistor remained in service. Simply connecting the unit's control power to the mine power system and exposing it to anomalies and transients constitutes one test of mine worthiness.

Eight prototype GFR's were available for the demonstration. Since their durability was unknown at the outset, it was decided to utilize only six, keeping two as spares. Consequently, no sensitive GFR's were installed on the rarely utilized auxiliary circuits in A-Butt. Two analog and two digital versions were installed underground in the load center; two digital units were placed in building 07.

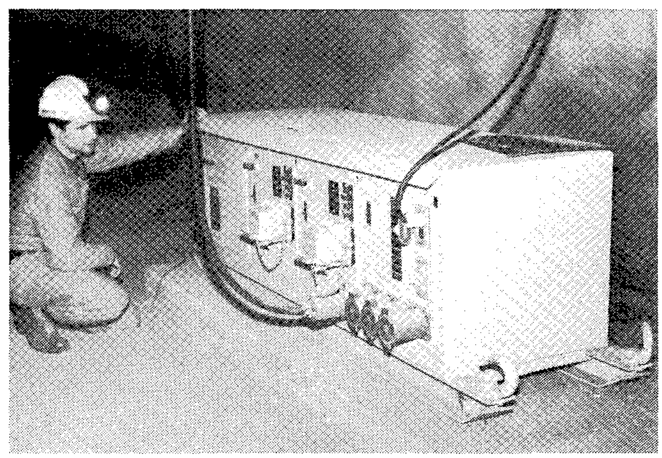

Figure 23.–Power feedthrough in A-Butt, Bruceton Mine.

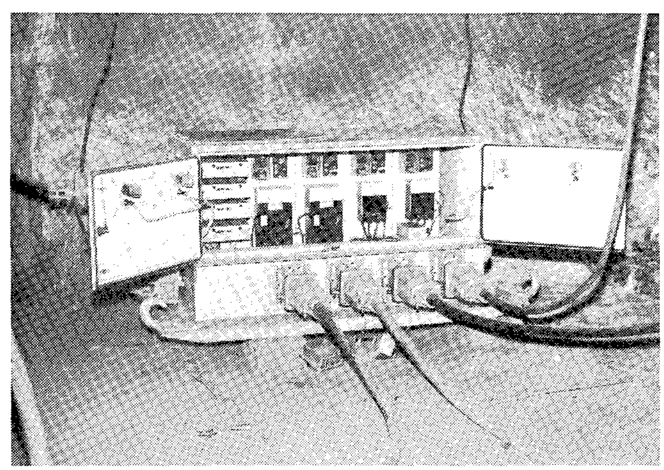

Figure 24.–Load center in 12-Room, Bruceton Mine.

All prototype GFR's installed underground were adjusted for a definite time delay of 100 ms, the recommended setting for shock protection. To incorporate a degree of coordination, the upstream devices in building 07 were fixed with a delay of 250 ms.

As shown in figure 25, the CT's of the sensitive GFR's were installed around the three 480-V phase conductors. The single-phase control power for the electronic relays was obtained using 480/120-V control transformers. The electromechanical counters were rated at 120 V and 6 W.

Upon installation, the test circuit of each GFR was exercised to verify operation. At each location (building 07 or the 12-Room load center) all relays tripped when the test button of any one was activated. The following were investigated as possible sources of this false tripping:

- Physical orientation of the relays (because of space limitations the units were installed on their sides in the load center),
- Induced currents in parallel CT secondary leads,
- Low control voltage,
- Voltage transient from the counter activation.

The GFR's were tested in the laboratory with the relays upright, on their sides, upside down, etc.; the sensitivity and time delay were unaffected. Next, two GFR's were energized with their CT secondary leads at various distances and orientations with respect to each other. No differences in performance were detected. Voltage measurements of the control transformer underground showed it remained constant at 120 V when the test buttons were pushed. Further tests in the laboratory revealed that the relays would not trip until the control voltage dropped to 65 V. Finally, the counters were disconnected, and the relays operated properly without interfering with each other. These counters consist of an electromagnetic coil that, upon loss of signal, counts by disengaging a ratchet wheel. The switching of this inductive load created a voltage transient that activated the other units.

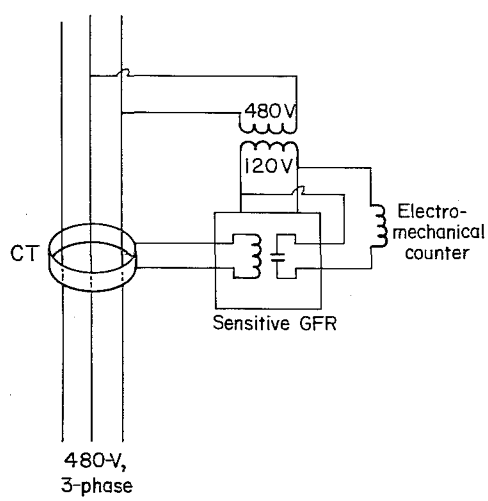

Figure 25.–Sensitive GFR installation, Bruceton Mine.

Several methods of transient suppression were tried in the laboratory without success. Metal-oxide varistors (MOV's) were connected across the input of the relay electronics; capacitors were placed across, and ferrite-core inductors in series with, the relay power supply. Only the placement of 0.33-μF capacitors across the counter coil solved the problem.

It was felt that GFR transient immunity was not compromised by the tripping associated with the electromagnetic counters. The voltage transient created by the inductive coil switching was severe, but extremely localized in the power system. The switching of large motor loads should not give rise to similar problems because of the damping effect of the intervening cable impedance.

Ground Fault Relay Performance

The relays were then connected to the mine power system, with mine personnel periodically inspecting the units and resetting those that tripped. Table 1 lists the GFR performance at the end of 30 days.

Table 1.–Counter readings of GFR performance

Relay location[1]	1	2	3	4	5	6
After 30 days	3	9	5	1	2	0
After additional 2 weeks	1	3	3	0	1	0

[1]See figure 22.

At this time all units were removed from service and examined in the laboratory. Both digital units installed in building 07 were malfunctioning. GFR 1, protecting the SRCM, could not be reset and remained in a trip mode. The GFR for the Experimental Mine would not trip when tested. After troubleshooting, the following components (fig. 21) were found defective and repaired:

GFR 1: Digital IC_5, CD4001.

GFR 2: Thyristor Q_1, 2N1595; reset switch S_1; in addition, the main power transformer T_1 was resoldered.

Before the evaluation was continued underground, the prototypes were thermally stressed at 120° F while energized in an environmental chamber for 1 week. No additional malfunctions were uncovered. The units were then reinstalled at their original locations on the mine power system and monitored for 2 weeks by mine personnel. The largest motor fed from the load center, the 60-hp, 480-V pump motor for the cutting machine, was started repeatedly to determine if the resultant current inrush would affect GFR 3. No false trips were observed. The absence of tripping when the pump motor was started is encouraging from the standpoint of immunity of transient common-mode currents. At the end of this time, digital GFR 5 was found inoperative because of defective IC_5, CD4001. In addition, it was observed that when the relay electronics cards were inserted into the relay enclosures, they did not always contact the rear terminals without being jiggled.

The prototype ac GFR's were installed on the Bruceton Mine power system for a total of 6 weeks. During this period they were exposed to anomalies and transients associated with the system. The count history revealed a high number of trips for the GFR protecting the Experimental Mine (GFR 2, table 1). It may be speculated that the relays in building 07 were more accessible than those underground and were reset with a higher frequency by mine personnel. Also, it may be speculated that the malfunctions of the digital relays in building 07 were the result of a design flaw or their greater exposure to upstream power system transients, especially lightning. Additional studies were necessary to pinpoint the causes of these malfunctions.

Ground Fault Relay Modifications

The 6-week evaluation at the Bruceton Mine pointed out several deficiencies in the test setup and the GFR design, which were addressed in followup laboratory work. First, the use of 120-V electromechanical counters to monitor relay activation was judged to be of limited utility, since mine personnel were relied upon to check the units visually. An unattended GFR may count one trip when in reality it could have tripped many times with prompt reset. Consequently, electronic totalizers were procured as replacements for the electromechanical counters. Characterized by high input impedance, the totalizers featured an internal battery power supply and were sensitive to 6-V pulses. These monitoring devices were connected to the GFR's internal circuitry via amplifier circuits shown in figure 26. The totalizers monitor the presence of tripping signals, internal to the GFR, that are present any time leakage currents through the CT exceed 50 mA for the prescribed time delay. Since the internal tripping signals are unaffected by relay status, trip events can be monitored without reliance on mine personnel.

As shown in figure 21, outputs 3 and 11 of NOR gate IC_{5B} were grounded. However, through inversion these outputs became high and should be floated. Correction of this error eliminated the overheating of IC_{5B} (CD4001) in the digital GFR models.

In addition to these basic changes, further modifications were recommended. Troubleshooting in the laboratory was hampered by the lack of readily identifiable test points on the printed circuit board. Key circuit locations could be made more accessible by the installation of color-coded test points on the side of the board. Also, to permit measurements while the GFR is in service, extender boards could be fabricated.

Extracting the printed circuit board from the metallic enclosure opens the CT secondary. During service, high voltages could be present across these terminals, endangering personnel in close proximity. Consequently, a means should be devised to ensure that the CT secondary is shorted if the circuit board is removed. This could take the form of a shorting connector or a high-ohmic-value resistor in combination with back-to-back Zener diodes to limit high voltages.

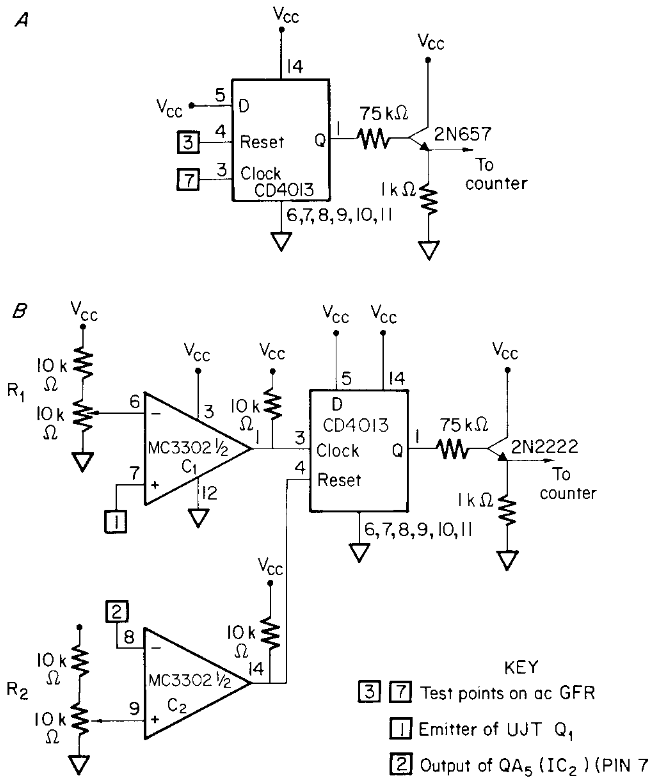

Figure 26.–Totalizer amplifier circuits for digital (*A*) and analog (*B*) GFR's.

To ease CT installation, metal mounting brackets and screw terminals should be added to the CT housing. Also, a connector should be installed on the relay enclosure to facilitate connection of the CT and the 120-V control power.

Many modifications can be implemented to improve ruggedness and reliability. The CT assembly can be potted. To improve connector contact, the circuit board can be double sided with plated through-holes. In lieu of commercial-grade components, parts built to military specifications can be employed.

Many of these changes were incorporated subsequently in GFR's built for the Bureau by a small electronics firm. These prototypes were then used in field evaluations at commercial sites.

Commercial Tests

Through announcements in trade magazines and the Bureau's "Technology News," the mining community was made aware of the potential safety benefits of sensitive ground-fault protection. Several companies inquired about the availability of prototypes for field evaluations.

Three GFR's were forwarded to a western haulage-equipment manufacturer for testing on two types of new electrical scooptrams used in hard-rock mines. One vehicle, intended for use in small-diameter haulageways, had a tramming capacity of 1,500 lb with a 0.5-yd^3 bucket. Electrically powered at 380 V, three-phase, 50-Hz, via a 250-ft, No. 6 AWG trailing cable, it featured a 30-hp motor onboard. Existing ground-fault protection was set at 4 A with no fault-limiting resistance. With the sensitive GFR trip set at 60 mA, the vehicle was operated through load-haul-dump cycles under start, run, and stall conditions for over 8 h without any GFR trips.

Next, a prototype GFR was evaluated with a large scooptram of 27,000-lb tramming capacity and 8-yd^3 bucket capacity. Electrically powered at 600 V, three-phase, 60-Hz, it featured a 200-hp motor onboard. Nuisance-free GFR operation was experienced with a trip setting of 100 mA. When adjusted to lower settings, the GFR would activate upon motor startup.

These tests, the first commercial evaluations of the prototype GFR's, proved their viability for 50-Hz power. It is believed that further reductions in the trip setting would have been possible if a grounding resistor of suitable ohmic value had been utilized at the source transformer. Nevertheless, the manufacturer was quite pleased with the results and noted that a high degree of safety was obtained with protection set at 100 mA. This manufacturer is now considering equipping all new vehicles with sensitive GFR's.

Through assistance from the Mine Safety and Health Administration, arrangements were made with a mine operator to evaluate the sensitive GFR in an underground coal mine in southern Ohio. The prototype was installed within a 1,040-V ac load center and protected a 750-ft, 1/0 AWG, SHD-GC cable powering a continuous miner. When the power was energized, the relay immediately activated, indicating a ground fault was present. Troubleshooting by the mine electrician revealed that the high-frequency signal of the local ground-check monitor, superimposed on the power conductors, was induced into the relay through the GFR toroidal CT. Repositioning the monitor's tone filter eliminated this problem. However, the sensitive GFR continued to activate whenever the circuit breaker was closed. This was attributed to the significant charging current of the shielded cable and was eliminated when the GFR trip setting was increased to 75 mA.

DIRECT CURRENT UTILIZATION

The second phase of the Bureau's sensitive ground-fault research program focused on protection of dc power systems feeding offtrack vehicles. For the past 25 years the use of dc for powering underground mining equipment has continually declined, with a concomitant rise in the consumption of ac. This trend is logical as ac can be transmitted and distributed more efficiently and ac motors require much less maintenance. At first glance, it may seem that dc systems in the mining industry are destined for obsolescence. However, for certain mining applications such as traction where high starting torques are needed, the series-wound dc motor is more suitable. Thus, dc will continue to play a role in powering mining machinery, especially in the form of onboard rectification. Workers will continue to operate and repair dc machines, and the dc shock hazards associated with these jobs will continue to exist.

Previous Bureau-sponsored research (*9*) showed that of all possible ground-fault protection schemes, a differential-current arrangement using a saturable transformer appeared to provide the greatest measure of safety because of its fail-safe operation and selectivity in protecting individual circuits. As shown in figure 27, a toroidal transformer serves as the ground-fault current sensor and encircles both the positive and negative outgoing conductors of the dc circuit. The primary winding of the sensor is excited by an ac signal, while the secondary is connected to the GFR.

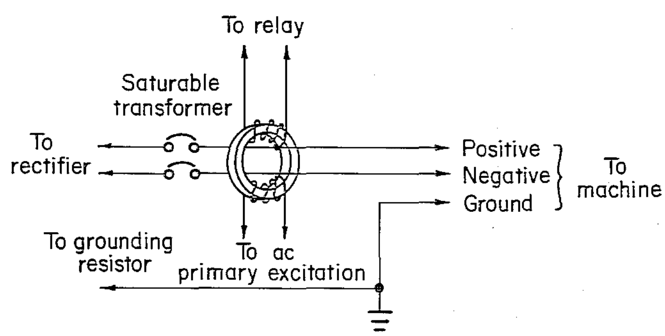

Figure 27.–Differential current relaying using saturable transformer.

Under unfaulted conditions, ac is induced in the secondary winding, causing the relay to operate in the normal mode. The circuit current through the positive conductor equals that through the negative conductor, and the magnetic fields about both conductors tend to cancel each other. When a ground fault occurs, the currents in the positive and negative conductors become unequal. The resultant magnetic field alters the transformer action of the sensor and reduces the voltage across the transformer-secondary winding, causing the relay to initiate a tripping action. These two components, the saturable transformer and the solid-state relay, comprise the sensitive dc ground-fault protection.

PROTOTYPE DESIGN AND CONSTRUCTION

Current Sensor

The sensor was designed (*20*) using theoretical predictions of performance along with experimental observations. The parameters to be quantified are shown in figure 28. They include R_s, the series resistance; N_p and N_s, the primary and secondary turns; the core material and dimensions. A 0.5-in, tape-wound core was constructed of a high-permeability, low-loss nickel-iron alloy. To accommodate two power conductors, the core was sized at 2.5 in; its overall outside diameter was 3.5 in. After winding, the core was annealed to remove strain and impurities from the tape.

Dc was then applied through the window while the ac secondary voltage was measured, with the objective to maximize the drop in ac output for dc fault currents in the milliampere range. By varying the number of primary and secondary turns, the series resistance, and the exciting voltage, plots of the ac output versus the dc fault current were derived, as shown in figure 29. Satisfactory performance was obtained with a series resistance of 470 Ω and 25 turns on the primary and secondary.

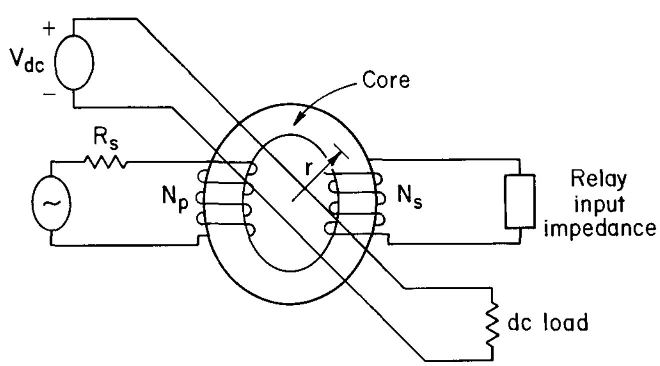

Figure 28.–Saturable transformer current sensor.

Primary excitation frequency was plotted against the drop in output voltage during a ground fault. From figure 30, it can be seen that a relatively low frequency is desirable. A nominal value of 110 Hz was chosen to avoid interference with 60- and 180-Hz induced voltages.

The completed design is shown in figure 31. The sensor's magnetic properties are mechanically protected by a metal and phenolic housing.

Electronic Relay

Analysis of the electronic relay shows that it consists of a series of building blocks (fig. 32). The 110-Hz oscillator powers the primary of the saturable transformer sensor.

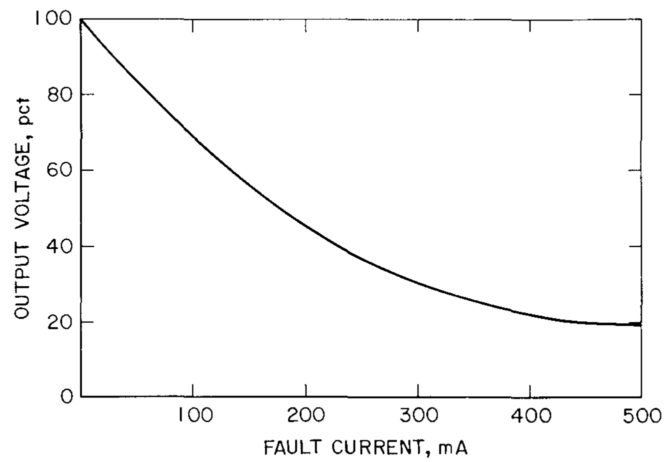

Figure 29.–Saturable transformer output voltage versus dc fault current.

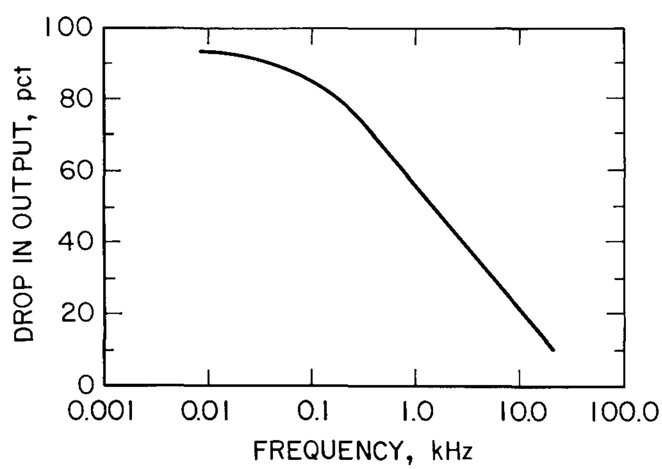

Figure 30.–Drop in sensor output versus frequency.

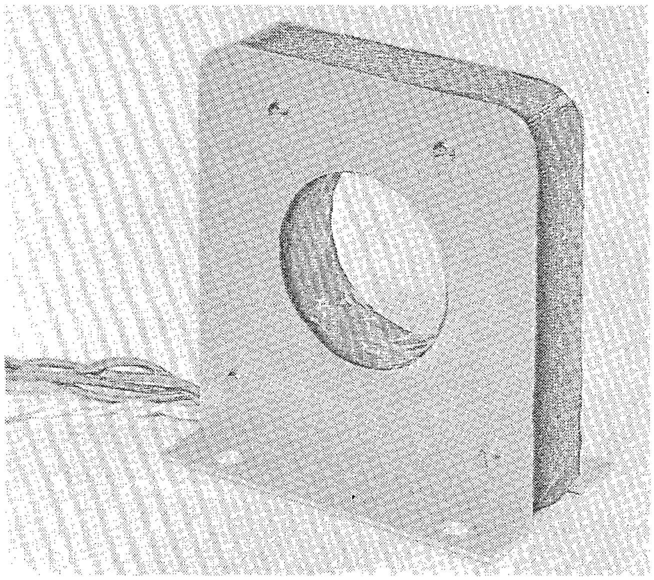

Figure 31.–Saturable transformer prototype.

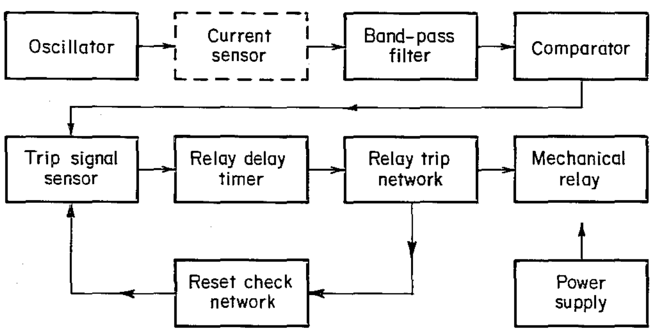

Figure 32.–Dc relay block diagram.

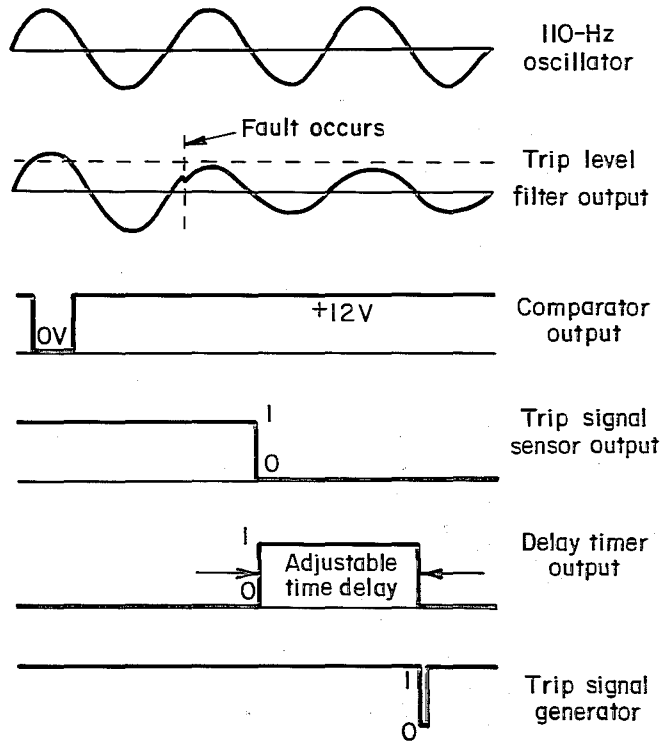

Figure 33.–Dc relay timing diagram.

Figure 33 displays timing diagrams from the circuitry shown schematically in figure 34. During the imposition of a ground fault, the magnitude of the primary input signal remains constant. The sensor output, essentially identical to the input, feeds a second-order band-pass filter designed with a 3-dB bandwidth of 10 Hz and a midband voltage gain of 5. When a ground fault greater than or equal to 150 mA dc flows through the sensor window, the sensor core saturates and the filter output drops to 55 pct of its original value. The peak ac output of the band-pass filter is compared with a positive reference voltage at the input of a comparator. Adjustment of this reference voltage sets the current pickup or trip level, recommended at 150 mA dc.

During a fault the comparator no longer sends periodic pulses to a retriggerable one-shot acting as a trip signal sensor. Accordingly, the output of this one-shot switches from 1 to 0, its stable state. This transition triggers an adjustable timer, which in turn activates the relay trip network via the gating of a silicon-controlled rectifier (SCR), if the fault duration is 100 ms or longer. The firing of this thyristor diverts current from the coil of an electromechanical relay. This deactivated relay in turn operates the trip mechanism of the circuit breaker. As with the ac sensitive GFR's, the dc prototype features a reset switch and a test circuit. In addition, the GFR acts to remove power upon loss of signal from the sensor or upon loss of the 120-V ac control power.

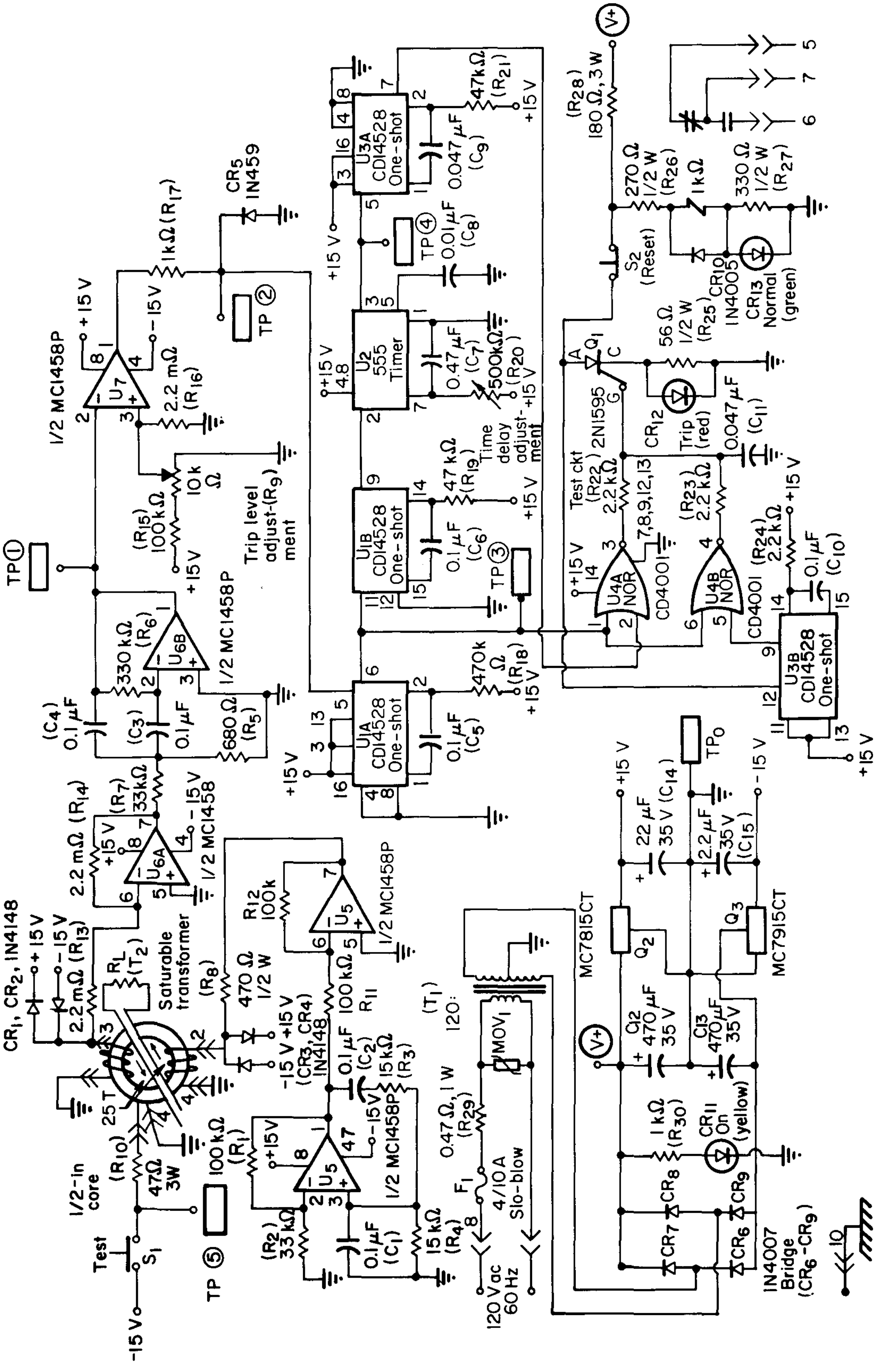

Figure 34.-Schematic diagram of dc relay prototype.

The components of the prototype are mounted on an interchangeable board within a metallic housing as shown in figure 35. This compact design measures 8-3/4 in high by 5-1/2 in deep by 2 in wide.

LABORATORY EVALUATION

The sensitive dc GFR prototypes were evaluated for immunity against voltage and current transients in a manner similar to that used for the ac prototypes. In all tests, the relays did not falsely activate nor did they become damaged by the simulated power system surges. The dc GFR's are available for installation in an underground mine having dc face equipment fed from a three-phase full-wave rectifier.

ALTERNATING CURRENT DISTRIBUTION

The final phase of the Bureau's ground-fault research program focused on the ac distribution portion of coal mine power systems. These high-voltage circuits feature a series of switchhouses, each with inherent ground-fault protection, distributed along the way from the surface to the section load centers. The operation of the electromechanical GFR's, installed in these switchhouses, is coordinated by large, intentional time delays to ensure that faults are cleared without interrupting power to sound, upstream circuit portions. These additive delays may in practice average 2 s per relay. As a result, upstream relays respond slowly to hazardous ground currents and workers are exposed to fire and burn hazards. In response to these problems, the Bureau conducted research to design and construct a coordination-free relaying system that reacts to a ground fault 50 to 100 times faster than present protective systems.

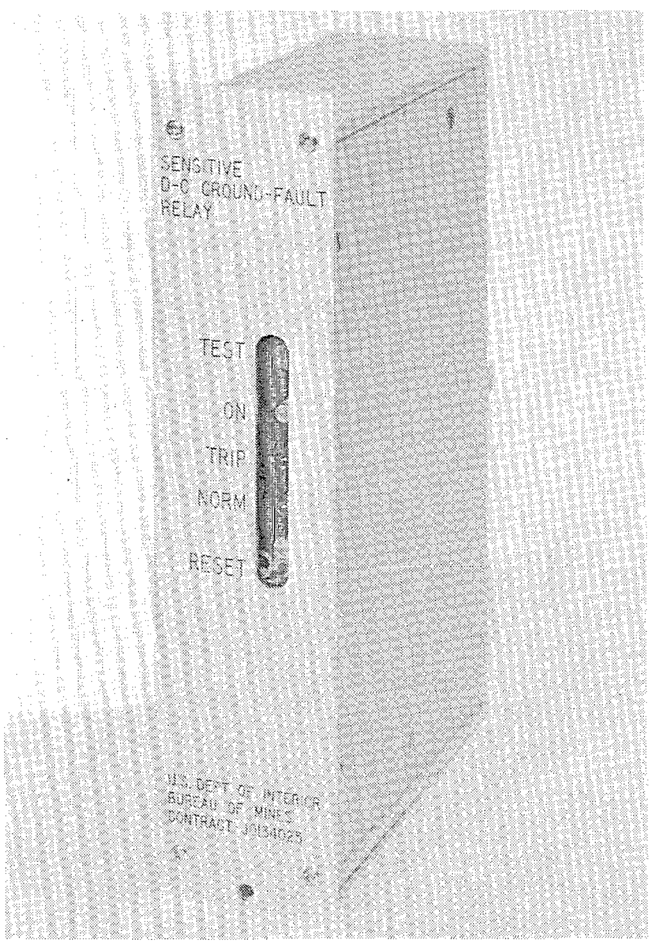

Figure 35.–Dc relay prototype.

To understand the concept of coordination-free relaying, a series of switchhouses must be visualized installed along a high-voltage distribution line (fig. 36). If a relay in an upstream switchhouse detects a ground fault and a downstream relay does not, the fault must be in the zone joining them. Consequently the upstream relay will activate the local circuit breaker. If both upstream and downstream relays detect faults, the fault must be downstream from the zone and neither relay will activate.

BACKGROUND RESEARCH

Initial research centered on determining the highest practical ohmic values for high-voltage grounding resistors. These components, connected between the transformer-secondary neutral point and the earth grounding medium, restrict ground-fault current magnitude. To provide protection against electrocutions, this limitation should be in the milliampere range.

Underground high-voltage cable is required to have metallic shielding around each power conductor. Consequently, this cable exhibits significant distributed

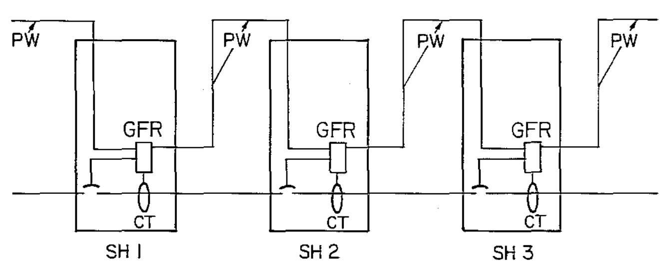

Figure 36.–Typical high-voltage distribution circuit.

capacitance not only among power conductors, but also between power and ground conductors. In addition, the use of discrete capacitors for surge and power-factor correction adds to the circuit capacitance. Thus, distribution circuits feature charging currents of up to 10 A. Through a computer-assisted transient evaluation of mine distribution circuits, it was concluded that instability results if ground faults are limited below capacitive charging currents. Thus, it was recommended that present ground-fault-limiting levels of 25 A continue to be utilized, precluding complete personnel shock protection.

With coordination-free relaying, detected-fault status is continuously transmitted from the downstream to the upstream relay. Utilizing dependable blocking logic, the signal from the downstream relay acts to prevent tripping. The most practical communication link available appears to be the ground-check conductors already present in almost all high-voltage cables used with pilot ground-check monitors (GCM's).

Ground-check monitoring systems for high-voltage distribution usually monitor the integrity of the grounding conductor connected between switchhouses (fig. 37). Separate, independent GCM units are installed in each switchhouse. GCM's commonly circulate low-voltage 60-Hz signals through the pilot-ground circuit. Consequently, a transmission frequency of 1,000 Hz was chosen for the coordination-free ground-fault relay (CF-GFR) blocking signal. Active electronic filters were used to couple and decouple the superposed signals.

Two intentional delays were proposed for the experimental relays: 50 ms for primary and relay-racing protection and 150 ms for backup protection. Primary protection must include time for fault signal detection and a safety factor. Relay racing occurs if a blocking signal is not received in time to prevent false tripping upstream. The backup delay is desirable should the downstream breaker fail to open during a ground fault.

It was recommended that backup be graded in 150-ms increments, with the most downstream breaker in a series path having a 50-ms delay as primary protection and no backup relay. The next outby breaker would have a 50-ms delay for primary protection and a total delay of 200 ms in backup. The next relay would exhibit delays of 50 and 350 ms, respectively.

PROTOTYPE DESIGN AND CONSTRUCTION

Once design criteria were established, a CF-GFR was designed and three prototypes were constructed. Block diagrams for the overall system and each relay are shown in figures 38 and 39, respectively (*21*). The CF-GFR design has been fully documented through schematics, wiring diagrams, and component listings (*22*).

The blocking signal, tuned to 1,000 Hz, is coupled to the pilot and ground wires through a switch controlled by a logic device. When a ground fault is sensed locally, the coupling is accomplished. The purpose of the attenuator is to avoid a very low impedance path between the pilot and ground wires. Such a path would severely reduce the blocking signal amplitude and prevent its propagation to the upstream switchhouse and relay.

The upstream detector circuit checks for proper amplitude and frequency in the incoming downstream blocking signal. The 60-Hz GCM signal is attenuated by the bandpass filter. When the blocking signal is detected, a blocking logic signal is sent to the trip element actuator to inhibit primary protection tripping.

Local zero-sequence ground faults are sensed by the toroidal CT. When this ground current is greater than the pickup level of 5 A, a trip signal is sent to the trip element actuator after the appropriate delay interval. However, primary protection is inhibited if a blocking signal has been detected from the downstream relay. Backup delay time is then sensed. The trip element is then actuated at the end of the backup delay interval if the locally sensed ground fault is still greater than the pickup setting.

Additionally, if the local fault-sensing CT becomes open, then, irrespective of any other signals, a trip is

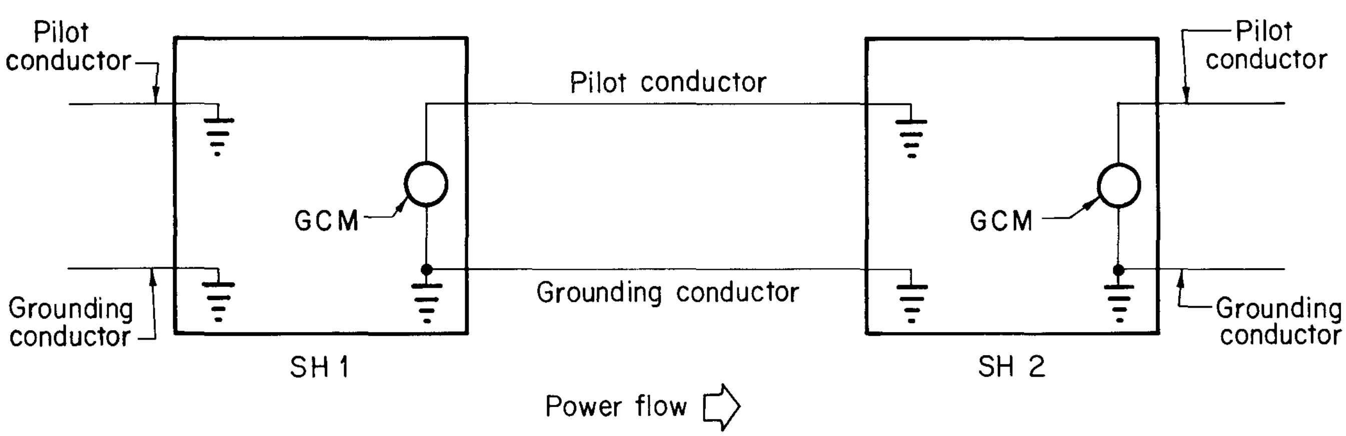

Figure 37.–Simplified diagram of ground-check monitoring system used in mine distribution systems.

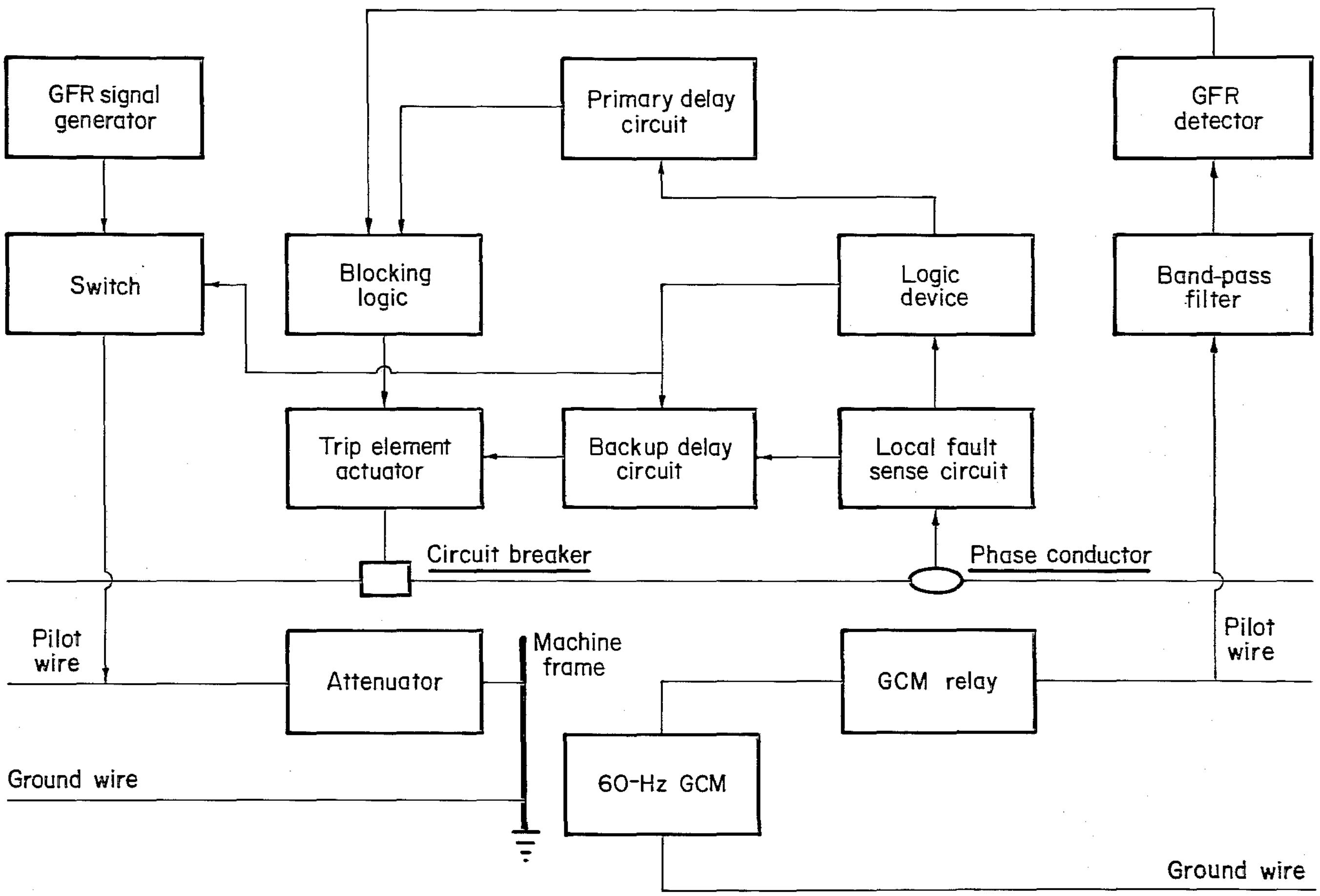

Figure 38.–System block diagram.

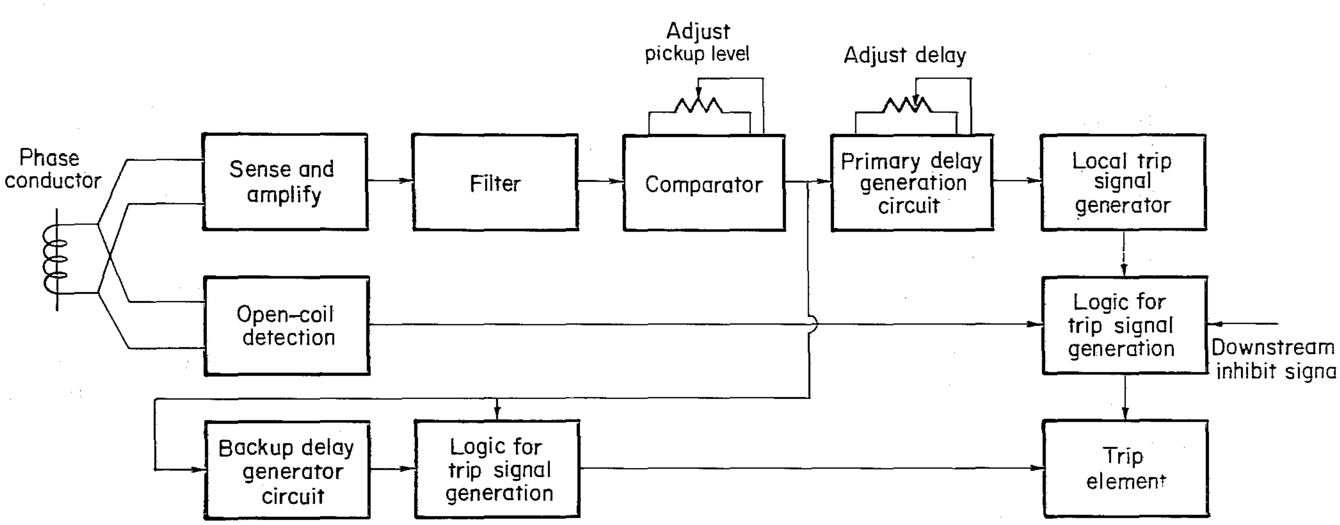

Figure 39.–Block diagram of relay circuit.

activated instantaneously. Also, if an increase in impedance of the pilot- and ground-wire circuits is sensed by the GCM, an instantaneous trip is activated.

LABORATORY EVALUATION

Laboratory tests with a 12-V commercial GCM and the CF-GFR prototypes verified that both safety devices will function without interfering with each other. The operating range of the GCM's, whose voltage is compatible with the GFR filters, is limited to 4,000 ft by the substantial impedance of No. 8 AWG pilot conductors. Nevertheless, this should not preclude the direct application of CF GFR's on most underground distribution circuits.

CONCLUSIONS

Sensitive and coordination-free ground-fault protection has been designed for use on resistance-grounded mine power systems. To facilitate commercial manufacture, the designs are fully documented by detailed schematics, assembly drawings, and component listings. Prototype units have been tested in the laboratory and are available for installation in underground mines. Implementation of this practical protection would not require extensive alterations to mine power systems. Existing GFR's would simply be replaced with solid-state units.

The sensitive GFR's, when installed on ac and dc mine utilization circuits, can prevent nearly all the potential electrocutions on these low-voltage power systems. CF GFR's, installed on ac distribution circuits in coal mines, can reduce the incidence of fires associated with high-voltage power systems by significantly decreasing response time to faults.

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APPENDIX.–ABBREVIATIONS AND SYMBOLS

ac — alternating current

AWG — American wire gauge

C — capacitor

CF-GFR — coordination-free ground-fault relay

CR — relay

CT — current transformer

D — diode

dc — direct current

E — RMS output voltage of transformer secondary

f — frequency

F — fuse

GCM — ground-check monitor

GFR — ground-fault relay

h — toroid core width

I — current

I_p — RMS value of ground-fault current

IC — integrated circuit

K — electromagnetic relay

L — inductor

LED — light-emitting diode

MOV — metal-oxide varistor

N — number of turns on secondary winding

N_p — primary turns

N_s — secondary turns

N.C. — normally closed

N.O. — normally open

PW — pilot wire

Q — thyristor

QA — operational amplifier

R — resistor

R_b — body resistance

R_g — grounding resistor

R_i — inner toroidal radius

R_L — load resistance

R_o — outer toroidal radius

R_s — source resistance

RMS — root-mean-square

S — switch

SCR — silicon-controlled rectifier (thyristor)

SH — switchhouse

t — time

t_1 — operating time of GFR

t_2 — operating time of molded-case circuit breaker

T — transformer

TP — test point

u — core permeability

U — digital logic component

UJT — unijunction transistor

V_{cc} — control voltage

V_{dc} — dc voltage

V_{ln} — line-to-neutral system voltage

Z — Zener diode

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