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Guide to Substation Grounding and Bonding for Mine Power Systems

By Wils L. Cooley and Roger L. King

UNITED STATES DEPARTMENT OF THE INTERIOR

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GUIDE TO SUBSTATION GROUNDING AND BONDING FOR MINE POWER SYSTEMS

by

Wils L. Cooley[1] and Roger L. King[2]

ABSTRACT

Although electric utility companies have been active in grounding and bonding within substations, the mining engineer or mine electrical engineer is not involved to the extent that he can be fully up-to-date on the most effective practices for substation construction. The coal mine power system is grounded in a fundamentally different way from most other industrial power systems and is subject to considerable Federal and State regulation. At this time, there is little information that is directly applicable to the mine situation, especially if the substation must be built in an area of limited size or in low-conductivity earth. The objective of this guide is to provide specific engineering information to the mining industry. Using as little theory as possible, it was written to be general enough to cover most substations, but specific enough to provide direct help with each substation. It will attempt to recommend practice that is in agreement with present Federal rules and regulations.

INTRODUCTION

Federal law requires that each coal mine establish a high-resistance grounded mine power system at its surface substation. This system is required to be connected to a low-resistance grounding medium at the power source. Low resistance is usually defined as being 5 ohms or less. Additionally, all conductors extending underground must be protected with surge or lightning arresters, which are to be connected to a low-resistance grounding medium on the surface; this grounding medium shall be separated from the power system neutral grounds by a distance of not less than 25 feet. (Larger separation distances may be used if hazardous conditions can thereby be reduced.) While such a requirement has a sound engineering basis for the mining industry, it does significantly complicate substation construction.

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The two grounds, when required, are meant to serve very different purposes, and therefore should be designed according to completely different standards. The safety ground bed resistance (neutral ground) should provide a zero-voltage reference under all conditions, whereas the substation ground must sink lightning and fault currents while maintaining the entire substation at the same potential. Each of these will be taken up in turn.

THE SUBSTATION GROUND MAT

The substation ground mat is a series of interconnected ground wires (and possibly ground rods) buried in the earth of the substation floor. To it are connected the frames of the power transformer and all substation switchgear, surge arresters within the substation, the steel substation structure, the substation fence, and static wires of associated pole lines (usually).

The primary purpose of the substation ground is to provide electric shock protection for personnel working in and around the substation, including during lightning strokes, short circuits, equipment failures, and many situations of human error or carelessness. This protection is provided by the multiple interconnection (grounding) of all accessible surfaces within the substation in such a way as to limit to a safe level the voltage differences that can appear from point to point on these surfaces. Substation equipment that cannot be grounded (the power bus, for instance) is placed so as to be inaccessible to contact by personnel.

A second purpose of the substation ground is to limit insulation stress by readily conducting lightning surges to earth via the station surge (lightning) arresters. Although this may be done somewhat more effectively by constructing a very low resistance ground, the improvement is usually not worth the effort. On the other hand, if Federal or State regulations require that a specified minimum resistance be met, this becomes an additional design criterion.

Grid Design

One of the most important aspects of substation ground design is the construction of the ground mat itself, that system of conductors that is to be buried within the earth of the substation. The purpose of these conductors is to hold the voltage reference of the substation floor at ground potential. A common hazard within the substation arises when a person stands on the substation floor and touches the metallic surface of the grounded equipment. If a large voltage difference exists between hand and foot, an injurious or lethal current may flow. These touch potentials can be minimized by covering the entire substation with a metal plate that is connected to the accessible surfaces, but this is neither practical nor necessary, since the body can tolerate some voltage differences without serious effects. An acceptable level of personnel protection can be achieved with an open grid of conductors buried beneath the surface. The maximum acceptable spacing depends on the available fault current, resistivity of the earth, clearing time of protective devices,

and overall station geometry. All these factors are covered in detail in IEEE Standard 80-1976 (2).[3] The following basic guidelines should provide safety in nearly every situation, however:

1. Completely enclose the substation with a continuous ground wire. To protect persons outside the station while they are in contact with the station fence (assuming the fence is metallic), this perimeter wire should be buried about 3 feet outside the station fence.

2. Lay out a rectangular grid of wires covering the substation area. These should be spaced approximately 5 to 15 feet apart, (IEEE Standard 80-1976 gives a method for more precise determination of spacing.) The wires should be reasonably uniformly spaced, and preferably located along rows of equipment to facilitate the making of ground connections.

3. Add extra conductors to the grid at the corners of the substation and in work areas of the substation, since extra protection is needed there.

4. Bond the grid together at all intersecting points, using either exothermic-welded connections or heavy clamps designed for grounding applications.

5. Bond all equipment within the substation to the ground grid at two different points, preferably at points of interconnection of the ground grid. Bond the station fence and posts to the ground grid. Bond the station fence gates.

6. If a borehole casing is located within the substation, bond it to the station ground grid.

7. Tie water pipes, gas pipes, and other buried conductors to the station ground grid, preferably at several points. (If possible, the substation site should be chosen to avoid gas and water pipes.)

8. Connect rails, telephone cable grounds, and other such conductors to the ground grid. Since they may carry hazardous station potentials outside the station area, it may be necessary to provide insulated joints or other means of isolation as they leave the substation. (Railroad track may require very special treatment in order to ensure safety.)

9. If the station is quite small, or if the soil is subject to severe freezing or drying or has very high resistivity, ground rods may be driven at mesh points and interconnected with the ground grid. These are most effective if driven near the periphery, especially near the corners. Driving rods closer together than 10 feet is not effective.

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

10. Be sure that all buried conductors are resistant to corrosion. Never mix copper with steel or aluminum. If steel clamps must be used with copper conductors, for instance, they will be rapidly destroyed by corrosion unless they are protected by an asphaltic coating or cadmium plated.

Under most conditions grids made with small-diameter wire are sufficient to carry current safely. Small wires are easily broken, however. Experience has shown that 2/0 wire or larger is usually required for mechanical strength, and many companies have set 4/0 as their standard. Prefabricated mesh is available that uses numerous smaller conductors welded together. This is also acceptable mechanically. The conductors themselves can be copper, copper-clad steel, galvanized steel, stainless steel, or aluminum (usually not a good idea unless special alloy is used). It must be remembered that dissimilar metals must not be buried together as part of the grounding grid.

The conductors should be buried about 18 to 24 inches below grade in the substation. The perimeter cable may be placed somewhat deeper to reduce the gradients present around the station perimeter. Close-mesh mats near operating handles should be brought up closer to the surface for maximum protection.

Rubber mats or wooden platforms can be used for personnel protection at operating handles instead of close-mesh mats, but they must not remain in the substation, since they do not protect when wet and are hazards in the winter. Care must be taken that the insulated area is large enough to protect the area around the handle.

The use of gravel surface in the substation greatly improves safety, since it significantly increases the contact resistance between earth and a person's feet. The use of gravel can increase the tolerable touch voltage by a factor of two or more. This gravel should be well drained, at least 4 inches thick, and extend more than 4 feet beyond the substation fence. Providing a thicker layer of gravel will afford even more protection.

Mat Topography

The total resistance of a ground mat is closely related to its perimeter. A long, narrow mat will have lower resistance than a square one of the same area. Decreasing the grid spacing will not significantly reduce total resistance, nor will driving ground rods within the station itself. The mat should be designed to cover a relatively large area with conductors arranged to reduce high-voltage gradients. Figure 1 and figure 2 show suggested ground mat configurations for large and small substations.

Although the equipotential characteristic of the substation ground mat will protect personnel regardless of its resistance to earth, it is desirable that the resistance of the substation ground be low. This reduces the voltage rise that lightning current causes, which reduces the stress on insulation throughout the power system and tends to reduce gradients in the earth around and within the substation. For moderate to large substations, the size of the grid will usually insure that the station resistance is sufficiently low.

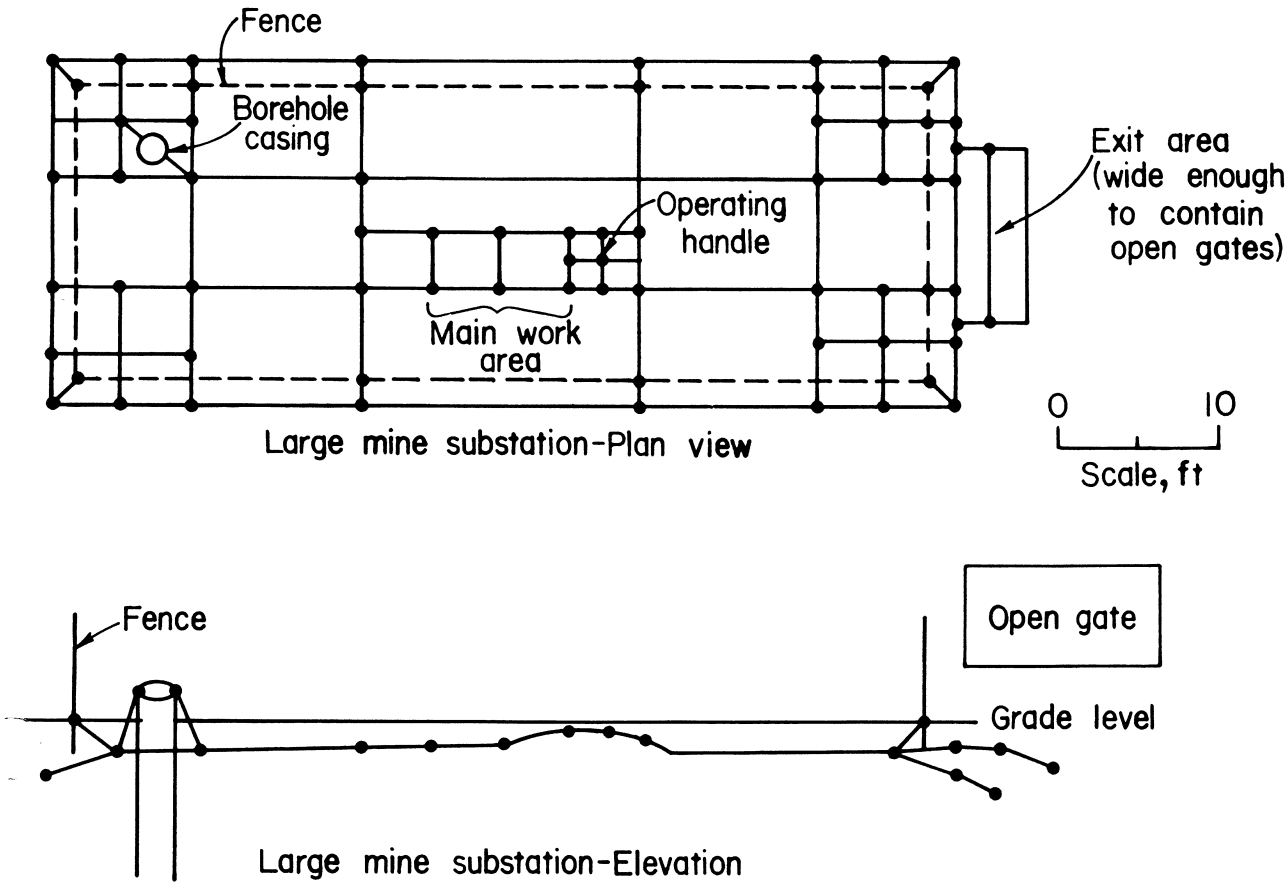

FIGURE 1. - Typical ground mat for a larger mine substation (24 by 65 feet) showing increased protection by adjustment of grid spacing and burial depth.

For small substations, or substations built on high-resistivity soil, it may be desirable to augment the earth connection with driven rods or other additional conductors. It is recommended that the substation ground resistance be reduced to 5 ohms or less where practical.

Additional Protection

As mentioned above, additional protection can be achieved by adjusting the burial depth and mesh spacing in critical areas. Close spacing and shallow burial are suggested in personnel areas at operating handles, while deeper burial is suggested at the station periphery to reduce the gradients along the station boundaries.

Besides being subjected to touch potentials within a protected area, a person may experience an excessive voltage between his feet as he enters or leaves the protected area. These step potentials can be lessened by providing "potential ramps" of progressively deeper buried conductor in the it area.

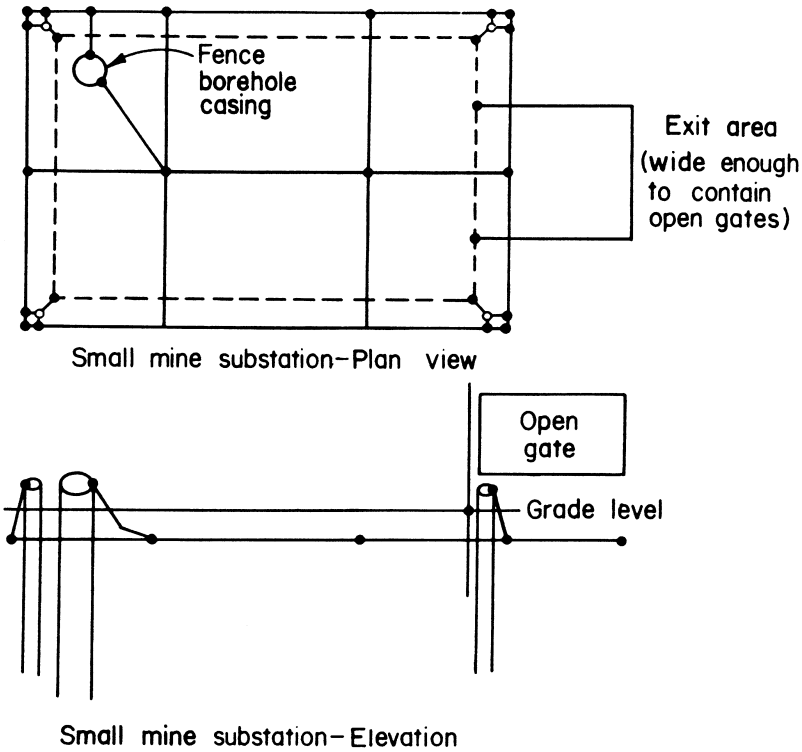

FIGURE 2. - Typical ground mat for a small mine substation (18 by 30 feet) with auxiliary driven rods to lower total resistance.

Such additional protection is necessary only where large fault currents (greater than 10,000 amperes) are possible.

SURGE ARRESTERS

Surge arresters are important components of any substation, and their proper interconnection to the ground grid is crucial to providing the proper level of protection for equipment and personnel. The term "lightning arrester" does not properly describe the function of the modern protection devices, and they are now more properly called surge arresters or surge diverters, since they are designed to divert any abnormal surge to ground.

The modern surge diverter is a fairly sophisticated device which automatically diverts abnormal transients to ground, interrupts any power-follow current, and often provides a visual indication of its failure when this occurs. Detailed accounts of device operation are given in several places and will not be covered here (8).

Sizing of Surge Arresters

To provide the proper level of protection, arresters must be correctly sized for the power system voltage and configuration used. The sparkover voltage should be low in order to divert as many surges as possible, but must be high enough to prevent operation during normal power system voltage fluctuations. In conventional applications direct-connected arresters are continuously energized at the line-to-ground power frequency voltage. To size the arrester, it is necessary to determine the highest line-to-ground power frequency voltage to which the arrester would be subjected during a ground fault on any of the system phases. This voltage may range from a minimum equal to the line-to-ground voltage on a solidly grounded wye system to a maximum equal to line-to-line voltage on an ungrounded delta system. Resistance-grounded mine power systems are essentially equivalent to ungrounded systems and therefore require that arresters be sized according to line-to-line voltage. Sizing of arresters for the primary line (from the utility company) will depend on how effectively their system is grounded, information which should be obtained directly from the company. If arresters

are not sized properly, they cannot fulfill their function. If they are sized too low, they will operate during ground faults and be damaged. If they are sized too high, they will not properly protect equipment.

Physical Location of Arresters

Surge arresters must be placed as close as possible to the terminals of the equipment they are to protect. Within the substation, arresters are primarily used to protect the power transformers and will not properly do so if placed more than a few feet away. Most manufacturers provide arresters on the substation equipment or provide mounting brackets for arresters to keep them close to the transformer bushings. It is estimated that the self-inductance of each foot of line lead to the arrester and the arrester ground lead causes a 1,600-volt drop for a typical lightning surge. As shown in figures 3 and 4, this means that the voltage transient produced by lightning at a piece of protected equipment is significantly affected by arrester location and lead placement. The transient voltage of concern is usually that which appears between the power conductors and the case or frame of a transformer or motor. To make this as small as possible, the arrester should be placed as directly as possible between these two points. Leads should be run as straight as possible with no sharp bends.

The only exception to this rule occurs when the installation also incorporates a fuse at this location. Since the operation of the arrester discharges a heavy current which may damage the fuse, it is proper to place the fuse between the arrester location and the protected equipment, as in figure 4. This increases the transient voltage slightly, but protects the fuse. However, this installation may necessitate working on an energized line if the arrester requires replacement.

Protection at Terminators (Potheads)

Federal law requires that surge arresters be placed on ungrounded conductors that pass underground, and that these arresters be no more than 100 feet from the point where the conductors enter the mine. In many mines, this provides transient protection for the power distribution cables, but some open pit mines require additional protection. In these mines the secondary distribution circuit (pit-feed) is carried as open pole line until it nears the pit, where it is converted to the shielded feeder cable lying on the earth. The cable should be protected by placing arresters as near as possible to the cable terminator. These arresters should be connected to the substation ground (if it is nearby) or to a separate ground established at this location.

Secondary Arresters

Since arresters are required on all ungrounded conductors leading underground, most mines incorporate secondary arresters into their power system designs. Whereas primary arresters are very often provided or specified by the manufacturer of the substation transformer, the mine operator or engineer may be forced into designing his own secondary transient protection.

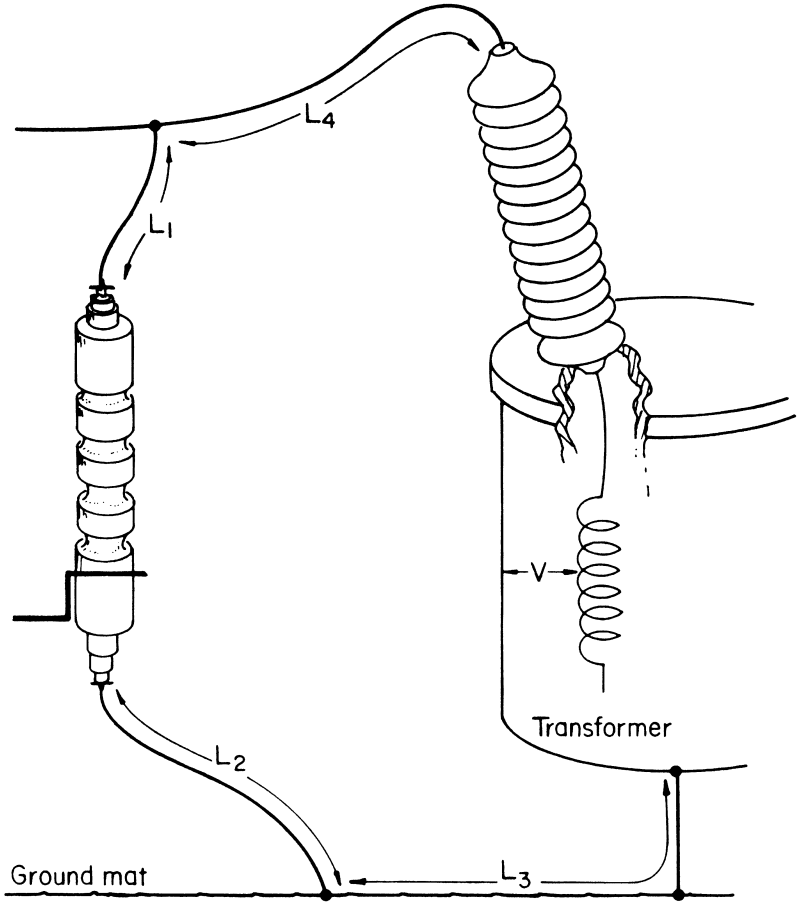

FIGURE 3. - Poor utilization of arrester for transformer protection. Lead lengths L_1 and L_2 add about 1.6 kv per foot to transient voltage V; L_3 and L_4 also add some voltage.

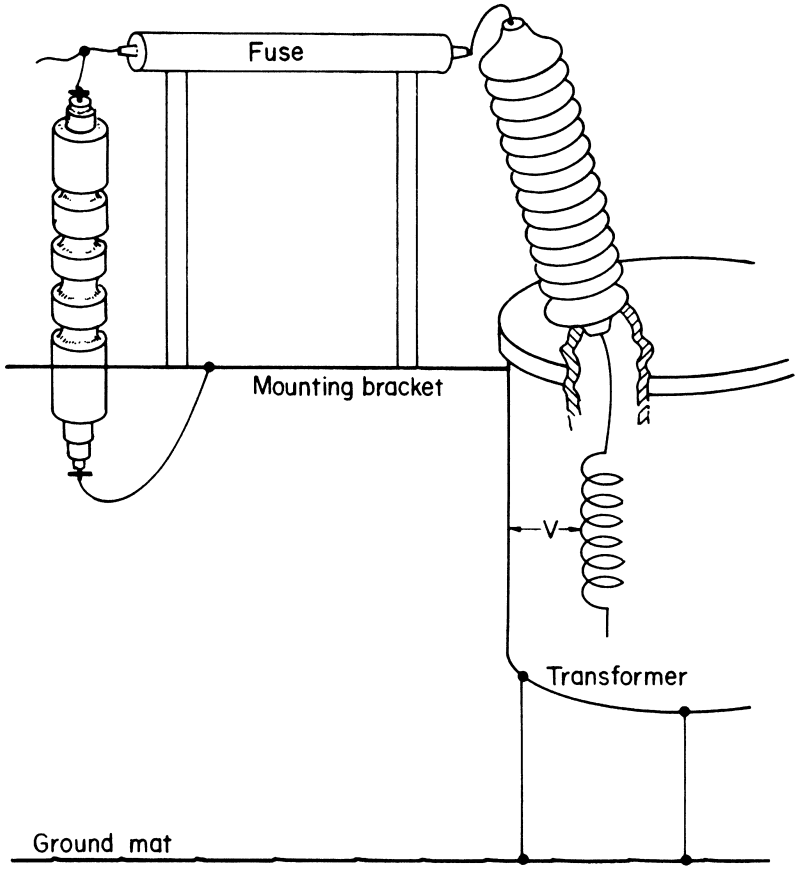

FIGURE 4. - Good utilization of arrester for transformer protection.

Manufacturers of load centers provide protection on their incoming lines, but usually more arresters are needed, especially on the surface as the conductors enter the mine. The same rules apply as when sizing and installing the primary arresters, except for two important differences. First, since the secondary circuit is grounded to the safety ground bed, these arresters offer maximum protection for equipment when connected to the safety ground and not to the substation ground. However, for reasons of personnel safety, this sometimes cannot be done since it may cause large voltages to appear on the safety ground. The proper choice of an arrester ground is discussed in the next section.

Second, arresters on the distribution system can be subject to sustained overvoltage if there is an insulation failure between the primary and secondary circuit. Such an overvoltage can cause the arrester to explode as it attempts to carry a heavy sustained current, sending debris flying with injurious force. Ferroresonance is also a source of secondary arrester failure. If the arrester cannot be located so that its explosion will not injure personnel, then it should be protected by a fusible "lockout" connection or other means of reducing the probability of secondary arrester explosion.

GROUNDING DISTRIBUTION SYSTEM ARRESTERS

Surge arresters used to protect the primary circuit in the mine substation ould be tied directly to the substation ground grid. When arresters are aced on the secondary distribution system, however, care must be taken to insure that they provide proper protection without endangering mine personnel by causing high voltage to appear on the safety ground (fig. 5). On the other hand, one must also be sure that circuit protection will operate when an arrester fails, lest this failure cause a lethal shock (fig. 6).

There are two opposing requirements for grounding of arresters placed on the distribution system:

1. To protect equipment effectively and provide for circuit protection in the event of an arrester failure, one should ground the arrester to the neutral reference point (the safety ground bed).

2. To protect personnel working with safety-grounded equipment from receiving a shock, one should ground the arrester separately from the safety ground system, thus preventing a current flow (and corresponding voltage rise) through the safety ground bed.

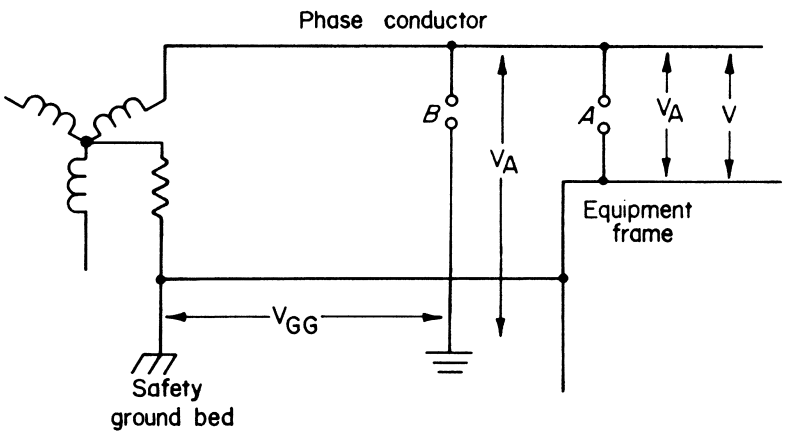

FIGURE 5. - Location of secondary arrester for equipment protection. The surge voltage V is limited to V_A for location *A*, but rises to $V_A + V_{GG}$ for location *B*.

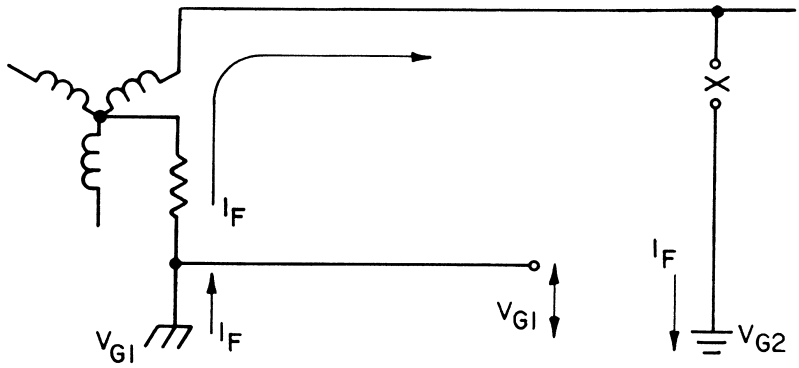

FIGURE 6. - Failure of secondary arrester. Fault current I_F flowing through the ground beds can cause potentials V_{G1} and V_{G2}. V_{G1} may be as high as 250 v and becomes a hazard throughout the entire mine.

Current practice for grounding takes three distinct forms:

1. On pieces of portable equipment that contain arresters (such as power centers or draglines), arrester ground connections are made to the frame ground (the safety ground system). A principal reason for this is that no other ground is available.

2. When the secondary arresters are placed at potheads or equipment at the substation, the arresters must be grounded to the substation ground mat. This prevents surges from the source from being communicated to the safety ground system. Since the arresters are connected to the station ground, care must be taken to insure that they are not also connected to the safety ground, since that would destroy the separation required. Connection of the arresters to the station ground means that the current-flow path in the event of an arrester failure is from one ground bed to the other, possibly causing hazardous potentials on both. This condition should not persist, and the system must be tested to see that ground fault protection or arrester lockout will operate if an arrester becomes shorted.

3. When arresters are placed on permanent equipment remote from the substation, they should be grounded to a low-resistance grounding medium separate from the safety ground whenever practical. This requires the construction of a local ground bed. This bed should be of sufficiently low resistance that ground fault protection will operate in the event an arrester fails, shorting it to ground. It may be interconnected with the substation ground via a static wire or some other means, but it must <u>not</u> be connected to the safety ground system; this is not permitted because it allows lightning entry to the safety ground.

SAFETY GROUND BED

As mentioned previously, the neutral of the mine power distribution system must be separately grounded from the substation ground grid. The reason for this separation is to prevent any large potentials that may develop on the substation ground as a result of primary faults or lightning activity from being coupled to the frames of mining equipment. Open pit mines may experience lightning strokes directly to the secondary system or to equipment frames, however, in which case separation affords no extra protection. Depending on conditions, therefore, establishing a separate safety ground (neutral ground) may or may not provide maximum safety. A separate safety ground appears to be generally safer except in situations where the mining equipment itself is very susceptible to lightning.

If the mine power system is to utilize a separate safety ground bed, this must be designed according to significantly different criteria than those that apply to the design of the substation grid. Its primary purpose is not to dissipate lightning or maintain low potential gradients within some area, but rather to provide a reference voltage for all the underground mining equipment. This voltage must be maintained as close to zero as possible so that no significant potential will exist between the equipment and the mine floor. This low potential is to be preserved in spite of the flow of stray and induced current through the ground bed.

The principal design requirement for the safety ground bed is, therefore, low resistance to earth. Since current flow through the bed is relatively small, potential gradients are of no concern. In fact, the achievement of minimum resistance for a given amount of electrode material tends to maximize gradients in the vicinity of the bed. The design of an acceptable safety ground bed is covered in detail in Bureau of Mines Information Circular 8767 and will not be repeated in any detail here (6).

Separation From Substation

Federal law requires that the safety ground bed be separated from surge arrester grounds (the substation ground) by 25 feet or more. Separation is required to reduce the likelihood that a heavy lightning discharge current the substation ground will find its way to the safety ground bed and elevate it to dangerous voltage levels. Twenty-five feet has been chosen as the minimum separation necessary to assure that dangerous substation potentials will not be transferred to the safety ground system. This has been based on normal conditions and may not be sufficient for all situations. Mines that have a large substation ground and a large safety ground are very likely to need longer spacing. It is a good idea to separate the beds by a distance equal to twice the maximum dimension of the safety ground bed. The maximum dimension is defined as the longest straight line that can be drawn within the volume enclosed by the bed. (If the bed is a borehole, the maximum dimension is equal to its length.) The separation distance should be measured between the two closest points on the respective beds, and the safety ground bed should preferably be placed off a corner or narrow side of the substation. This ensures that coupling between the two grounds is minimized. Figure 7 shows this in more detail.

Measurement of Ground Bed Resistance

Some regulating agencies require that safety ground bed resistance have a resistance less than some standard value, usually 4 or 5 ohms. Mine operators are required to measure the resistance of the bed periodically and are subject to verification by an inspector. The correct measurement of earth contact resistance is not a simple matter, however. It requires special equipment and specific procedures.

The major difficulty with making ground bed resistance measurements is that the bed has a single terminal and therefore provides no convenient way to measure the resistance. Measurement requires a rather complicated arrangement

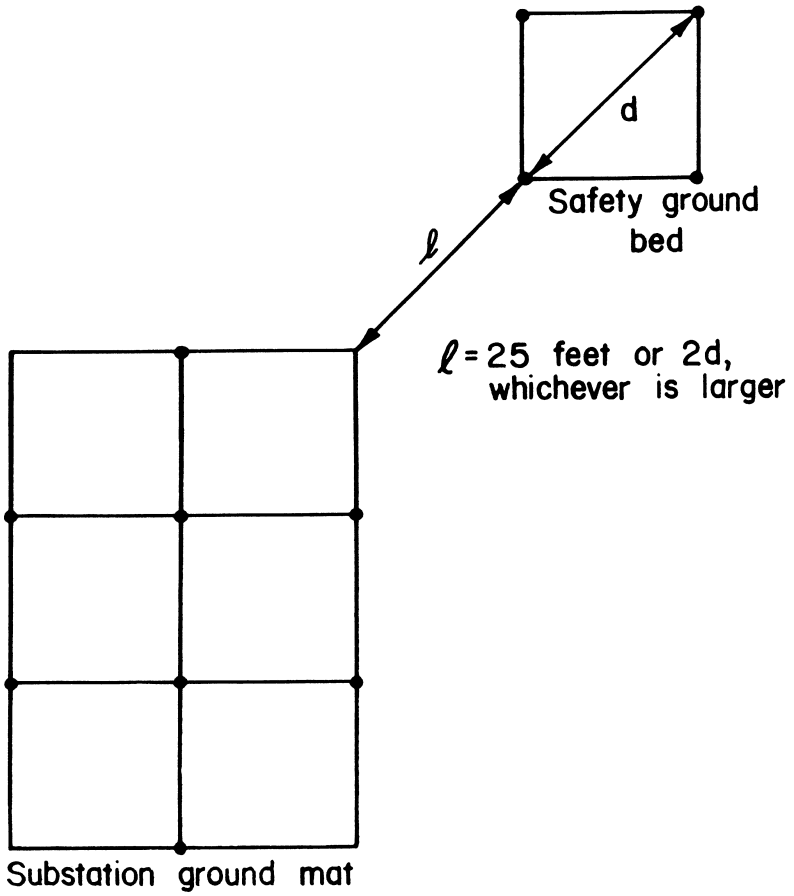

FIGURE 7. - Suggested location of safety ground bed with respect to the substation.

of electrodes, with the possibility of multiple measurements and intermediate calculations. The technique is called "fall-of-potential." Although several other measurement techniques can be found in the literature, they are subject to severe errors and are not recommended. It is important that the same procedure and electrode locations be used in followup tests as were used initially.

The fall-of-potential (FOP) technique is complicated in that it requires several measurements. These multiple measurements are its strength, however, since they provide redundancy in the data. This redundancy allows the operator to check the data against itself for consistency. Unrecognized factors can cause huge experimental errors in assessing resistance by any technique. The internal checking feature of the FOP will detect these errors.

Use of the FOP technique usually requires a meter designed especially for ground resistance measurements. A voltmeter and ammeter may be used in rare situations, but this is not recommended. The technique also requires a nonconducting measuring tape, two metal stakes, and several hundred feet of wire with clamps.

Fall-of-Potential Procedure

The following steps are necessary if the measurement is to be accurate.

1. Disconnect the ground bed from the ground system. Measurements made on a connected system do not yield correct results. They always show the bed resistance to be lower than it really is because of the connected equipment; this may allow a dangerously high bed resistance to go undetected. Extreme care should be taken when disconnecting the bed, since the occurrence of a fault during this time may produce dangerous potentials on the ground system. The mine should be shut down for the period of measurement, or some other

low-resistance ground bed should be used temporarily. High-voltage gloves should be worn when working with ground connections on active systems.

2. Be certain that the meter is tightly connected to the ground bed by short leads. If the meter provides the option of making separate current and voltage connections to the bed (a four-terminal meter), make these connections independently rather than using a jumper at the meter.

3. Estimate the dimension of the ground bed under consideration. As before, this is defined as the longest straight-line measurement within the volume of the bed. It is the length of any single rod, the diagonal of a rectangular grid, the diameter of a circular bed, etc.

4. Establish a straight line extending from the estimated center of the bed for a distance equal to five times the dimension of the bed, or 50 feet, whichever is larger. This line should lie on fairly uniform earth wherever possible and stay far away from any buried metallic objects such as water pipes or other ground beds. Drive one of the stakes a few inches into the earth at this point to form the auxiliary current electrode.

5. Mark off points along the line at 20 percent, 40 percent, 50 percent, 60 percent, 70 percent, and 80 percent of the distance from the center of the ground bed to the auxiliary electrode.

6. Make a series of resistance readings by driving the voltage electrode in at each of the marked points and taking a reading.

7. Plot the data, graphing resistance versus distance. This should form an S-shaped curve with a relatively flat portion at its center. If it does, then the true resistance of the ground will be found at the point the curve crosses a line 62 percent of the distance to the auxiliary current electrode. If the resistance value at 60 percent differs from the value at 50 percent by more than 10 percent, or if the curve is not relatively smooth, it suggests that the measurement is not satisfactory and should be done again along a new line.

Figure 8 indicates some typical data curves and the conditions that produce them. Conditions shown in B and D can usually be remedied by repeating the measurement with a longer or different base line. Condition C may require a completely different measurement procedure, which is beyond the scope of this discussion.

Measurement of Ground Bed Coupling

As mentioned previously, insufficient spacing between the safety ground bed and the substation ground mat may allow dangerous potentials to appear on the safety ground as a result of current flow from the substation ground. If one suspects that too much coupling exists between the grounds, it can be measured either directly or indirectly.

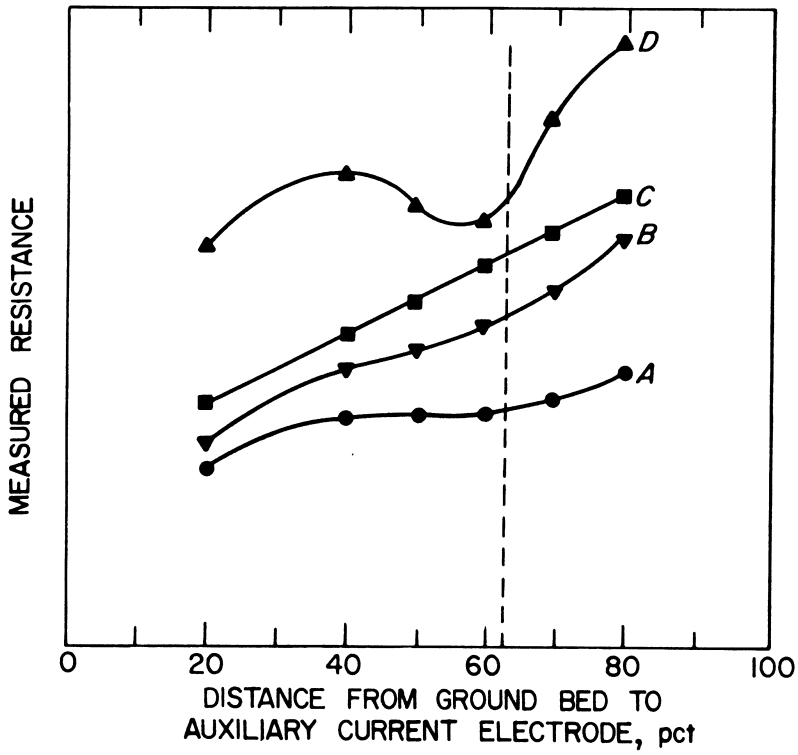

FIGURE 8. - Fall-of-potential resistance curves.

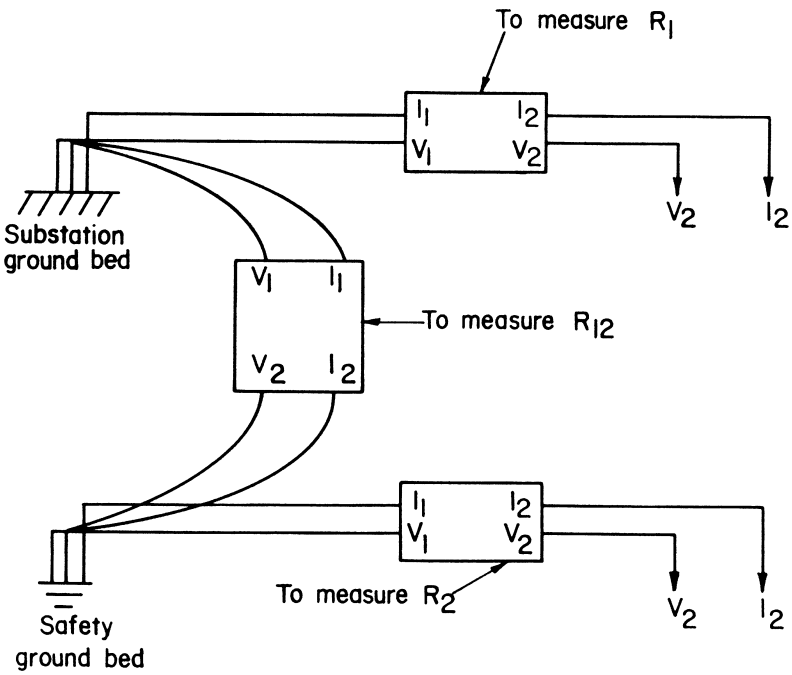

FIGURE 9. - Technique for determination of coupling between ground beds.

For the case where the safety ground bed is isolated from the ground system, it can be shown that the potential of the safety ground bed will rise to a value V,

$$V = V_o \left[\frac{R_1 + R_2 - R_{12}}{2R_1} \right], \quad (1)$$

where V_o = voltage on the substation ground mat,

R_{12} = measured resistance between safety and substation grounds,

R_1 = measured resistance of the substation ground,

and R_2 = measured resistance of the safety ground.

R_1 and R_2 can be measured by the techniques described above, and R_{12} is easily measured also (fig. 9). Since the safety ground bed will not be isolated when in use, equation 1 overestimates the coupling but should be able to verify the approximate value.

A direct measure of coupling can be obtained by circulating a large test current between the substation ground and some auxiliary current electrode far from the substation. The resultant voltage can then be measured between the substation and a remote voltage probe and between the safety

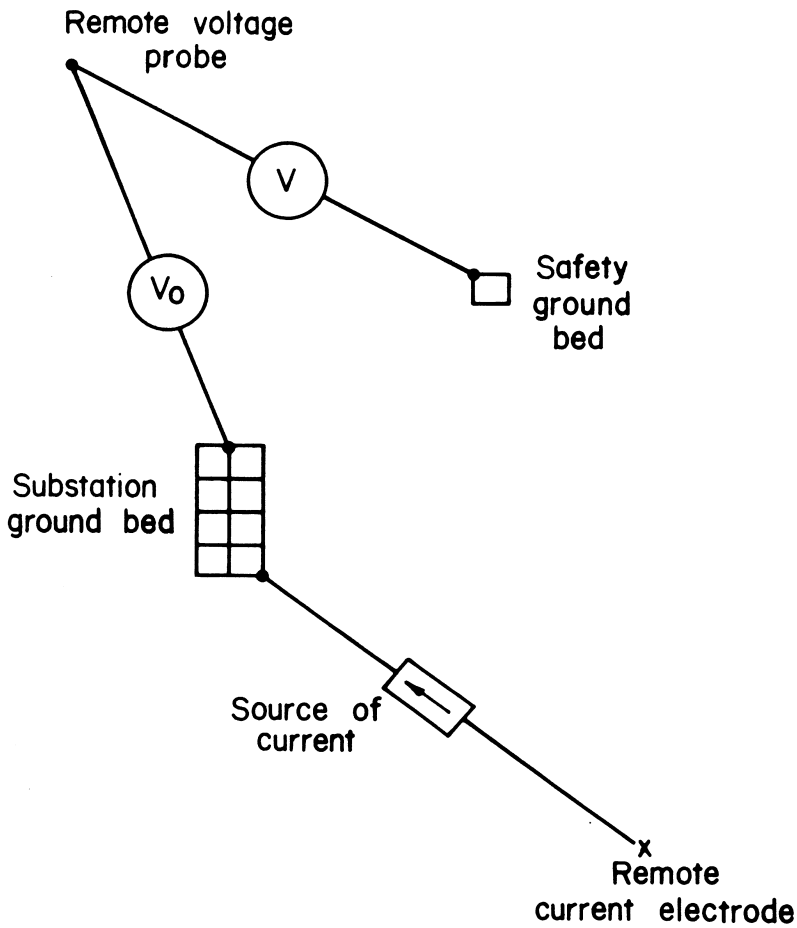

FIGURE 10. - Direct measurement of coupling.

bed and the remote probe, as shown in figure 10. This should directly indicate the coupling. No criteria have ever been set for maximum acceptable coupling, but mines with values as high as 15 to 20 percent have apparently not experienced any disastrous effects.

WIRING OF GROUND SYSTEMS

In addition to considerations of ground bed size, location, and construction, the design of a mine substation requires attention to other details of implementing the ground system. These are covered in a series of short paragraphs.

Wiring the Neutral Grounding Transformer

Regulations require a resistance-grounded power system for almost all mining operations. The only exceptions pertain to stationary equipment. This resistance-grounded system may be implemented either by Y-connection of the three-phase source transformer secondary or by the use of a separate transformer(s) to derive a neutral for the mine power system. If the neutral is derived separately from the source transformer, then certain precautions should be taken to insure the safety of the power system. Although Federal regulations state that the neutral shall be derived at the source transformer, some operators have chosen to place the neutral grounding transformer in some other location, such as depicted in figure 11. Although this technique allows for a large separation between the safety ground and substation ground, it can result in a shock hazard under some conditions.

The most serious hazard occurs if one or more leads of the grounding transformer become disconnected from their phase conductors. The grounding transformer then loses its ability to derive the neutral point. A current results that flows in the safety ground system, and hazardous potentials may appear on the frames of mining equipment. This particular type of failure is not restricted to remotely located grounding transformers and must be considered even when the grounding transformer is located close to the source transformer. The grounding transformer must therefore be of sufficient capacity to indefinitely sustain current flow from ground faults. It shall

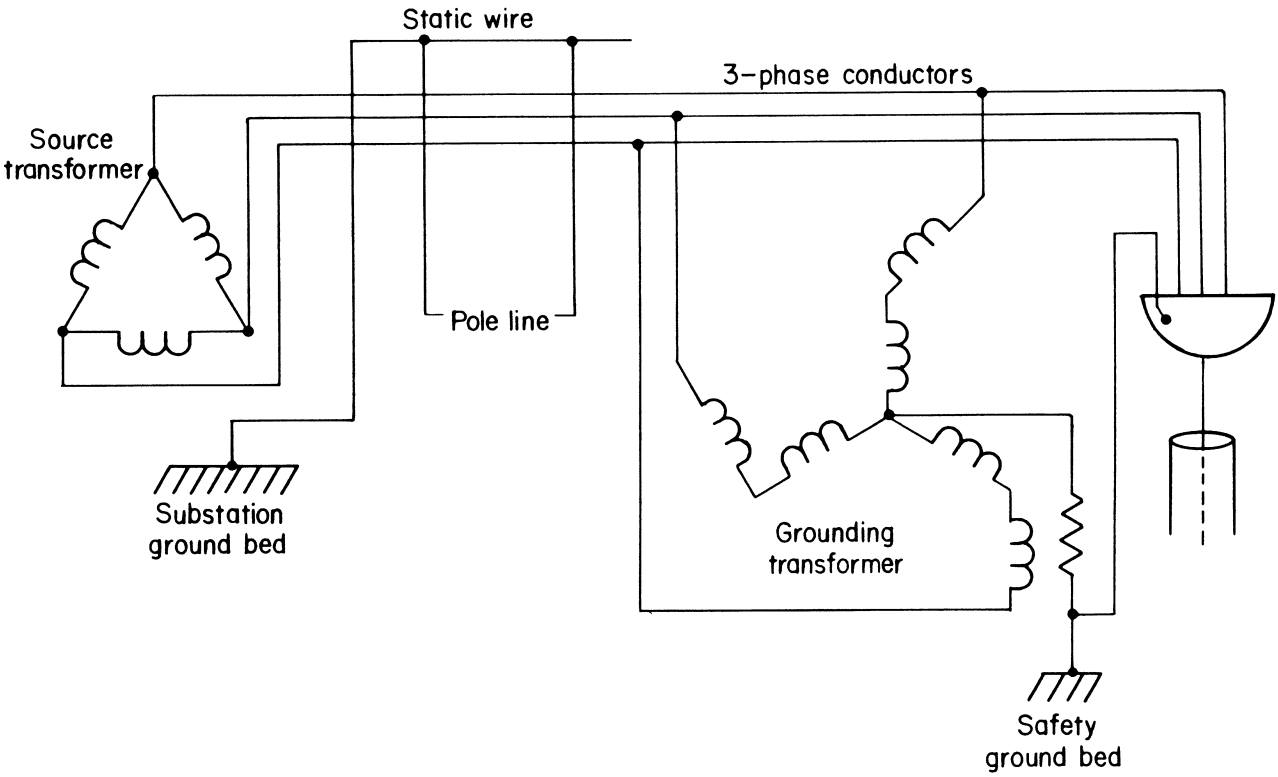

FIGURE 11. - Incorrect location of derived neutral at a point remote from the source transformer.

not be protected by fusing its legs but should be protected by overcurrent relays to trip the main current breaker if excessive current flows in one or more of its legs (a result of an open on some other leg). It is necessary to take great care when using a separate grounding transformer.

Hazards can also occur if a line were to fail between the source transformer and the point where the grounding transformer is connected. The probability that this will occur is directly related to the length of pole line between source transformer and grounding transformer. Besides destroying the ability to derive the neutral point, an open phase conductor will disrupt power to the mine. If the mine power system is provided with single-phase protection or ground fault protection (if the line contacts earth), the main breaker may trip. If not, a hazardous condition can exist for an extended period. It is therefore recommended that the grounding transformer be located as close as possible to the source transformer.

Insulation of Safety Ground

As stated before, the purpose of establishing a separate safety ground bed is to prevent hazardous potentials existing on the substation ground (as a result of a primary line fault or lightning activity) from being coupled to the frames of mining equipment. It is crucial, therefore, to insure that no inadvertent contact is made between the substation ground and the safety ground.

Failure to properly insulate the safety ground is a common occurrence and may be extremely hazardous. The safety ground wire must never be used as a static conductor, or connected to the static conductor, since this deliberately exposes the safety ground to lightning. When running a safety-grounded circuit on poles, the safety ground wire must be insulated and protected, preferably below the phase conductors.

A hidden source of improper connection between the safety ground and the substation ground can occur if belts are used for haulage of coal out of the mine to the preparation plant. Very often the conveyor frame is tied to the building ground or otherwise tied into the substation ground. If the belt drive motors are powered from the safety-grounded mine power system, their frames will be connected to the safety ground. Since the motors are normally mounted directly to the conveyor frame, a ground interconnection occurs, defeating the purposeful isolation of the safety ground.

It should be obvious then that no direct connection should be made between the two grounds and cause a ground-to-ground fault. This fault would couple the grounds together at the very moment when isolation becomes critical and can completely negate all efforts to provide protection to mine personnel.

It is extremely difficult to insulate the safety ground system to a voltage level that would prevent a lightning-produced arc from occurring. Lightning transients are extremely short, however, and do not propagate very far along static lines. Primary faults can produce high potentials on the substation ground for much longer times, especially if conditions are such that circuit protection does not operate. Depending on conditions, such a primary fault within the substation can cause the potential of the ground grid to approach primary line-to-neutral voltage. Thus it is proper to insulate the safety ground to the same level as the primary circuit within the substation. This level of insulation protection may be reduced if it can be demonstrated that such high voltage levels cannot appear on the ground grid. Figure 12 shows several areas in the substation where ground-to-ground faults are most likely to occur.

The cable connecting the safety ground bed to the ground system is quite often placed near or directly on the bare metal of the substation as it is carried out of the substation, which means that the cable insulation itself must withstand the voltage difference between grounds (A). Insulation rated at 600 to 2000 volts is often used, and this is simply not enough to guarantee protection. There is also a possibility of developing a ground-to-ground fault between the borehole casing (or Kellems grip) and the shield of the borehole cable (B), and care should be taken to see that these are adequately insulated. The neutral grounding resistor is a third source of possible ground-to-ground faults, since it may only be insulated for secondary line-to-line voltage (C).

A fourth source of ground-to-ground faults is the ground-check monitor installed in the substation (D). Most monitors are designed so that their cases and power supplies are connected to the substation ground. Since they monitor the continuity of the safety ground wire, the internal circuitry is

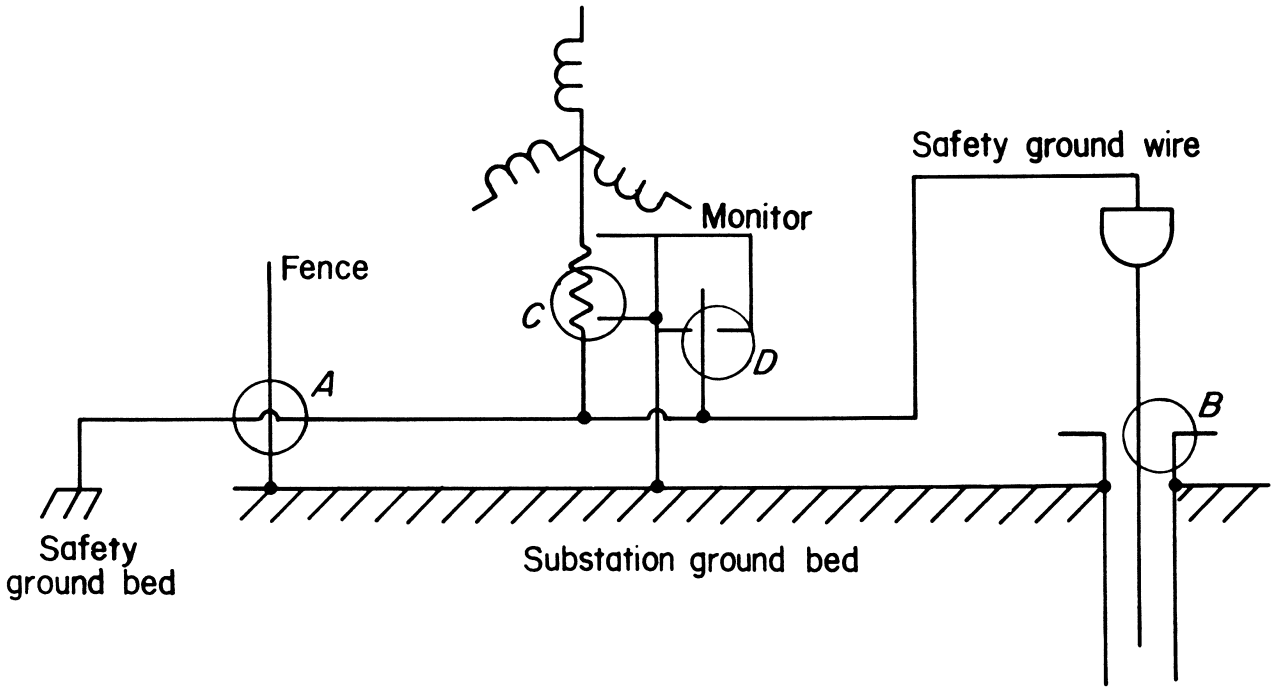

FIGURE 12. - Ground-to-ground faults may develop at several places within the substation unless the safety ground is well insulated.

is connected to the safety ground. Lightning transients and faults often damage the delicate circuitry of the monitors. In an attempt to protect the monitors, manufacturers have installed various surge protectors between the monitor case and the safety ground. This practice can cause a hazard to personnel, however. If a very large transient occurs, it can cause some types of surge protectors to fail short. This short permanently connects the two grounds together, negating all efforts to provide a safe system. Unfortunately, failure of a surge protector can go undetected indefinitely. If surge protectors are installed between the two grounds, they should either be a type that does not fail short or be checked for failure at frequent intervals.

Ground-to-Ground Shock Hazard

The previous paragraphs suggest that it may be required in some circumstances to deliberately isolate the two grounds when they appear in close proximity. Although isolation of monitor frames, motor frames, etc., is necessary to preserve the properties of the safety ground, a severe shock hazard can exist at such locations, since it would ordinarily be possible for personnel to simultaneously contact both grounds. Contact should be prevented where possible, and clear warning of danger posted.

Ground Fault Protection

Ground fault protection is normally carried out using one of three approaches:

1. A window-type current transformer (CT) encircling the three phase conductors to detect any zero-sequence current.

2. A bar-type CT in the grounding resistor lead to detect any neutral current.

3. A potential transformer (PT) across the grounding resistor to detect any potential difference between neutral and ground.

These methods all have equal ability to detect simple ground faults, but they differ somewhat in their reliability under adverse conditions.

The zero-sequence CT and the ground-lead CT are essentially equivalent, except that care must be taken to properly place the ground-lead CT. Figure 13 shows the details of CT placement. Positions C and D are not correct since they detect ground current rather than neutral current. Position A is preferred over B since it is closer to the transformer neutral and can detect neutral current in spite of a short in the grounding resistor circuit. It should be obvious that only the phase conductors are to pass through a window-type transformer. This means that high-voltage cables must not be shielded where they pass through the CT, or care must be taken to see that the shield is not terminated so as to produce a shorted turn through the CT.

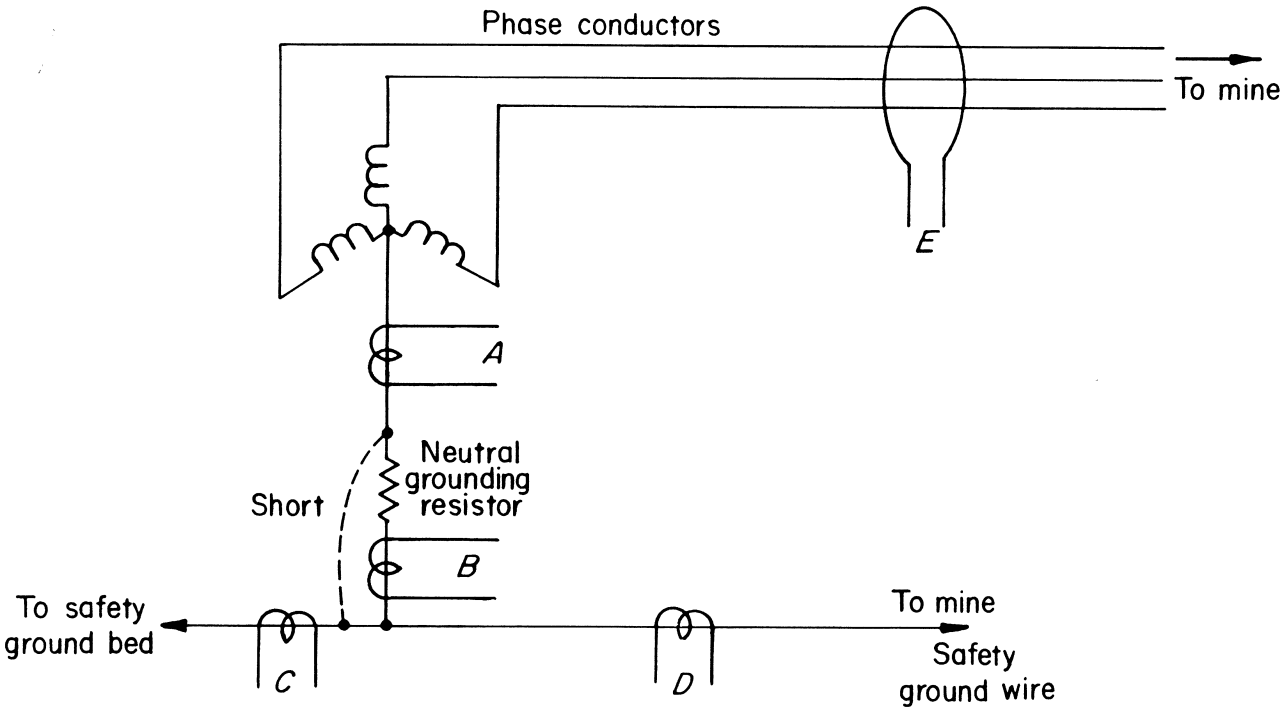

FIGURE 13. - Placement of ground fault CT. It must not be placed at *C* or *D*. *A* and *B* are satisfactory, but *A* is preferred. The CT must not encircle pilot or ground wires. The zero-sequence CT is shown at *E*.

A PT across the grounding resistor is often considered to be the safest method of detecting a ground fault. If the ground system becomes open, dangerous conditions can exist in which no neutral current can flow since the loop is open. Neither CT approach will detect such a condition. A potential will exist across the open, however, and can be detected by a PT. Figure 14 shows the preferred PT connection, in which the connections are made to provide verification of continuity for a large portion of the ground circuit.

The PT method of detecting ground faults can fail also if the leads to the PT become open, so they should be relatively well protected. The highest level of protection can be achieved by using both CT and PT protection. This redundancy makes the ground-fault detection system highly reliable.

Neutral grounding resistors must be sized to carry maximum ground fault current for an extended period. If ground fault protection does not operate for some reason, the resistor must also have an adequate voltage rating for the system (line-to-line). On very high voltage resistance-grounded systems it may be necessary to use a lower voltage resistor that is transformer-coupled to the neutral point of the source transformer (fig. 15). In this case the resistor must carry current equal to the maximum ground fault times the turns ratio of the transformer and should be rated accordingly:

$$\text{KVA rating} = I_{gf} \times V_{LN}.$$

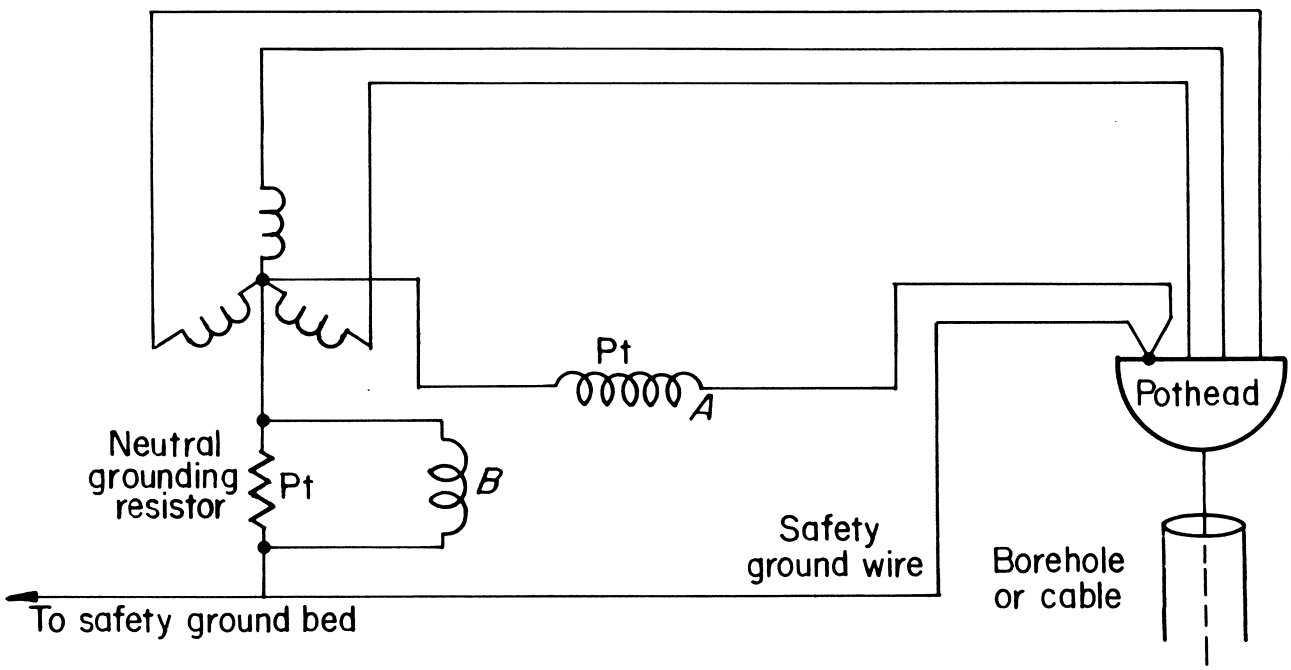

FIGURE 14. - PT connection for detection of ground fault. Method *A* is preferred since it monitors continuity from the cable ground at the pothead all the way to the neutral point on the transformer.

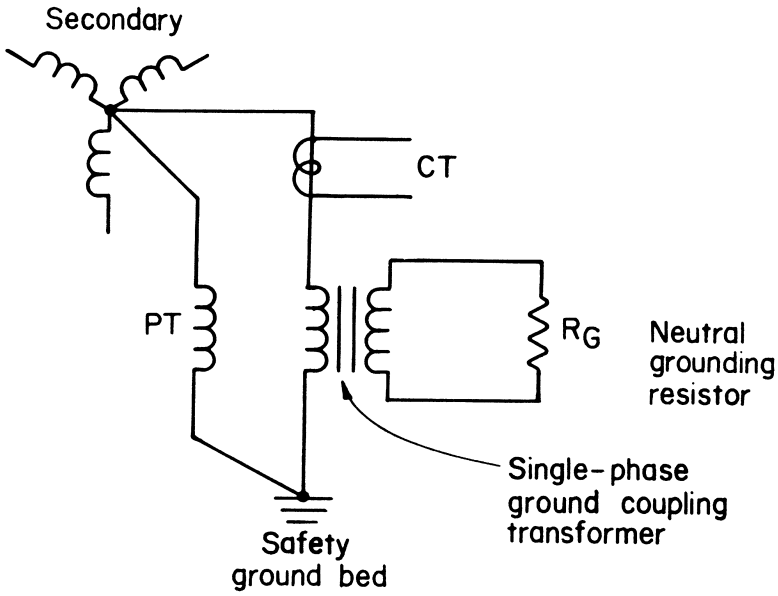

FIGURE 15. - Use of transformer-coupled grounding resistor for high-voltage mine distribution.

The coupling transformer should also be rated for full continuous current and insulated for line-to-line voltage. PT ground fault protection should ideally go across the transformer primary, and CT protection is best placed in a series with the primary. If the CT is placed on the secondary, it should be sized accordingly.

Ground Fault Relay Settings

Proper adjustment of ground fault protective equipment is often difficult because of the low level of fault current. Many of the techniques that work well for more solidly grounded systems work either poorly or not at all when used with high-resistance grounding. Neutral grounding resistors are usually chosen to limit the fault current from 15 to 25 amperes. If a 25/5 or 50/5 current transformer is used, this results in a relay current of as little as 1.5 amperes. It is customary to set the relay pickup at 50 percent of the maximum current, which would be less than 1 ampere. This is a very small current for relay operation and requires a high-burden relay. High-burden relays often cause the current transformer to saturate, causing a loss of calibration. A workable system can be implemented using a low-ratio bar-type current transformer, but the use of a high-ratio window CT with an improperly chosen relay may cause serious problems. Residual flux methods usually do not have the proper sensitivity for mine application.

If the mine power system employs several levels of ground fault protection that must be coordinated, the choice of current-transformer ratios and relays becomes extremely difficult.

Multiple Grounds

The configuration of some mine power systems requires that multiple grounds be established. Very often the additional grounds are lightning arrester grounds at potheads and service entrances. These additional grounds may or may not be interconnected with the substation ground via a static wire or other means. If they are part of the substation ground, they may develop a hazardous potential during a primary fault. They also extend the size of the substation ground, making it very difficult to measure its resistance properly. This also increases the coupling between the substation ground and safety ground bed, possibly to a dangerous level.

If these additional arrester grounds are not tied to the substation ground, then they must each have a low value of resistance. As discussed previously, these beds must be capable of passing enough current in the event of an arrester failure to operate the ground fault protection. If the ground is not for an arrester, but is simply to provide personnel protection at an operating handle, then it need not meet any specific resistance requirements.

The safety ground system is almost always multiple-grounded because it is connected to equipment frames in contact with the earth, but multiple surface safety ground beds are rare. Besides enlarging the effective size of the safety ground bed and thereby increasing coupling to the substation ground, the chief disadvantage of a multiply connected safety ground is a difficulty in implementing a ground-check monitor program. Some monitors have been conceived that can operate in the presence of multiple connections to earth, but they have not yet worked satisfactorily in the field.

Portable Substation and Power Centers

These pieces of equipment usually have only one ground, which must be considered the safety ground whether or not it is used as a ground for surge arresters. This is usually not a problem, however, since they are coupled to other equipment through cables, which have a high surge impedance, meaning that the current that must flow through the ground is small. The chance of a portable substation being struck by lightning is very remote, so this is not considered a problem. Having a separate ground for surge arresters in underground load centers is simply not necessary.

As with permanent substations and other equipment, care should be taken to insure that grounds are multiply bonded to the frame to reduce the possibility that protection will be lost.

GROUNDING THE BOREHOLE CASING

The borehole casing of an underground mine offers a unique grounding problem since it can provide a low-resistance path from the substation area directly to a working area of the mine. It is difficult to address all possible situations, so only a few will be covered. Generally, if the casing is accessible on the surface it must be made inaccessible underground, or vice versa. Personnel protection cannot be provided at both ends of the same casing.

Many boreholes are located within the main substation. Since the casing is located within the substation ground mat, a serious personnel shock hazard exists. Unless the casing is bonded to the substation ground (as shown in figures 1 and 2), a person standing within the substation and touching the casing may receive a lethal shock. The casing may be made inaccessible by placing it in an enclosed vault, but it is still likely to be closely coupled to the substation ground and cable-supporting structures and should be bonded to them.

If the borehole casing is bonded to or closely coupled to the substation ground mat, it then has the capability of carrying dangerously high potentials underground. It should therefore be treated accordingly. It must not be used as a ground reference for any underground equipment or haulage system. It should be made inaccessible and labeled as dangerous. If a high potential were to occur on the casing, the field would extend into the earth all around it, so that the area within at least 10 feet of the casing should be avoided.

If a borehole casing is located outside the substation, it should not be connected to the substation ground unless the ground mat is extended to surround the casing. Instead, the casing can either be connected to the safety ground or left ungrounded. If the borehole is 50 feet or more away from the edge of the substation mat, it can probably be made a part of the safety ground bed. Since it is usually quite large compared with the safety ·d, incorporating it into the bed can significantly reduce safety ground ·d resistance. It must be verified that coupling to the substation ground (discussed earlier) is satisfactorily low, however, and will probably require at least a 50-foot separation. The borehole cable supporting structure should also be bonded to the casing, and great care must be taken to assure that this is not also attached to the substation ground and that surface personnel cannot simultaneously touch it and the substation ground. Nor should this structure be located where it can contact a primary line. The small increase in lightning exposure caused by connecting casing and cable support to the safety ground is offset by the low resistance provided. If the casing is connected to the safety ground, then it can properly be used as a ground reference point at the mine bottom.

If the casing is outside the substation, it can be left ungrounded, that is, unattached to either the substation or the safety ground. Depending on its location relative to the substation, it can develop a hazardous potential during lightning or faults. If the casing is left ungrounded it should be avoided at both ends, but not as scrupulously as when it is specifically grounded.

If boreholes are used to carry dc power underground from the surface, they deserve careful treatment also. If the borehole additionally carries ac power within the mine substation, then it should be grounded according to the previous discussion. If the borehole is dc only and/or need not be grounded on the surface, it can be placed in parallel with whichever dc lead supplies the rail underground. It will thereby reduce the impedance of the circuit and help maintain the haulage rail at earth potential. This ·actice should improve the performance and safety of the dc system.

If the borehole is more than 100 feet from the substation, it may be necessary to locate a surge arrester at the borehole. This arrester must not be grounded to the borehole structure, but must have its own ground bed 25 feet away.

GROUND-CHECK MONITORING

Because the safety ground system is essential to personnel protection, it is important that its continuity be preserved. Since the grounds are subject to accident and abuse, it is necessary to monitor safety ground continuity on a continuous basis. Monitoring is often a difficult endeavor, however, and must be carried out very carefully within the surface substation.

Monitor Connections

Because continuity is essential to the safety ground system, as much of the system as possible must be checked. There are really three classes of conductors within the safety ground system, as shown in figure 16. Highest monitoring priority goes to those portions of the system that are essential for safety and vulnerable to damage or abuse--the ground wires of the trailing cables themselves. Other portions of the ground system are just as crucial, but are fairly well protected, such as the ground connections within power centers and switch houses. In the third group are those conductors that are often vulnerable but are somewhat less likely to cause a severe hazard if continuity is lost. This includes the lead from the neutral grounding resistor to the safety ground bed and the connections of the bed itself.

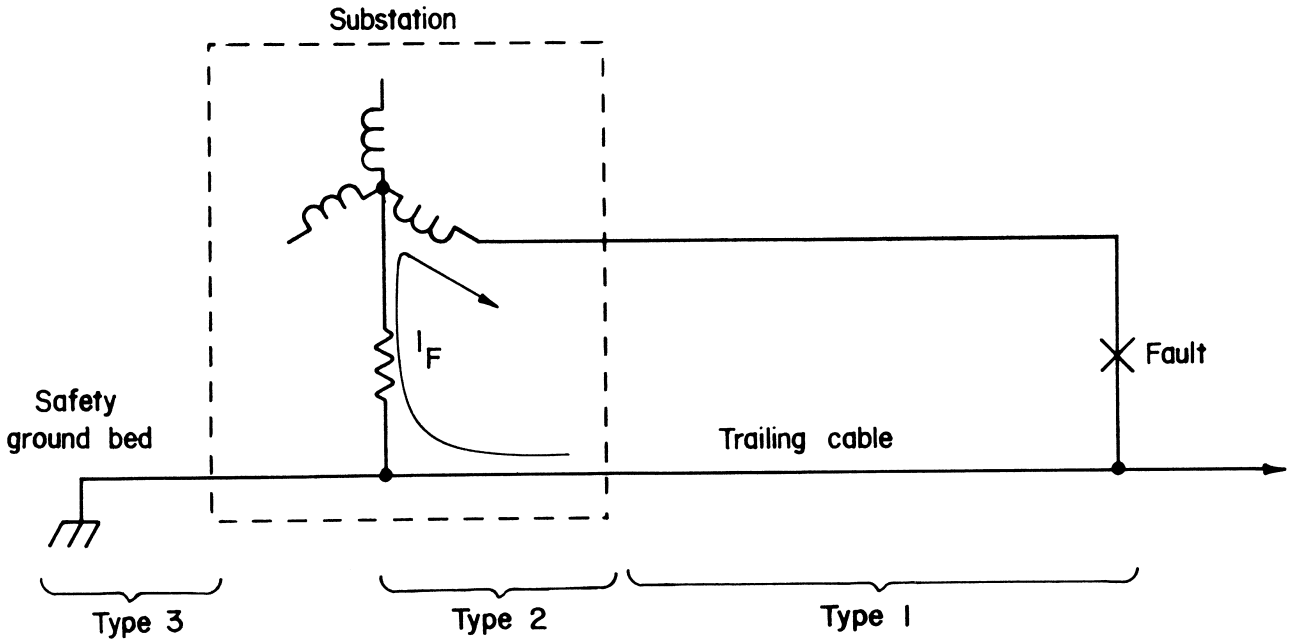

FIGURE 16. - Sketch of parts of the safety ground system, showing various types of conductors. Type 1 is crucial and vulnerable. All parts that carry ground fault current I_F should be monitored.

These conductors are usually less important because in most ground fault situations they are not part of the current path. If an arrester failure or other unusual fault occurs that requires the safety bed to carry current, these conductors become important also.

Two guidelines to follow in making monitor installations are to monitor as much of the system as possible and to carefully protect any part that cannot be monitored. Often a simple change of design can significantly increase monitor coverage, such as separately connecting pilot and ground wires to an equipment frame instead of connecting them both to the same stud. When locating monitor connections within the substation, no portion of the safety ground should be left unmonitored unless it cannot be included without affecting safety in some other way, such as reducing monitor sensitivity to parallel paths.

There is not yet any good method to monitor safety ground bed continuity, but periodic (every 6 months) checks of resistance should uncover most such problems before they have serious consequences.

Lightning and Transient Damage

Experience has shown that monitors located in surface substations are subject to a high rate of failure due to transient voltages arising from lightning activity or system faults. As mentioned briefly earlier, the substation monitor case is usually connected to the substation ground, while its internal circuitry is connected to the safety ground. Since the whole purpose of separated grounds is to prevent high-voltage surges from being coupled from one ground to the other, a well-designed system will often experience significant voltage differences. Based on field measurement and research literature, it was estimated that a typical open pit substation experienced two surges per year in excess of 1,000 volts from lightning alone (1), which can seriously damage most monitors. It is strongly suspected that monitors have been destroyed by ground-to-ground voltages during system faults, also.

If the monitor cannot be double-insulated to provide personnel protection while avoiding contact with the substation ground, then it must be protected by surge arresters or suppression devices. As mentioned earlier, these can present a serious hazard if they fail short, and must be chosen carefully. Since most surge suppression devices can fail short, they should be placed in conjunction with series impedances to limit the energy they are subjected to, or be designed so that a failure can be detected.

GROUND BED CORROSION

Most mines with underground dc haulage systems experience stray current flow in the safety ground as the result of leakage from the track. The current flow pathway can include the safety ground bed itself with disastrous corrosive effects. Even if no dc is present, the wrong choice of metals can cause corrosion of the ground bed.

The entire ground structure in and around a substation should be constructed of the same material or compatible materials if possible. Very often copper is used for beds even when steel is buried in the vicinity. This usually works satisfactorily, because when these two metals are connected together, the copper will cause the steel to corrode but will not be harmed itself. Since the steel is usually quite massive (such as the substation structure, fence posts, or borehole casing), the corrosion has little effect. Aluminum has approximately the same effect as copper on steel, but it can be rapidly corroded by mine acid. If copper conductors are secured with steel clamps, serious problems can arise. Since the copper will cause the steel to corrode, these clamps will soon be destroyed, destroying the integrity of the bed.

Proper bed construction requires the use of compatible connectors. Commercial thermit[4] weld connections and most specially designed ground clamps are compatible, but one should be certain. If any doubt exists, the connections should be protected by applying a watertight coating of asphalt or some other compound before burial. If this cannot be done, connections should all be made above the surface of the earth, which will reduce corrosion and allow for visual inspection. Exposed connections are not necessarily ideal, however, since they may be damaged by activity in the substation area.

[4]Reference to specific trade names does not imply endorsement by the Bureau of Mines.

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