

Avoid generating capacity losses in aging hydropower plants

Best practices to address ground fault conditions

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Abstract

Turbine generators are essential to hydropower systems, and the loss of a generating unit for an extended period of time could result in costly repair and opportunity costs. As machine insulation systems degrade over time, aging mechanisms progressively increase the risk of a possible ground fault internal to the generator. High- and low-impedance ground fault protection systems have been integrated to avoid downtime and production losses, as well as mitigate safety concerns in hydrogenation applications.

This paper addresses one of the most common electrical fault conditions in existing power stations. Case studies will be used to illustrate the drawbacks and advantages of high- and low-impedance grounding.

Why grounding systems matter

This paper addresses one of the most common electrical fault conditions in existing power stations: single-line-to-ground (SLG) faults. Across electrical systems in various applications, upward of 85 percent of electrical faults are SLG faults. More pertinent to hydrogenation systems, medium-voltage (MV) generators are not engineered to withstand the full fault current during this type of event, and are often generally connected to a system with either high- or low-impedance devices.

There are many methods to ground generators, each with various advantages and disadvantages. It's important to note that the means by which a power system is grounded impacts system performance, safety considerations for personnel and equipment protection.

An overview of grounding methods

Fundamentally, all power systems are grounded. Even so, the grounding and bonding of electrical power systems is often misunderstood and misapplied during power system installation.

In broad terms, there are three basic ways a power system is grounded:

- Ungrounded systems are in theory grounded through distributed capacitance (system capacitance)
- Solidly grounded systems involve a solid connection between neutral and ground
- Impedance grounding includes both high- and low-resistance grounding methods

The impact of an SLG fault will vary depending on how the power system is grounded.

Ungrounded systems

In earlier power systems, ungrounded systems were very common. Today, ungrounded configurations are not typical and have several key issues.

Ungrounded systems involve a delta-configured transformer. When a single-phase-to-ground fault occurs, there will be a minimum increase in fault current, as the system is not directly coupled to the ground grid.

In theory, an ungrounded system is bonded to the ground through distributed capacitance, which is associated with the cables and is inherent to a power system. There are no physical capacitors connected from the phase conductors to ground; this is the capacitance of the system. When an electrical power system is first energized, there is a slight increase of current for a few cycles, known as the capacitance charging current or the charging of the distributed capacitance.

In ungrounded systems, there are two types of SLG faults: bolted and arcing ground. Arcing faults are far more common in ungrounded systems. Arcing faults would result in equipment damage, while in low-fault-current conditions, the system could maintain power.



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Arcing ground faults in ungrounded electrical systems will keep increasing the voltage line-to-ground (L-G) until the insulation of the power system breaks down.

Line-to-line (L-L) voltage values are measured even though the actual measurement location is L-G. For every peak in the voltage, there is a restrike in the arc. Because there is no ground reference, the distributed capacitance keeps increasing in voltage. If an arcing fault occurred on a 480 volt (V) system, for example, the L-G voltage could increase to 5.5 PU or 1,523 V. At this point, insulation would break down on the phase conductors of the un-faulted phases and a flash over-to-ground would occur due to system overvoltage. This type of event would result in serious equipment damage as well as potential risk to personnel.

Bolted faults in ungrounded systems typically occur when maintenance is being performed on the power system. Once voltage is removed from a power system, and de-energization is verified, safety ground leads are connected to the phase conductors, bonding the system to the ground bus. This discharges the distributed capacitance of the power system and can provide a safety barrier for personnel performing work on the power system. Because the ground leads are bolted onto the phase conductors and the ground, if the system is energized, a bolted fault would occur. If this were a 480 V system prior to the ground fault, the line-line voltages would be 480 V for all three-phase conductors and L-G voltages would be 277 V for all three-phase conductors.

When a bolted fault occurs on one phase, the voltage will respond as follows: line-to-line, 480 V for all three phases; L-G on the faulted phase, 0 V; and for the other two phases, L-G would be 480 V instead of 277 V. Note that ground fault current could be 1 ampere (A). That said, the system can withstand the ground fault and power can be maintained. However, once a second ground fault occurs on a different phase, an L-L fault will occur and power interruption will be required to minimize damage due to thousands of amperes of fault current.

Grounded systems

A grounded electrical power system has a portion of the system that is intentionally bonded to the ground grid. This can be accomplished in several ways, depending on whether it's configured as a wye or delta system.

Grounded system: wye configuration

If the power system is wye configured, the neutral point is bonded to the ground grid as shown in **Figure 1**. This helps ensure that the neutral voltage is about equal to ground.

Solidly grounded systems that are properly installed will bond the neutral ground at one point. The location of neutral-to-ground (N-G) bond points can disrupt the ground fault sensing system.

With this type of system (see **Figure 1**), the measured line-to-neutral (L-N) voltage will be $V_{LL}/\text{SQRT } 3$. If there is an SLG fault on the system, voltage will approach zero and fault current will be very high, equivalent to three-phase fault current, which would result in equipment damage at the location of the ground fault.

Grounded system: delta configuration

If the power system is delta configured, one of the phases could be intentionally bonded to ground. In other words, a ground fault is intentionally being placed on one of the phases. This is known as a corner grounded delta system.

In this case, the measured L-G voltage is V_{L-G} , and will be equal to V_{LL} on the two ungrounded phases. The grounded phase will be zero V_{L-G} . If a ground fault occurs on one of the two ungrounded phases, the SLG fault current would be extremely high. However, if an SLG fault occurs on the grounded phase, no ground fault current will be measured.

The advantages of a corner grounded delta system are that it establishes a ground reference for each current, it is somewhat low cost and it eliminates the problems (overvoltages, transients) of an ungrounded system. Yet, there are significant disadvantages:

- The grounded phase needs to be marked throughout the distribution system
- Lower cost (slash rated) circuit breakers cannot be used
- Ground fault sensing is not defined for the grounded phase

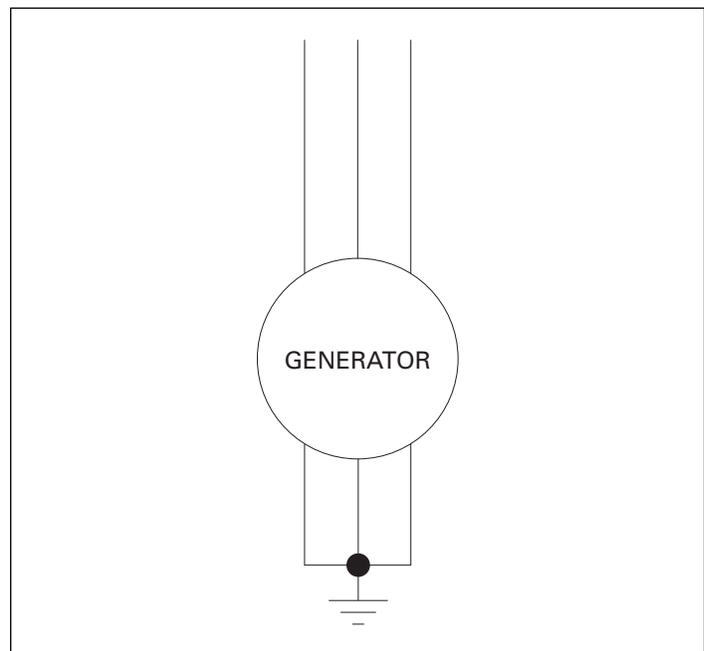


Figure 1. Wye solidly grounded system

Resistance-grounded systems

There are two kinds of resistance-grounded systems: high- and low-resistance.

Low-resistance grounding (LRG)

Low-resistance grounding is typically used to help reduce potential damage caused by high currents that flow through ground faults on medium-voltage systems (see **Figure 2**). LRG reduces current to hundreds of amperes (compared to thousands), yet the source of the fault must be disconnected immediately, as the fault current magnitude is still large. The voltage does not escalate due to the arcing ground fault.

LRG schemes can be used with both wye and delta configured medium-voltage systems. Ground fault current reaches between 100 A and 1200 A; for medium-voltage systems, ground fault needs to be less than 1000 A to avoid damage to the medium-voltage cable shields. It should be noted that LRG schemes cannot be applied on low-voltage systems, as there is a voltage drop across the resistor.

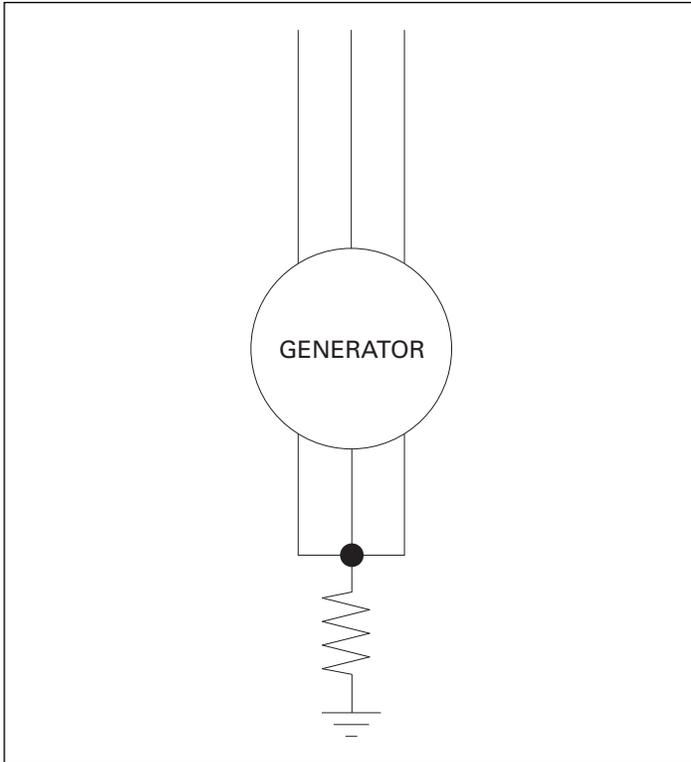


Figure 2. Low-resistance grounding (LRG)

High-resistance grounding (HRG)

High-resistance grounded systems are much like low-resistance grounded systems (see **Figure 3**). The main difference is that a neutral grounding resistor with a higher resistance is used. This change significantly reduces the amount of ground fault current, in the order of about 10 A, and even less on low-voltage systems. Further, these systems can include features to help locate the fault, which can help expedite repairs and enhance safety for personnel and the reliability of the system.

HRG can be used with both wye and delta configured systems. Systems that are greater than 5 kV are required to trip when a ground fault occurs. This is due to corona: the increase in voltage and partial discharge occurring due to insulation breakdown. Power systems less than 5 kV can continue to operate with a ground fault on the system, yet the fault must be located and removed before a second ground fault occurs.

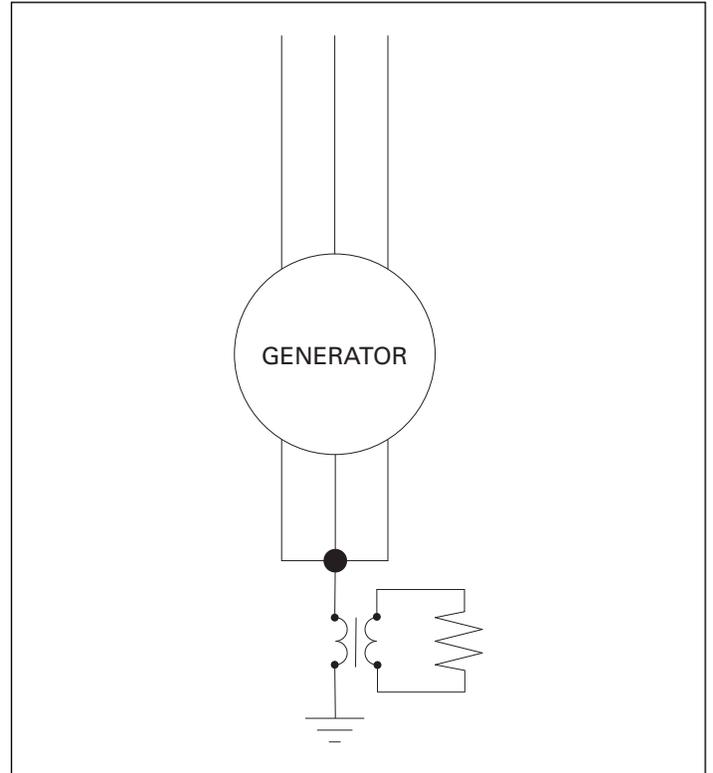


Figure 3. High-resistance grounding (HRG)

When a ground fault occurs on this system, the ground fault current will = 10 A maximum:

$$V_{L-G} = V_{L-L} \text{ (voltage L-G will equal voltage L-L)}$$

Voltage L-L will not be affected.

No ground fault protection is required on systems less than 5 kV; they just need the ground fault detection.

Hybrid-grounding systems

In a hydrogeneration system, if a ground fault occurs between a generator protective device and the generator, including the windings of the generator, significant damage could occur as voltage is still applied to the ground fault as the generator winds down. Typically, generators are low-resistance grounded to allow downstream ground protection to pick up the ground fault and trip the ground fault protection—isolating the fault from the rest of the power system. For this to work, a protective device coordination study needs to be performed on the overall power system.

Even with low-resistance grounding systems and reduced fault current, excess damage could occur—resulting in complete re-winding of the generator. This could cost millions of dollars and will likely result in significant downtime (compounding financial losses).

By tapping hybrid-grounding systems, the generator can be both low- and high-resistance grounded. Hybrid-grounded systems were specifically developed to protect generators from an internal ground fault. In this case, under normal operation, the generator will be low-resistance grounded. If a ground fault occurs between the generator and its protective device, the system will switch through a bypass device to high-resistance grounding. This results in minimal damage at the fault location. As the generator winds down, about 10 A of ground fault current will flow. If the ground fault is downstream, the isolating device closest to the fault will isolate the ground fault.

Hybrid-grounding systems need to be installed per the National Electrical Code® (NEC) 250.36. This limits the use of these systems to three-phase installations:

- No L-N loads are connected
- Ground detectors must be installed
- Personnel who service the system must be experienced
- Service continuity is required

With a hybrid-grounding system, the generator is not left ungrounded and the stator windings are protected. This method reduces the current, and therefore, the likelihood of internal generator damage. It also provides protection against overvoltages and helps improve system reliability by helping to locate the fault. In summary, hybrid-grounded systems protect against transient overvoltages and enable service continuity.

If there are multiple generators online, the hybrid-grounding systems should not be identical, as it could cause high ground fault current. The system should be reconfigured—ground faults downstream should be isolated by the breaker closest to the fault and the ground faults near the stator will be isolated by the differential scheme.



Small hydro high-resistance ground and generator neutral enclosure (hydroelectric facility in Maine)

System	Protection against overvoltages	Ability to operate during a fault	Ability to locate faults
Ungrounded	No	Yes	Limited
Solid grounded	Yes	No	No
Low resistance	Yes	No	No
High resistance	Yes	Yes	Yes



Combination generator termination cabinet (surge equipment) and high-resistance ground enclosure (hydroelectric facility in West Virginia)



Two high-resistance ground cabinets (hydroelectric facility in Virginia)

Conclusion

High-impedance grounding units provide a cost-effective solution to a potentially expensive problem while dramatically enhancing equipment reliability and personnel safety by increasing protection against harmful and damaging ground fault events. Customized units can be engineered to help manage the transient overvoltages that result from arcing ground faults. When a ground fault occurs on a system, high-transient voltages can occur, causing a host of issues, including equipment and cable insulation failure.

High- and low-impedance grounding units have been proven effective in other industrial environments—reducing the unsafe and damaging overvoltage conditions that may occur under arcing ground fault conditions. This technology is especially desirable in hydrogenation applications, as it does not necessarily have to take the system offline. Relay settings can be coordinated to eliminate nuisance events and increase the operational time of the generator, should there be an event external to the machine.

High-impedance grounding systems provide significant generator stator protection with limited additional components and reasonable financial commitments. Due to the relatively small nature of the system, most generation stations can accommodate the installation relatively easily.

With each additional generator protection function, the operational life of the machine improves dramatically. The addition of high- and low-impedance grounding systems to any hydroelectric generator will increase the machine reliability and online time for years to come.

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