Ground-Fault Protection and Ground-Conductor Monitoring for Portable Mine-Power Cables

G.E. Paulson, P. Eng.
and
J.J. Dudiak, P. Eng.
Littelfuse Startco
3714 Kinnear Place
Saskatoon, Saskatchewan
Canada S7P 0A6

Abstract—**Resistance grounding offers many of the advantages of both solidly grounded and ungrounded systems. This paper describes a practical approach to the selection of a grounding resistor let-through current and the operating value of the ground-fault relays. When portable mine-power cables are used, ground conductors must be monitored. It is suggested that ground-conductor monitors should be resistance sensitive and that the resistance trip-level should be determined by the allowable ground-fault voltage and the operating value of the ground-fault relays.**

I. System Grounding Methods

A solidly grounded system is a system in which the wye point of the supply transformer is connected solidly to ground. This configuration has the advantage of a fixed phase-to-ground voltage; however, a solidly grounded system has several disadvantages. When a ground fault occurs, high point-of-fault damage can result as power available to the fault is limited only by the system impedance. Also, ground-fault voltage, which is equal to the product of the fault current and the ground impedance, can exceed 100 V when a high fault current is available.

An ungrounded system is a system in which no point in the system is intentionally grounded. Grounding occurs only through system capacitance to ground. An ungrounded system has the advantage that there is no point-of-fault damage and the system can continue to operate with one phase faulted. The chief disadvantage of an ungrounded system is that intermittent or arcing faults can produce high transient voltages to ground. These voltages are impressed on the phase conductors throughout the system until the insulation at the weakest point in the system (often motor windings) breaks down.

A resistance-grounded system is a system in which the transformer neutral is connected to ground through a current-limiting resistor. This configuration has the advantages of both previous systems. Transient-overvoltages are eliminated because the neutral-grounding resistor provides a discharge path for the system capacitance. Also, the neutral-grounding resistor limits current available to the fault and this minimizes point-of-fault damage and controls ground-fault voltage. In some cases, a resistance-grounded system can be allowed to operate with one phase faulted.

II. System Charging Current

Charging current is defined as that current which will flow into the grounding connection when one phase of an ungrounded system is faulted to ground [1]. In an ideal ungrounded system, no current will flow if one phase is grounded because the circuit is not complete. In an actual ungrounded system, current will flow as shown in Fig. 1. The capacitors represent the total distributed capacitance of the system and are made up of the capacitance to ground of cables, motor windings, and other components such as surge-protection capacitors which are deliberately connected from the phases to ground. Power-factor-correction capacitors are connected phase to phase and do not contribute significantly to the capacitance to ground.

When designing a new system, charging current can be estimated from data for the system components. On an existing system, charging current can be measured as shown in Fig. 1. With the system powered, the switch is closed and the ammeter reading is taken. The ammeter reading is the vectorial sum of $I_1 + I_2$ and is equal to the system charging current. The system charging current should be the same for each phase; however, the charging current for each phase should be measured. For safety reasons, a fast-acting fuse and a current-limiting resistor should be connected in series with the ammeter when performing this test. The following rule-of-thumb can be used to estimate charging current: for low-voltage systems, a typical value is 1 A per 2000 kVA; and for medium-voltage systems a typical value is 1 A per 1000 kVA [2, 3]. Consequently, charging current will be in the range of 0.5 to 2.0 A for most trailing-cable applications. If a neutral-grounding resistor is used to discharge the

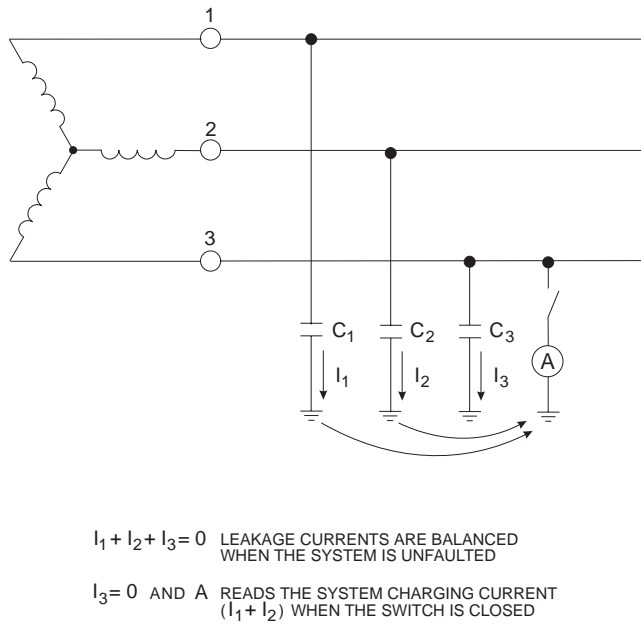system capacitance, its let-through current should be larger than this charging current.

$I_1 + I_2 + I_3 = 0$ LEAKAGE CURRENTS ARE BALANCED
WHEN THE SYSTEM IS UNFAULTED

$I_3 = 0$ AND   A   READS THE SYSTEM CHARGING CURRENT
$(I_1 + I_2)$ WHEN THE SWITCH IS CLOSED

Fig. 1. System charging current.

III. GROUND-FAULT PROTECTION

Ground-fault protection is low-level fault protection. The function of ground-fault protection is to minimize the damage to electrical equipment when low-level phase current returns to the supply transformer through a ground-return path. In special cases, protection of personnel is a consequence of ground-fault protection. This should not be confused with ground-fault interrupters, which are designed to prevent shock by tripping at the 4 to 6 mA level. Ground-fault protection does not protect people from electrical shock; it does not prevent ground-faults from happening; and it does not protect a system against high-level faults. High-level faults (phase-to-phase or three-phase) must be cleared by fuses or circuit breakers which limit the energy let-through to the fault.

IV. SELECTIVE GROUND-FAULT PROTECTION

A typical power-system configuration for a mining application is shown in Fig. 2. A 15-kV/5-kV portable substation supplies power to a 5-kV/600-V portable substation. This substation supplies 600 V for a conveyor system and 5 kV to a mining machine through a vacuum contactor. The mining-machine electrics also contain a vacuum contactor that supplies power to the mining machine motors. If a ground-fault occurs in the mining-machine

motor circuit, ground-fault current flows back to the 15-kV/5-kV substation. If the ground-fault-protection philosophy is that no more of the system should be shut down than is required to clear the fault, then a motor fault on the mining machine should cause only the mining-machine vacuum contactor to be tripped.
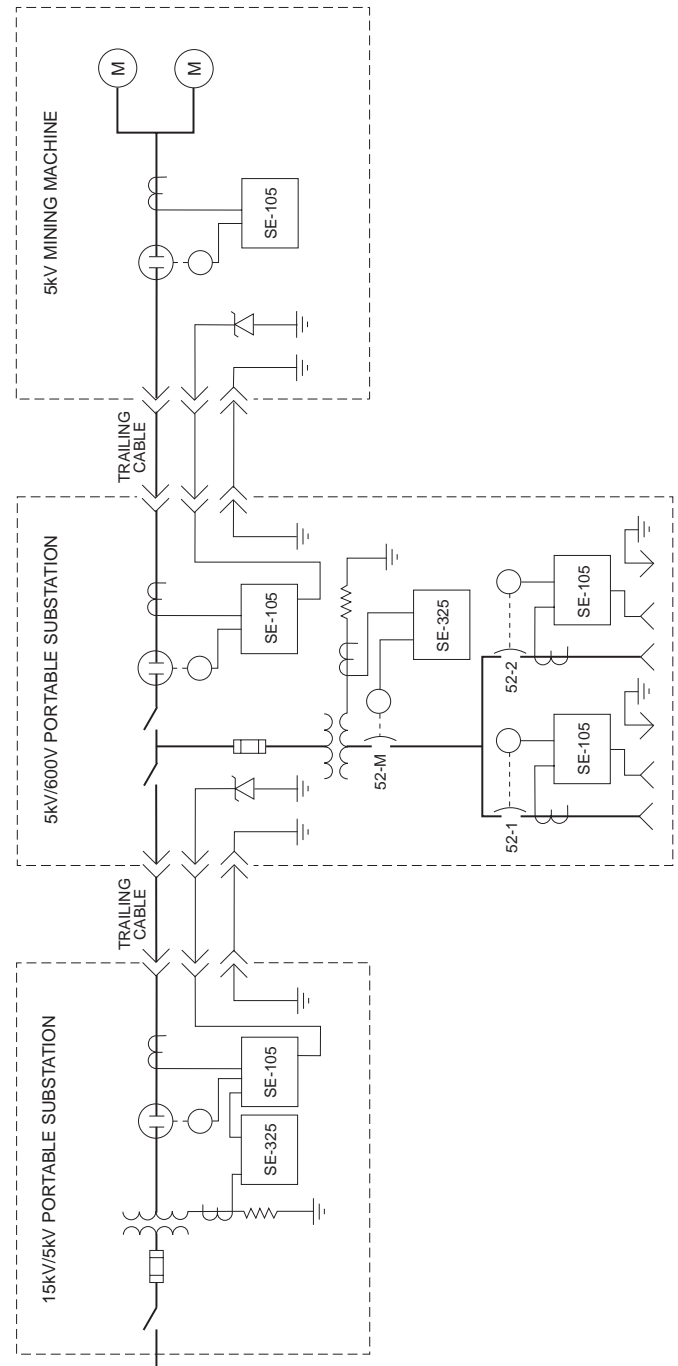

Fig. 2. Typical mine power system.

G.E. Paulson, P. Eng. and J.J. Dudiak, P. Eng.

A multiple-feeder, ungrounded system with zero-sequence current measured at each feeder is shown in Fig. 3. If a single-phase-to-ground fault occurs, the meter on each unfaulted feeder will read the charging current of that unfaulted feeder. The meter on the faulted feeder will read the sum of the charging currents of all unfaulted feeders. To selectively trip feeders on an ungrounded system, it is necessary to know the charging current of each feeder. If the charging current changes (as the result of adding more cable for example) the detection system must be recalibrated. For this reason, selective relaying on ungrounded systems is difficult.
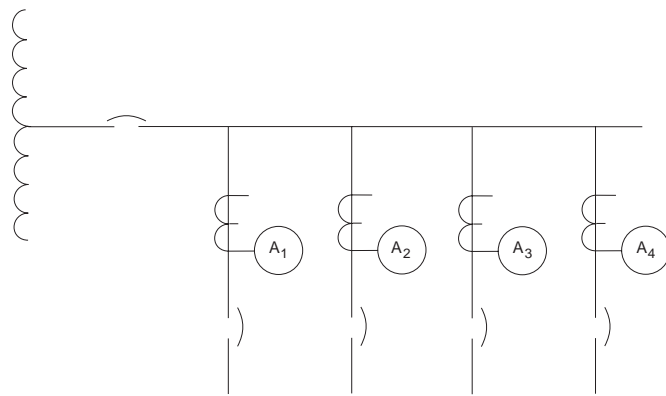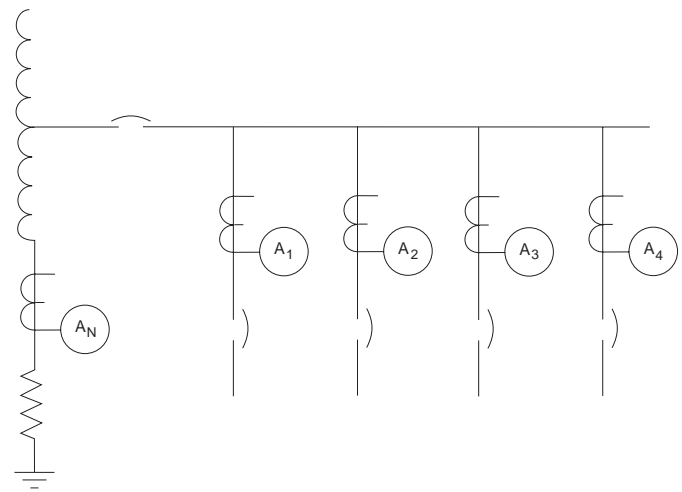

SINGLE-PHASE-TO-GROUND FAULT ON ANY FEEDER

a) EACH METER ON EACH UNFAULTED FEEDER WILL READ THE CHARGING CURRENT OF THAT UNFAULTED FEEDER.
b) THE METER ON THE FAULTED FEEDER WILL READ THE SUM OF THE CHARGING CURRENTS OF ALL UNFAULTED FEEDERS.

Fig. 3. Ungrounded system.

A multiple-feeder, resistance-grounded system is shown in Fig. 4. Zero-sequence current is measured at each feeder and the neutral-grounding-resistor current is measured at the transformer neutral. If a single-phase-to-ground fault occurs on any feeder, the meter on each unfaulted feeder will read the charging current of that unfaulted feeder. The meter on the faulted feeder will read the vectorial sum of the neutral-grounding-resistor current and the charging currents of all unfaulted feeders. To selectively detect the faulted feeder, the operating or trip current of the ground-fault relays must be higher than the charging current of any feeder. To avoid nuisance tripping, it is suggested that the operating value of the ground-fault relays be higher than the total system charging current.

The operating value of the ground-fault relays determines the grounding resistor let-through current. The National Coal Board (United Kingdom) recommends that the grounding resistor let-through current be at least 7 times the operating value of the ground-fault relays [4]. If this ratio is less than 7, current in the neutral-grounding resistor will be

less than the operating value of the ground-fault relays when a two-phase-to-ground fault occurs. Although this type of fault will probably be cleared by the overcurrent devices, a ratio of 5 to 7 is recommended for machine winding protection as well as for ground faults through rectifying elements. Consequently, in trailing cable applications with system charging currents of 0.5 to 2.0 A, the grounding resistor let-through current should be in the range of 5 to 15 A.

SINGLE-PHASE-TO-GROUND FAULT ON ANY FEEDER

a) EACH METER ON EACH UNFAULTED FEEDER WILL READ THE CHARGING CURRENT OF THAT UNFAULTED FEEDER.
b) THE METER ON THE FAULTED FEEDER WILL READ THE VECTORIAL SUM OF THE NEUTRAL-GROUNDING-RESISTOR CURRENT AND THE CHARGING CURRENTS OF ALL UNFAULTED FEEDERS.

PRACTICAL APPROACH — OPERATING VALUE OF GROUND-FAULT RELAYS > SYSTEM CHARGING CURRENT.
— NEUTRAL-GROUNDING-RESISTOR LET-THROUGH CURRENT ≥ 7 X OPERATING VALUE OF GROUND-FAULT RELAYS.

Fig. 4. Resistance-grounded system.

Selective relaying cannot be achieved by increasing the operating value of upstream ground-fault relays. When a bolted fault occurs, ground-fault current will rise to the neutral-grounding resistor let-through current. Since the let-through current must be larger than all operating values, co-ordination must be accomplished by increasing the operating time of upstream relays.

For the example previously discussed, the ground-fault relay for the contactor on the mining machine should have the shortest time delay. Progressively longer time delays are set for the 5-kV/600-V and 15-kV/5-kV substations. A fault in the mining-machine motor circuit will cause the contactor at the mining machine to open first. This contactor opening will clear the fault before upstream relays can trip.

Fig. 5 shows a typical installation of a ground-fault relay and a distribution panel in a portable substation. Only one feeder breaker is shown but it applies to panels with multiple

feeders. Each feeder is monitored by a zero-sequence-current transformer. The neutral-grounding resistor let-through current is an order of magnitude larger than the system charging current so that each relay can selectively trip its respective breaker without interference from the other feeders. Back-up protection is provided by a ground-fault relay that senses current in the neutral of the transformer. If the feeder relay fails or if the tripping mechanism of the feeder breaker fails to operate, then the main breaker on the distribution panel will be tripped after a short delay.

This discussion of ground-fault protection is intended for applications in open-pit and non-gaseous mines. In hazardous locations, the most important consideration is to limit the power available to a fault and a different approach is required. For example, coal mines in the UK derive power at the face from explosionproof, transportable substations up to 750 kVA. Neutral-grounding resistors with a let-through current of 750 mA are used and the operating value of the ground-fault relays is 80 mA.

V. GROUND-CONDUCTOR MONITORING

If the neutral-grounding resistor let-through current is an order of magnitude greater than the system charging current, ground-fault current will be limited by the neutral-grounding resistor and the ground-path impedance. Ground-path impedance must be low to minimize ground-fault voltage and to avoid interference with ground-fault detection. A ground-conductor monitor is used to ensure the integrity of the grounding circuit external to the grounding resistor. Most ground-conductor monitors use a ground-check wire (included in the portable power cable) to monitor continuity of the ground conductor. If the ground-check-loop resistance becomes excessive, the monitor causes the power conductors to be disconnected.

In addition to monitoring the ground conductor, a ground-conductor monitor offers several additional benefits. For example, most monitors will not allow open receptacles to be energized. When a ground-check-wire completion device is used at the load, the load must be connected before the phase conductors can receive power. A start-stop switch in a ground-check circuit is often used to control a monitor which controls the power supplied to mobile equipment. Although cable couplers are not to be uncoupled under load, a ground-check monitor offers some protection in this regard. Since the ground-check pin is the shortest pin, it will initiate a tripping function prior to the power pins separating if the coupler is inadvertently disengaged. However, this can be dangerous because the power contacts may attempt to break under load if the coupler is separated too quickly for the interrupting device to operate.
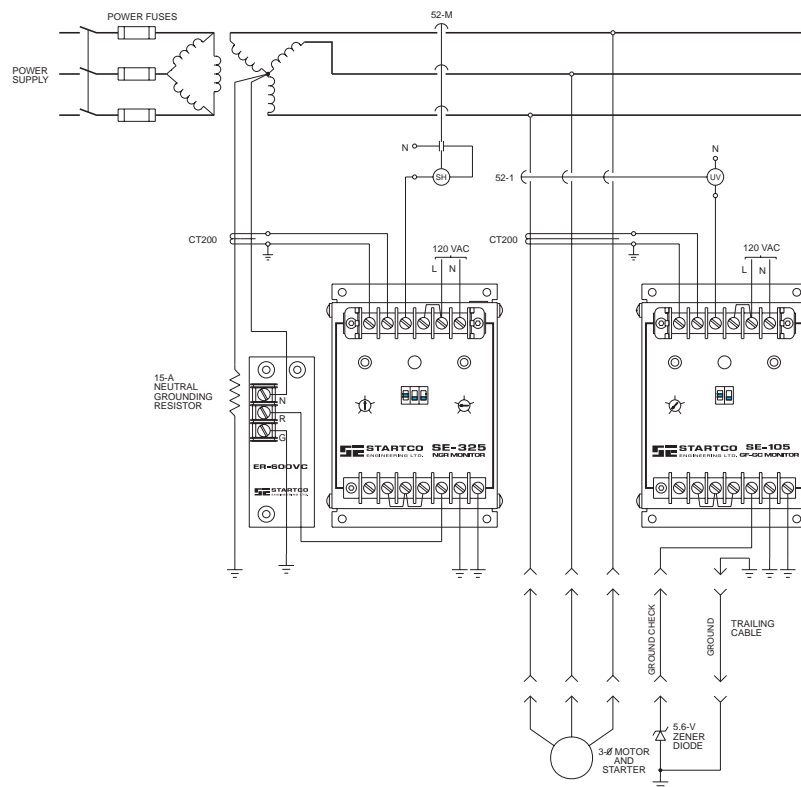

Fig. 5. Typical ground fault-ground check installation.

G.E. Paulson, P. Eng. and J.J. Dudiak, P. Eng.

Edited in 1995.

VI. PREFERRED GROUND-CONDUCTOR MONITOR CHARACTERISTICS

A ground-conductor monitor should have the following characteristics:

— The open-circuit ground-check voltage should be low. CSA Standard M421 allows 100 V. In wet locations 100 V can present a hazard to personnel. It is somewhat inconsistent for a safety device to be a hazard itself.

— The monitor should use an end-of-line device so that ground-check-to-ground shorts can be detected. MSHA (USA) investigations indicate that cable splicers have a tendency to connect the ground-check conductor to the ground conductor when splicing a cable [5].

— The monitor should have a high tolerance to induced ac in the ground-check loop. Since ground check and ground conductors run parallel to high-current phase conductors, induced ac is often present. MSHA approval requires monitors to tolerate 50 V induced or be marked to indicate this limitation [6].

— Ground-check circuits should be failsafe. MSHA defines a circuit to be failsafe if the failure of any one circuit component (in all possible failure modes) initiates a tripping function, or allows the circuit to continue to operate properly [6].

— The monitor should not tolerate a high ground-check loop resistance. In fact, a good design should consider both the ground resistance and the operating value of the ground-fault relays so that ground-fault voltages will be less than 100 V.

— The monitor should operate over a wide temperature range.

— The monitor should operate over a wide supply-voltage range and tolerate large voltage dips (voltage can dip 50% on long cables).

— The output relay should be capable of switching currents of only a few mA. This is important when the monitor is used to energize an undervoltage release coil which may draw 20 mA or less. Bifurcated contact relays are designed to switch currents in the 1-mA to 2-A range.

VII. GROUND-CONDUCTOR MONITOR LIMITATIONS

The following limitations can be encountered with some ground-conductor monitors.

— Some ground-conductor monitors use line-frequency signals. Circuits of this type often cannot discriminate between changes in loop impedance and induction in the ground-check loop.

— Some impedance-type monitors use a step-down transformer to detect an increase in the impedance of a ground-check loop. The secondary winding is connected in series with the ground-check wire and an increase in loop impedance is observed as a decrease in transformer current. This method works very well on a de-energized cable with no induced voltage in the ground-check loop; however, a small induced voltage opposing the secondary drive voltage will cause a similar decrease in transformer current and trip the monitor. To prevent this nuisance tripping, monitors of this type must have a phase-reversal switch so that induced voltage can be added to the secondary drive voltage. The problem with this is that loop impedance can now increase well above the trip level without detection. For example, a monitor with a 32-V/3.2-V transformer and a 4-ohm loop will allow loop impedance to increase by 4 ohms for each 3.2 V of induced voltage.

— Some ground-conductor monitors use a rectifier diode for a completion device. Voltages induced in the ground-check loop are ac but the diode only allows current to flow in one direction. Consequently, completion diodes are susceptible to damage from switching transients unless they are protected in the reverse direction by a suppressor. These units can be affected by induced ac which can cause nuisance tripping. Reducing this sensitivity is often accomplished at the expense of the ability to detect increases in ground-check loop impedance.

— Some ground-conductor monitors use high-frequency signals. These circuits are often limited to short cable lengths by the line-to-ground capacitance of trailing cables.

VIII. SUMMARY

— To prevent transient overvoltage damage, the let-through current of the grounding resistor should be equal to or greater than the system charging current.

— To achieve selective detection of a faulted feeder in a resistance-grounded distribution system, the operating (or trip) current of the ground-fault relays should be larger than the system charging current.

— For reliable tripping on all types of faults, the grounding resistor let-through current should be at least 7 times the operating current of the ground-fault relays.

— A ground-fault detection system will operate only if the grounding conductor is continuous; therefore, a system is required to ensure ground-conductor continuity.

— The resistance that the ground-check circuit will tolerate should be selected so that the product of the operating value of the ground-fault relays and the allowable ground resistance is less than 100 V.

REFERENCES

[1] C.A.A. MacPhee, "Ground fault protection for ungrounded distribution systems". Conference record of *I.A.S 1975 annual meeting*, Atlanta, GA: pp. 630—637, Oct. 1975.

[2] Arthur Freund,. "Ground-fault protection for ungrounded distribution systems". *Electrical construction and maintenance*. 1979.

[3] Baldwin Bridger, Jr., "High resistance grounding". Conference record of the *Industry applications society IEEE-IAS 1981 annual meeting*, Philadelphia, PA: Oct. 18—24, 1981.

[4] J. Stoddard, "Sensitive earth fault protection in mines". Conference Record of the *IEE on electrical safety in hazardous environments*, London: pp. 166—171, March 1971.

[5] Arlie B. Massey, "An introduction to ground monitoring". Conference record of the *Western mining industry electrotechnical conference*, Reno, NV: pp. 61—82, Sept 1981.

[6] MSHA, "Approval and certification procedures for ground check currents". *Mine Safety and Health Administration*, P.O. Box 1166, Building F. Berkley, WA 25801. 1982.