High-Resistance Grounding Design for Industrial Facilities

PROVIDING CONTINUITY OF SERVICE IN COMPLEX DISTRIBUTION SYSTEMS

By Paria Sattari and Sergio Panetta

CONTINUITY OF SERVICE IS CRUCIAL IN MOST industrial facilities. Insulation failure due to a line-to-ground fault is the most prevalent cause of service interruption in such facilities. Solidly grounded systems create fatal and costly arc-flash hazards that cause substantial damage at the fault location. Resistance grounding limits the line-to-ground fault current. This practice has been in use for years and is widely applied in industry. This article explores the application of resistance grounding in hospitals, emergency power systems, and data processing facilities, where the distribution systems are complex and involve various sources, such as multiple transformers, generators, or a combination of both. It also proposes solutions for the integration of high-resistance grounding (HRG) in the distribution system design of various industries to increase the reliability and safety of these systems. Application examples are presented, and the concept of hybrid grounding in low-voltage (LV) and medium-voltage (MV) systems is discussed.

Background

HRG is recognized by both the Canadian Electrical Code and National Electrical Code (NEC) and is considered the best practice in the process industry [1], [2].

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The advantages of incorporating HRG in a design include the following:

- power continuity
- negligible damage at the point of fault
- insignificant arc-flash hazard
- low risk of single fault escalating into line to line of a three-phase fault
- minor shock hazard [3].

To implement HRG, a resistor is installed between the system neutral and system ground. An alarm is raised upon the occurrence of a ground fault. Phase-to-ground voltage is used to identify the faulty phase. The alarm level is commonly set for 50% or less of the resistor let-through current. This prevents false alarms caused by the unbalanced capacitive leakage current in unfaulted feeders [4]. In modern relays, the zero-sequence sensor signals pick up the fault first, and the presence of unbalanced voltage is verified before the alarm is indicated. To avoid nuisance alarms caused by inrush currents and nonlinear loads, the zero-sequence current sensor output is filtered, and only the fundamental signal is extracted. These measures are effective in avoiding nuisance alarms and trips in sensitive ground-fault relays [5]. This article explores resistance grounding applications and offers suggestions for performance enhancements for both LV and MV systems in different industrial and commercial facilities [6].

High-Resistance Grounding

The 2018 Canadian Electrical Code [7] allows an impedance-grounded system to remain energized if

- the system nominal voltage is 5 kV or lower
- no line-to-neutral loads are present
- the ground-fault current is kept at 10 A or lower
- the impedance grounding device is rated for continuous duty
- the health of the impedance grounding device must be monitored and the alarm indicated, if faulty.

The NEC and National Fire Protection Association (NFPA) Standard 70E allow the use of HRG for low-voltage systems to keep the system energized when faulted.

Figure 1 illustrates an application for a delta/wye transformer with a 480-V secondary. The 5-A rated grounding resistor is placed between the transformer secondary neutral point and ground. All the feeders are monitored by a multicircuit ground-fault relay that identifies both the faulted feeder and phase.

Four key points are to be considered when resistance grounding is applied.

1) All cables rated for higher than 5 kV need to be suitable for line-line voltage for the maximum duration of the line-to-ground fault.
2) Lightning arrestors and surge suppression devices see the phase-to-phase voltage with respect to ground during the fault and must be adequately rated.

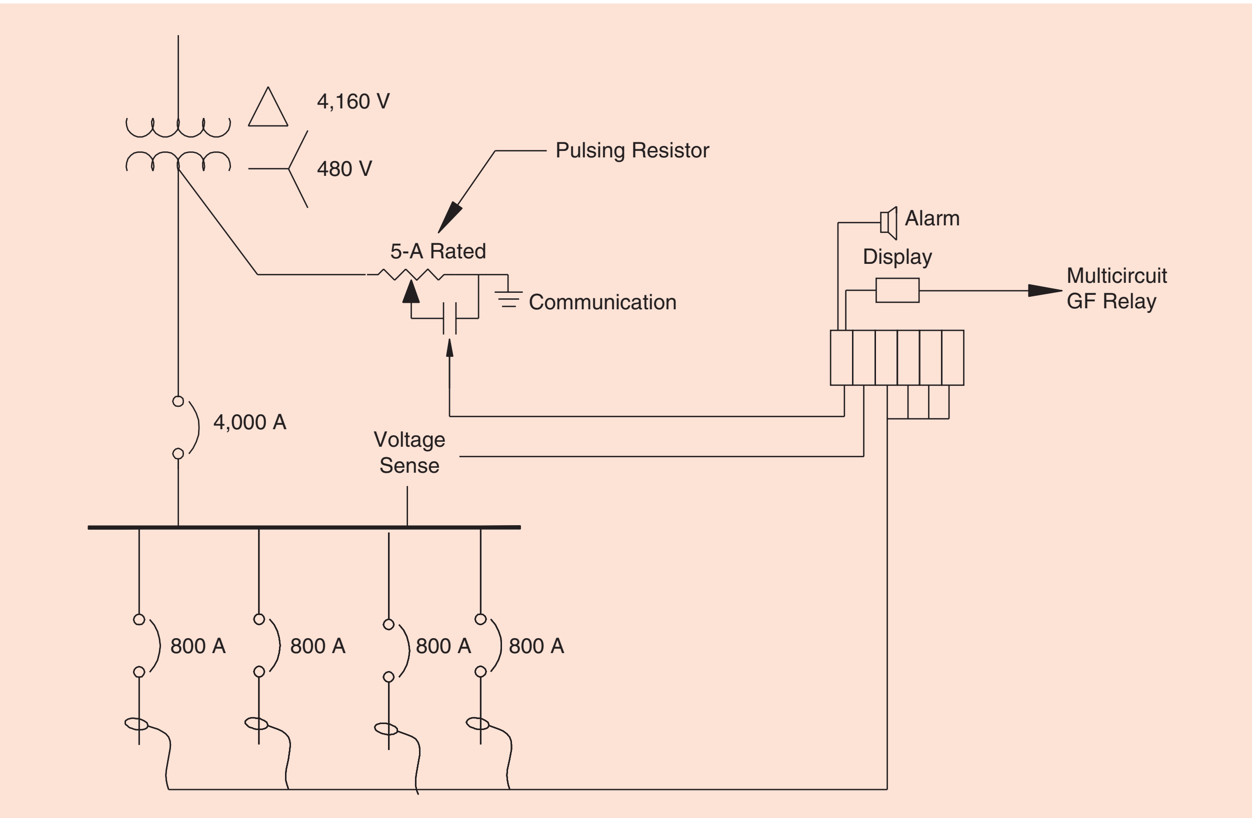

FIGURE 1. A typical delta/wye installation. GF: ground fault.

3) Surge capacitors and filtering capacitors should be rated to carry the extra 73% current during faults.
4) Circuit breakers and contactors' trip settings should operate under second-fault conditions.

Figure 2 shows a distribution system, with a 480-V normal power system and a 480-V generator power system. The critical loads are fed from the emergency power distribution, downstream of the transfer switches. The transfer switches get power from both the normal and generator power systems. In this scenario, assume that a ground fault occurs in the switchboard downstream of a transfer switch. The cause of this fault ranges from insulation failure due to overvoltage stress to tracking due to surface contamination, component failure, rodent intrusion, or human error.

In a solidly grounded system, the ground fault results in a large current flow. The upstream breaker trips in response to this fault current. The loss of main power is sensed by the transfer switch, and the loads as well as the fault are transferred to the emergency generator. At this point, the fault would cause the emergency generator to trip. The loads remain unpowered until a new source of power can be supplied. Full restoration of the system is conditional on the replacement of the switchboard, which is a lengthy process.

This article explores the application of resistance grounding in hospitals, emergency power systems, and data processing facilities.

In contrast to solidly grounded systems, in resistance-grounded systems, the first ground fault generates an alarm, the continuity of service is maintained, the main transformer is not stressed due to fault, the emergency generator is not exposed to fault current, and the damage to the switchboard is minimal. As a result, the inconvenience to the facility is minimal.

Low-Voltage, High-Resistance Grounding

Locating Ground Faults

Monitoring all of the feeders for the purpose of locating the ground fault is a major functional enhancement in ground-fault detection systems. To achieve this, the fault current is modulated at a slow rate (1 Hz) by changing the value of the grounding resistor. This is called pulsing. Locating the fault is achieved by encircling the

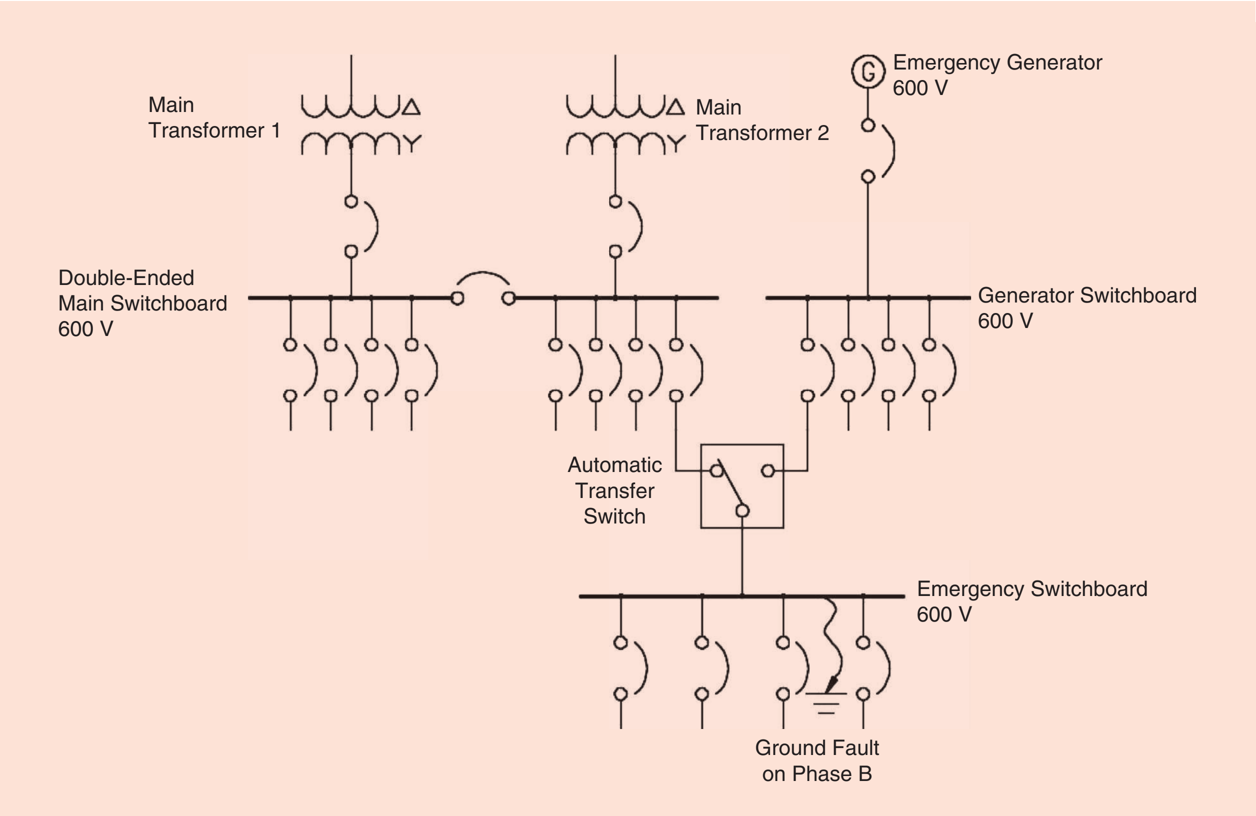

FIGURE 2. A single-phase fault scenario.

phase conductors by a zero-sequence sensor and following the modulated signal to the point of the fault. Measurements are done while the system is energized and in operation without needing open access to any switchgear or cabinet. The portion of the fault current that returns via the ground path in the conduit is sufficient to start the oscillation required for ground fault locating [8], [9]. This technique is used safely for systems up to 4,160 V. Switching a resistor at higher voltages is complicated. MV systems are not permitted to operate continuously, and the faulted circuit should be isolated promptly.

Selective Second-Fault Tripping

The first fault in HRG systems does not need to be isolated. There is a possibility that, during the operation of the faulted system, an additional phase-to-ground fault occurs in another weak spot. Upon the occurrence of the second fault, the fault current is no longer limited by the resistor and has a larger magnitude. The zero-sequence sensors will monitor the fault current, and if they detect a current larger than that limited by the resistor, the system identifies the occurrence of a phase-to-ground-to-phase fault. One feeder breaker or the main is tripped to revert the system to a single-faulted system. Each feeder breaker is assigned a priority level based on its importance. The priority settings of the two feeders involved in the faults are checked, and the lower-priority feeder is tripped without any intentional delay.

Figure 3 provides an example of a grounded transformer using a pulsing resistor. All the loads are monitored using zero-sequence sensors. Shunt trip coils of all feeder

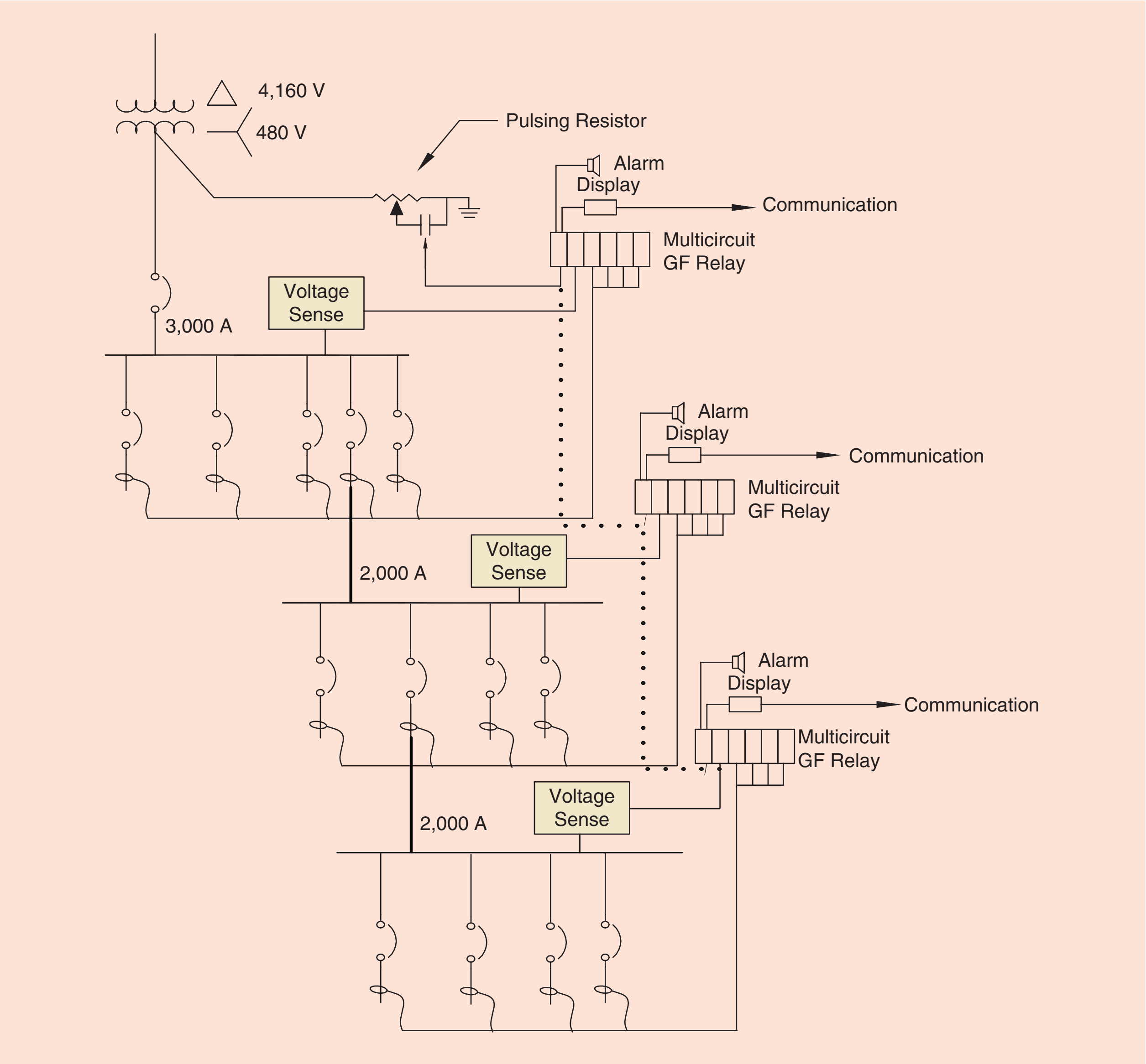

FIGURE 3. A fully integrated system.

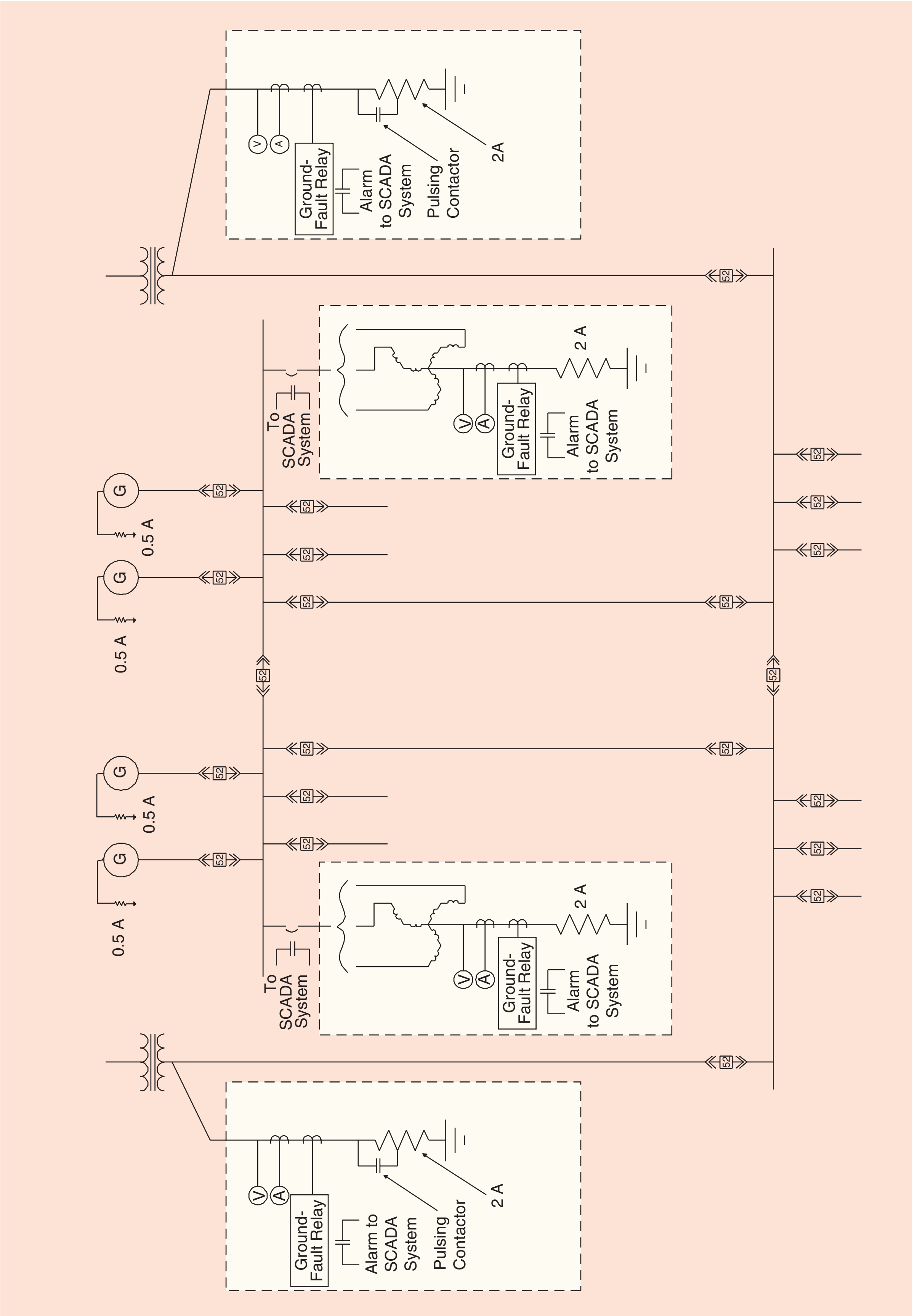

FIGURE 4. A typical distribution system of a hospital. SCADA: supervisory control and data acquisition.

breakers are connected to the fault tripping contact of the multicircuit relay. The relay provides communications via RS485 and sends a signal to indicate the faulty phase and fault current value. The relay continues to monitor the system and sends trip signals to one feeder should a second fault occur on a different phase before the first fault has been removed.

Distribution Systems With Multiple Sources

Hospital distribution systems are more complex than a simple radial distribution. Transformers are typically in double-ended arrangements with two mains and one tie, sometimes in a triple-ended arrangement with three mains and two ties, or connected in parallel. When systems are solidly grounded and the neutrals are distributed, providing ground-fault protection becomes expensive and cumbersome. By changing to a three-wire distribution with HRG, ground-fault protection is simplified. In distribution schemes with multiple sources, separate grounding resistors are used at each source, provided that the total fault current does not exceed the 10-A limit required by the Canadian Electrical Code and NEC.

In case there are numerous sources or the selected resistor current is high, a fault current higher than the 10-A limit is generated. In such cases, the solution would be to relocate the resistor. A single grounding resistor is applied at the switchboard instead of applying grounding resistors at the neutral of each transformer. If generators are also involved, a second grounding resistor is applied at the neutral bus of the generator switchboard. Figure 4 shows an example of two generator buses, each grounded with a resistor connected to the neutral point of the zigzag transformer. The utility transformers are grounded using a pulsing resistor. In multiple-source distribution systems, the minimum current flow is required to be greater than the charging current of the system. For most 480-V systems, the charging current will be lower than 1 A unless there is an outstanding amount of distribution.

Emergency Power Integration

If the emergency generator is resistance grounded in solidly grounded systems, the bonding path becomes parallel to the neutral and code violation occurs [10]. Two methods are proposed to avoid this issue.

1) Use a four-pole transfer switch.
2) Remove the generator ground so that only one ground on the service neutral is available.

When three-wire distribution is used, the issues with the emergency power system are resolved. The distribution system becomes more reliable when HRG is applied. This allows the use of three-pole transfer switches and the emergency power system can be resistance grounded even if the normal power from the utility is solidly grounded. Figure 5 provides an example of a generator bus grounded by a zigzag transformer. All loads are three-phase, three wire distribution, and the utility supply is resistance grounded. Three-pole transfer switches are used. Figure 6 shows another example of grounding the generator bus. The generator feeders are monitored by zero-sequence current sensors that scan the generator cables and the generator windings for a ground fault.

The emergency power system commonly consists of several generators in parallel, with more to be added in

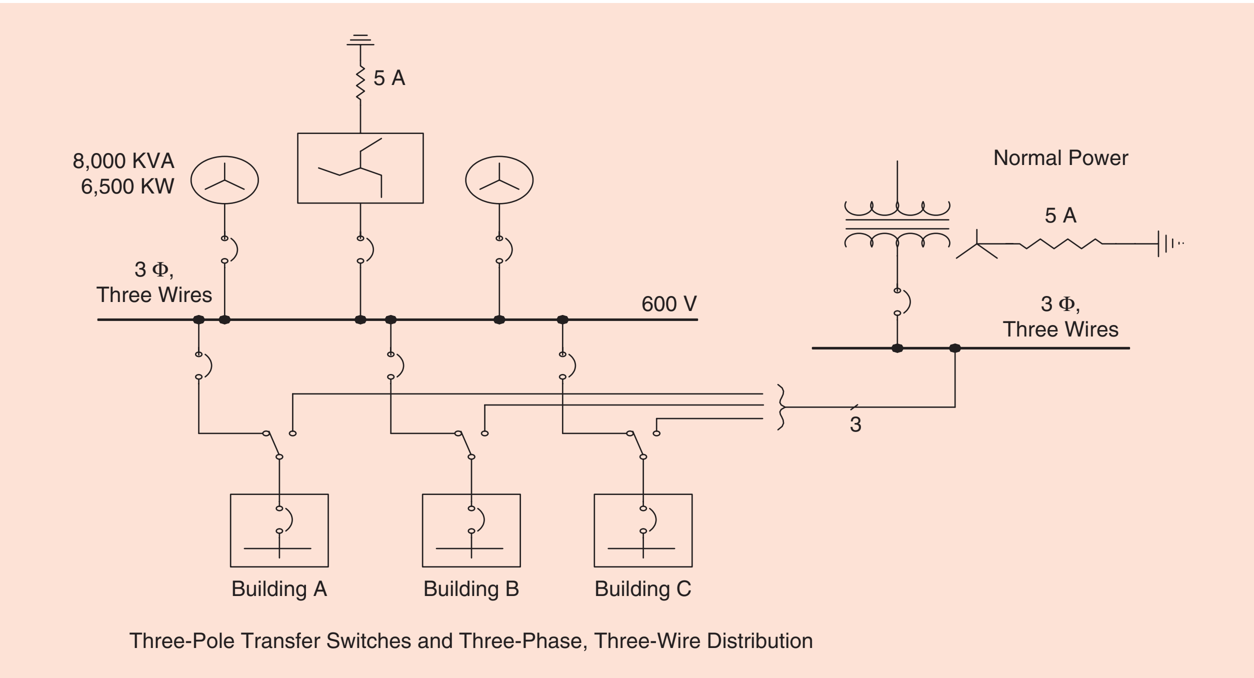

FIGURE 5. A standby generator and three-pole transfer switches.

the future. On solidly grounded systems where generator neutrals are interconnected, the neutral is grounded in the switchgear to avoid parallel paths between neutral and bonding. This causes a circulating current between the generator neutrals, requiring de-rating, which should be advised by the generator manufacturer. In three-wire distribution systems, neutrals do not need to be interconnected. In these systems, grounding is applied

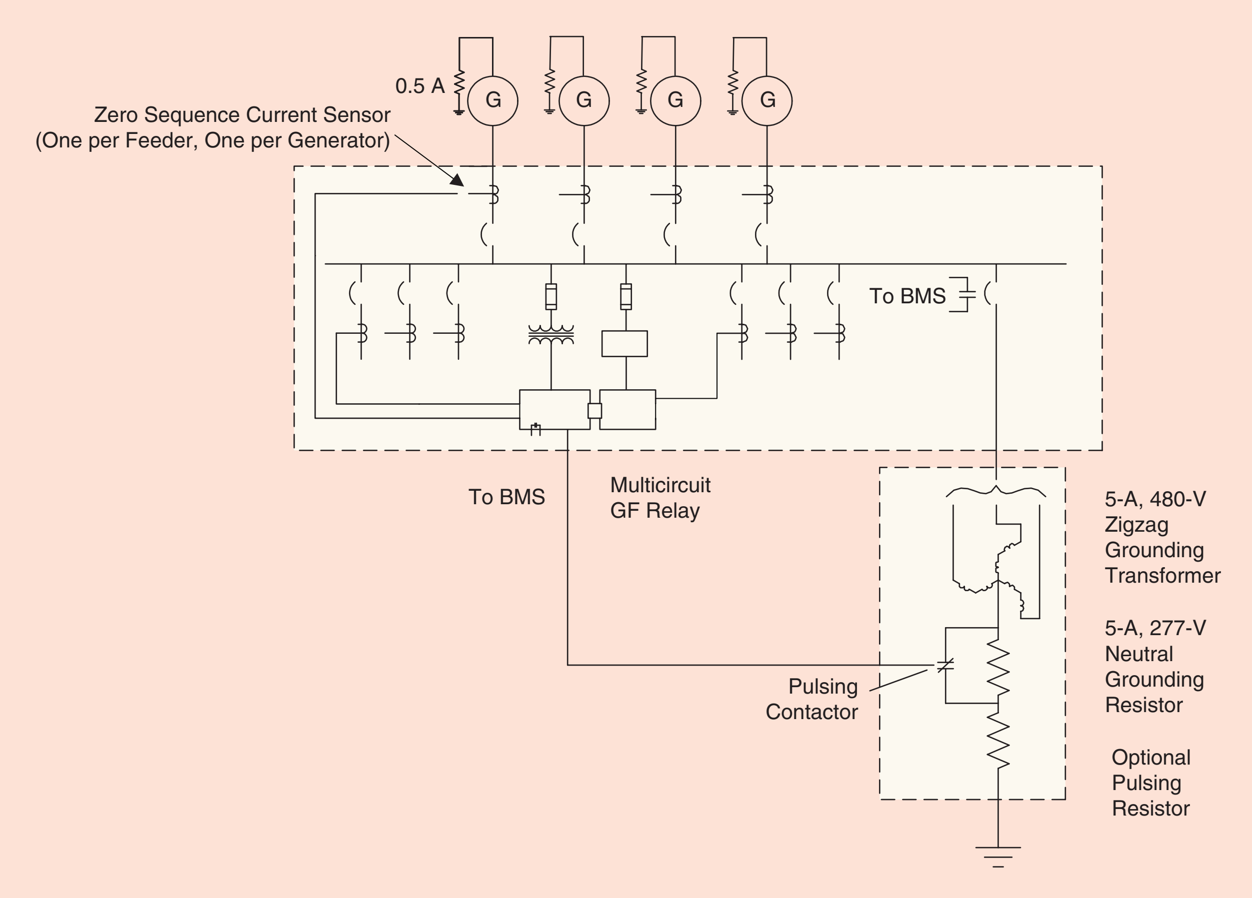

FIGURE 6. The HRG at the main bus. BMS: building management system.

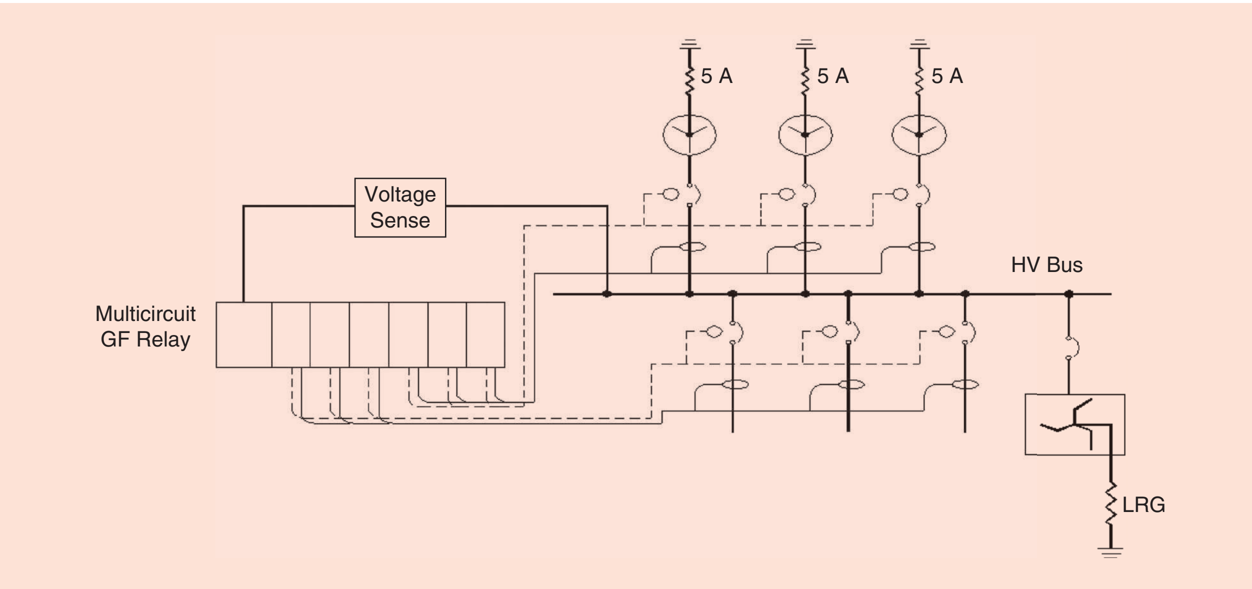

FIGURE 7. An extended MV hybrid system. HV: high voltage.

at the generator switchboard bus through a grounding transformer and not at the generators. This results in the elimination of the current circulation and generator derating. When HRG is in use, only the first ground fault will raise an alarm, and this enhances the reliability of the stand-by distribution system [11].

Examples of High-Resistance Grounding at Data Processing Facilities

In this scenario, each transformer and generator in the substation is equipped with a 5-A rated grounding resistor. Two generators are in parallel with each other, meaning that under emergency and test conditions, the grounding system is rated 10 A continuous, which is acceptable by the NFPA 70 standard. In the event of one generator failure, the grounding system is 5-A rated. Three substations, each at 12.47 kV to 480 V, are presented in this project. The resistors are rated at 5 A, but the pulsing feature pulsates the ground-fault current between 5 and 2.5 A at 1-Hz frequency for the fault-locating purpose. All the feeders are being monitored, so in the event of a line-to-ground fault, the faulted feeder can be identified. The automatic monitoring along with the pulsing capability facilitates the location of the ground fault in the system.

When uninterruptible power supply (UPS) systems are implemented in the distribution system, multiple modules are used in parallel, and one extra module is set as a standby. To provide further redundancy, a bypass switch is placed that can directly connect utility or generator output to the load. If there is an issue with the UPS output voltage or if the UPS voltage is reduced due to a downstream fault, the bypass switch operates so the utility substitutes the UPS as the power source. A third level of redundancy is provided using a second bypass switch connected to an alternate utility or generator bus.

The distribution systems are commonly organized to provide two identical systems, A and B. Each system connects to the server providing power from two sources of 120 V each with a 5-kW contribution from each side. The servers have the ability of switching instantly from one to the other and take 10 kW from one side should the other side be lost. This is the fourth level of redundancy being provided. The reliability and availability of such distribution systems can be improved by employing HRG at 480 or 600 V. The line-to-ground fault current is limited to 10 A, and no circuit breaker trip is required. As a result, the continuity of service is maintained. A ground-fault alarm is raised, and the ground fault is located by using the pulsing system while everything remains energized and operational.

Various UPS types and circuit arrangements are available:

- static double conversion with or without a transformer or with two transformers
- rotary
- in-line UPS without full conversion.

A double-conversion UPS with a transformer isolates the grounding systems from the supply side, and an independent grounding system must be provided. If an output transformer is used with the Y configuration and a neutral is used internally in the UPS with multiple modules, the neutrals need to be connected to a bus, and four-pole breakers must be used to provide isolation when one module is removed for maintenance. Rotary UPS requires independent HRG on the UPS output. Parallel modules operate through a common UPS output bus. The UPS output common bus is grounded through a zigzag transformer and grounding resistor. An in-line UPS without double conversion has no isolation, and the supply side resistance grounding prevails.

There are two major concerns in application with these arrangements.

1) What is the $3I_{co}$ (the capacitive charging current of the system) contribution from the UPS? This is dictated by capacitance to ground connected in each phase in the UPS.
2) Are these capacitances and any other components connected from phase to ground rated for full line-to-line voltage?

MV Low-Resistance Grounding

MV Application

Resistance grounding of MV systems reduces the line-to-ground fault current and the potential damage at the fault location. The general rule of applying resistance grounding is to ensure that the resistor let-through current (I_R) is greater than the capacitive charging current of the system ($3I_{co}$) [12]. With this rule, most

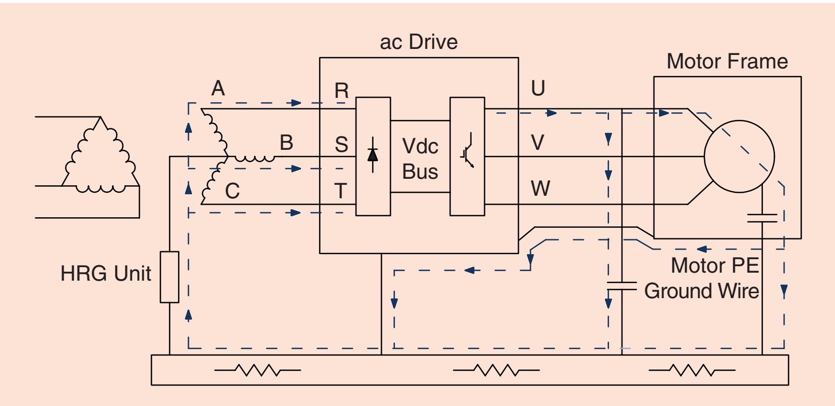

FIGURE 8. A UPS or ASD indicating common mode current due to switching supply. PE: protective earth.

high-voltage (HV) systems will have a let-through current of 20–100 A.

As the system voltage increases, the net capacitive charging current does also, and the total fault current ($I_R + 3I_{co}$) becomes significant. The system cannot continuously operate with the large fault currents (≥ 10 A) due to the danger of fault escalating to phase-to-phase or three-phase fault. Instant tripping on the first fault is required for these systems. Present electrical codes [7] and application rules allow the continuous operation of currents up to 10 A for system voltages up to 5 kV.

At voltages above 15 kV, the fault current contributed by the distributed cable capacitance $3I_{co}$ will become greater than 10 A. The resistance let-through current is higher than the allowed value to keep the system running continuously. In this instance, the faulted circuit must be tripped automatically, which means that the resistor should be short-time rated. Time-coordinated relaying can be applied to ensure selectivity.

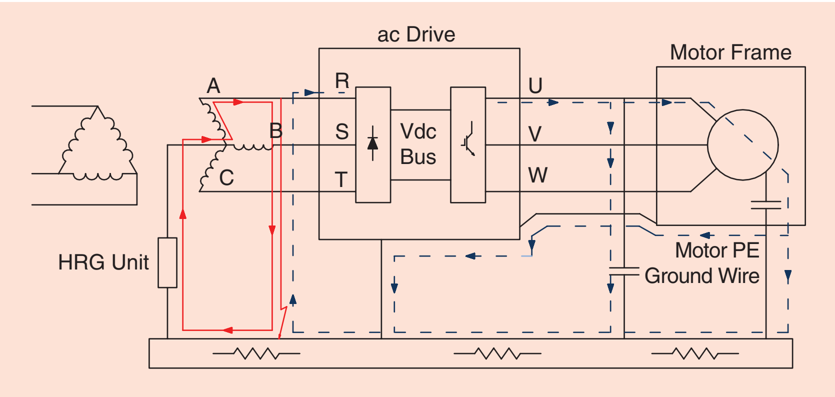

FIGURE 9. A UPS or ASD indicating a common mode current due to the switching supply and a zero sequence due to a ground fault on the line side.

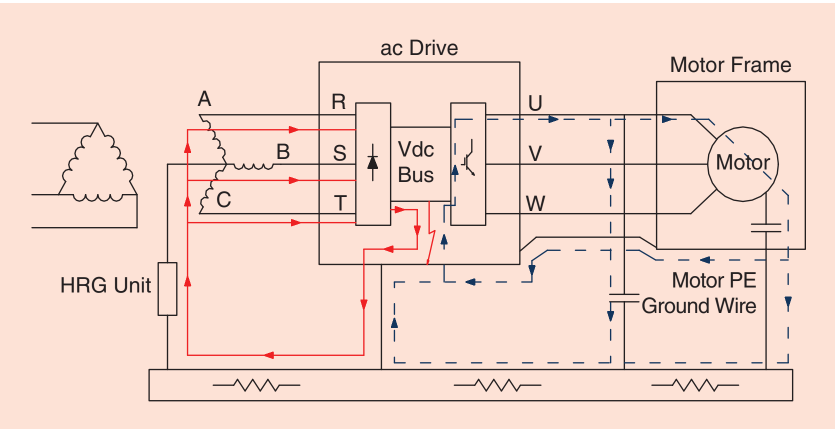

FIGURE 10. A UPS or ASD indicating a common mode current due to the switching supply and a zero sequence due to a ground fault on the dc link.

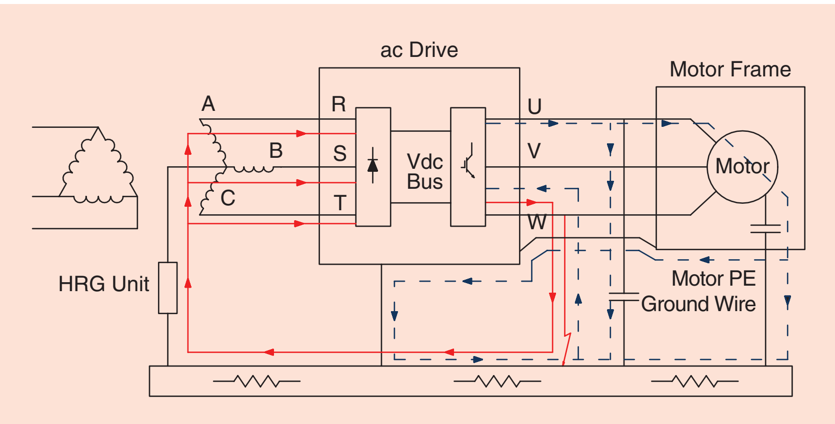

FIGURE 11. A UPS or ASD indicating a common mode current due to a switching supply and a zero sequence due to a ground fault on the load side.

Hybrid Grounding in the HV–HRG on the Generator and Additional Low-Resistance Grounding on the Main Bus

In HV systems with large charging currents, hybrid grounding is a viable option. If the generators are low-resistance grounded, the connected generators will contribute to the fault, and the magnitude of the fault current will depend on the number of running generators. This would make relay setting difficult. To solve this problem, HRG with 5-A rated resistance is applied on each generator, and the main generator bus is grounded using a zigzag grounding transformer connected to a low-resistance grounding (LRG) resistor. This low-resistance ground is introduced to overcome the estimated capacitive charging current of the system. A zigzag transformer sizing guide can be found in IEEE Standard 32-1972 [13]. This approach allows the use of zero-sequence sensors and ground-fault relays to be applied for the time-coordinated protection of the distribution. Zero-sequence sensors are applied on the generator feeds and sense the ground fault toward the generator. The stator winding is also protected, as shown in Figure 7.

Example of LRG at a Major Data Processing Facility

This example involves replacing existing generators, switchgear, and load management controls, as well as the addition of closed transition transfer switches. Each generator is

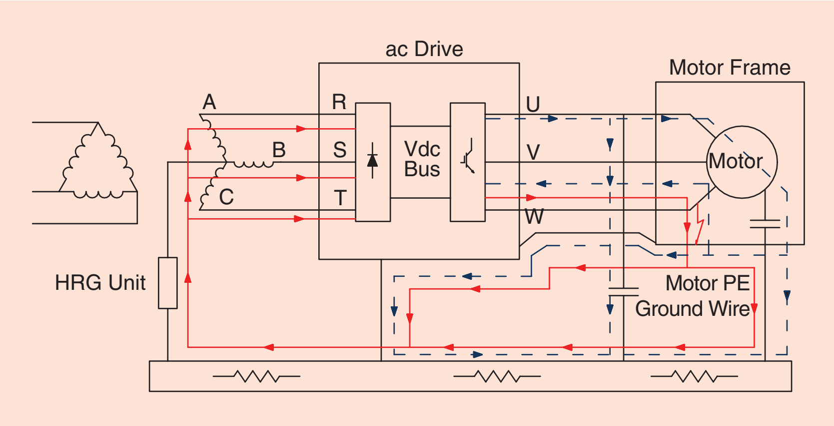

FIGURE 12. A UPS or ASD indicating a common mode current due to a switching supply and a zero sequence due to a ground fault at the motor.

equipped with LRG, with a resistor rated at 100 A. When the generators are paralleled, the total ground-fault current will be 400 A, which matches the ground-fault current available from the existing normal power system via grounding resistors on the 27.6-kV–4,160-V main transformers. LRG limits the fault current in the event of a line-to-ground fault, and this protects the shields on the extensive network of 5-kV cables. It also protects the generators and limits the arc-flash hazard, providing protection for the personnel.

UPS and ASD

Caution is necessary when choosing a UPS or variable-frequency drive (VFD). Figures 8–12 [14] show the common mode-switching current and the zero-sequence current due to ground faults at various locations. The continuous generation of power pulses from VFDs produces waveforms, and their instantaneous sum is not zero as in a smooth sine wave. The result damages common mode over voltage, which causes devastating effects to the equipment. Research shows that if the VFD is not at 100% duty when the ground fault occurs in the output, smart HRG might not detect the occurrence of a ground fault due to the frequency shift of the fault current and voltage.

Figures 9–12 show UPSs and VFDs working with HRG systems. The fault current always returns back to the source. The benefits of HRG systems outweigh the alternative of solidly grounded systems.

Conclusions

On LV systems (up to 5 kV), HRG provides a safer and more reliable distribution system compared to solid grounded and ungrounded systems. In the presence of a line-to-ground fault in such systems, there is less damage at the point of the fault, limiting the cost of repair. There is also less shock hazard since the touch and step potentials are lower. HRG is an arc-flash mitigation technique. Use of neutral ground resistors with low temperature coefficients, monitoring the NGR continuously, and using a pulsing system to locate the ground fault would increase the performance of the distribution system.

On MV systems, the let-through current of the resistor should be higher than the net capacitive current. The duty of the resistor depends on the current level and the system voltage. It is recommended that distribution systems with multiple sources be resistance grounded at the main bus. Distribution systems with multiple generators can be hybrid grounded using HRG at the generators and additional LRG on the main bus. Older LRG generators can be retrofitted with hybrid grounding.

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