IEEE standards may not sufficiently address grounding issues in rotor, stator windings

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There are two, unfortunately common, generator-winding failure modes that the IEEE standards overlook: the fracture of a rotor (field) conductor and the fracture of a stator conductor. This article describes these types of failures, discusses associated negative impacts of them, and recommends corrective actions.

On rotor windings, IEEE Standard C37.102 implies that a single ground may not be a major concern, except for exposure to a double ground. But on turbine/generator rotor windings, experience has shown that single grounds, which result from the fracture of a rotor-winding electrical conductor, can cause dangerous burning of rotor forgings.

On stator windings, the electromechanical ground relay (59GN) commonly used in generator protection, does not respond to grounds in the bottom 5% (approximately) of the winding. Four recent failures in this portion of the winding each caused massive damage to the generator and collectively had a total cost, including repair and loss of generation, of close to half a billion dollars. But IEEE Standards C37.101 and 102 imply that this detection deficiency may not be a major concern.

Rotor-winding ground protection

Recommended standard rotor-winding relay protection systems for generators are spelled out by IEEE Standard C37.102-2012, "Guide for AC Generator Protection." Relative to rotor windings, this recently re-issued guide states on p 46:

"The field circuit of a generator is an ungrounded system. As such, a single ground fault will not generally affect the operation of a generator. However, if a second ground fault occurs, a portion of the field winding will be short-circuited, thereby producing unbalanced air gap fluxes in the machine. These unbalanced fluxes may cause rotor vibration that may quickly damage the machine; also, unbalanced rotor winding and rotor body temperatures caused by uneven rotor winding currents may cause similar damaging vibrations." This statement does not appear to be completely accurate relative to a single ground, as is discussed below.

Except for turn shorts, ground insulation failure is probably the most common failure mode in rotor windings. Ground-fault detection in rotor windings is provided by a relay system that injects a low voltage into the (ungrounded) rotor winding. If a ground develops, this relay is activated. Based on industry guides and experience, the relay normally is set to alarm rather than trip. This is probably a rational approach—but with a caution.

A single ground can be a serious condition, if the ground results from a broken conductor (or shorted coils) rather than a simple failure of the ground insulation. Since conductor fracture is a somewhat common rotor-winding failure mode, a single ground should not be taken casually.

During a short period of time, the author was involved in the analysis of five rotor ground failures. One was a double ground and it resulted in minor forging burning in two locations. Fig 1 identifies one of those locations. The forging burn damage was in an area of low mechanical stress and easily corrected by minor iron removal similar to that shown in Fig 2.

1, 2. Minor rotor-forging burn damage (left) in an area of low mechanical stress is relatively easy to correct by light grinding of field iron, as shown at the right

The other four failures were single grounds resulting from broken conductors or shorted coils. Each of these failures involved forging burning of a serious nature. When the turn in Fig 3 broke, current continued to flow through a conduction path that involved the retaining ring and rotor body (Fig 4).

3, 4. Single-ground failure initiated by a broken top turn (left) caused serious burning of the forging and copper (right) when current continued to flow

The conditions shown in Figs 5 and 6 resulted from shorting between the two largest coils in a large rotor. (Because the ground detection circuit was incorrectly connected, the ground persisted for a significant period of time.) These conditions would constitute a single ground, but the damage to the retaining ring (Fig 6) was extremely serious and dangerous.

5, 6. Arc damage from shorting between two coils (left) effectively removed the coils from the excitation circuit. The single ground lasted for a significant period of time because the detection circuit was connected incorrectly. Result: Near-fatal burn damage to the retaining ring (inside diameter)

Rotor-winding ground relay system

Rotor windings operate at a low voltage, and an ungrounded design normally is used. This permits easy identification of a ground. Furthermore, the rotor-winding relay system itself is also relatively simple. If it is set up correctly, the relay will perform reliably.

On brush/collector excitation systems, the relay is connected to the rotor winding via the collector rings. On rotating rectifier rotors, however, ground detection involves complicating factors, since there is no direct method of connecting the relay system to the rotor winding. But, because ground detection is vital to reliability and safety, the connection for ground detection often is provided to the winding via a separate instrumentation slip ring or a wireless signal.

Stator-winding ground detection relaying

Recommended stator-winding relay protection systems for generators are covered by IEEE Standards C37.101-2006, "Guide for Generator Ground Protection," and C37.102-2012, "Guide for AC Generator Protection."

One of the recommended protection devices is a ground detection relay on the stator winding. Relative to this relay, C37.101 states on p 29: "The importance of detecting ground faults close to the neutral point of the generator is not dependent on the need to trip because of fault-current magnitude, since it may be negligible and will not, in general, cause immediate damage. If a second ground fault occurs, severe damage may be sustained by the machine because this may result in a short-circuit current not limited by the grounding impedance."

This statement does not appear to be completely accurate either. Historically, the common ground relay is an electromechanical relay powered by the voltage of the stator winding itself. Thus, if a ground occurs low enough in the stator winding, there is insufficient stator winding voltage to cause the relay to activate. This inactive voltage range covers about the bottom 5% of the winding.

As a result, any time a ground occurs near the bottom 5% of the stator winding, the electromechanical relay does not respond and there is no stator-winding ground relay protection at all. A generator trip does not occur until there is sufficient damage to cause other type of relay protection to become involved—generally the differential relay.

If the stator-winding ground is caused by a failure of the groundwall insulation by itself—for example, foreign object damage or badly cracked groundwall—this condition may not be particularly hazardous. There will be a current flow to ground but this circulating current returns to the winding through the high impedance stator neutral grounding system—typically a resistor-loaded distribution transformer.

The ground circuit impedance is set to limit current to a small value, about 3 to 10 amps, which cannot result in burn damage to the winding or core iron. So while the existence of a ground at any location of the winding is undesirable, consequential damage to the generator will not occur. Thus from this narrow viewpoint, omission by the standards of recognizing the condition of low-end grounds in the stator winding may be understandable.

However, the condition of failure-to-ground caused by the fracture of a stator conductor is not rare. If the failure location is in the bottom 5% of the winding, this failure mode is far from benign. The author has been deeply involved in four such incidents in a recent two-year period. All occurred on a neutral bar or neutral connection ring and caused massive damage to the generator. In addition, three other similar failures have been reported to the author, with similar massive damage. Examples of these failures are shown in Figs 7-9.

7-9. Failure-to-ground caused by the fracture of a stator conductor is not rare; examples are shown in these three photos. Core and winding damage attributed to a burned open bar in a slot is shown in the left and center photos and the burned-away copper of a fractured connection is at the right

Stator-winding ground faults

Category 1: In-service stator-winding failure-to-ground is a relatively common failure mode in generators. There are many possible causes. Some relate to mechanical damage of the ground insulation. Examples include: ground insulation wear-through from a foreign object or loose component, fracture of the groundwall because of a sudden short circuit, deficient groundwall insulation system, partial discharge combined with vibration, vibration sparking, inadvertent damage during maintenance, wet insulation attributed to a strand header water leak, and bar vibration in the slot.

Category 2: Other failures relate to the fracture of the conductor with the resulting burning away of the groundwall insulation. Examples include these: fracture of bar copper from high-cycle fatigue associated with vibration, fracture of bar copper attributed to gross overheating of the copper, melting of core iron, failure of a bolted connection, failure of a brazed or welded joint, and failure of a series or phase connection.

Category 1 failures generally should be benign. Unless a second ground occurs, the current flow to ground is limited to the 3-10-amp range and no peripheral damage is likely to result from this ground current itself. However, there is always the possibility that a second ground may occur simultaneously. The probability increases if the first ground is on a higher-voltage bar, thus elevating the voltage on the high-voltage bars of the other two phases. Two such simultaneous grounds guarantee that massive arcing will occur at each of the ground locations.

Category 2 failures in all situations, almost certainly will be highly destructive to the generator. These failures involve fracture of the current-carrying copper. When a conductor breaks, current will temporarily continue to flow within the stator-winding groundwall insulation, as in a welding arc; the heat generated will be extremely intense. This current will flow inside the insulation until the insulation is mechanically destroyed. Experience has shown that the copper will be vaporized for perhaps 8 to 12 in. before the internal arcing breaks through the insulation wall and becomes an exposed and widespread arc—and involves ground.

If the failure occurs in the slot, and is in a low-voltage portion of the winding, protective relays still will not trip. But if the failure is in a higher-voltage location, an immediate trip will occur; however, there may be significant damage because the arc will continue while the rotor current decays.

If the failure is in a low-voltage portion of the winding, a generator trip will not occur until some other relay system recognizes there is a problem—for example, core melting damage progresses to the point where bars at higher voltage become involved, arc current bypasses a current transformer and differential relay trip occurs, or arcing becomes so widespread that other portions of the winding become involved.

Root-cause investigation of stator windings that have failed because of a broken conductor generally is very difficult. This is because there is always massive burning and arc damage. Usually the actual cause of failure will be destroyed by the resulting arcing. In virtually all cases, the root cause only can be deduced from circumferential inference—that is, condition of similar components within the winding, conditions of similar generators, conditions of nearby portions of the failed components, engineering judgment, and engineering intuition. Obviously, each of these “inference” tools includes some inherent uncertainty. Regardless of root cause, the resulting damage is likely widespread and very costly in terms of repairs and loss of generation.

Costs of recent stator-winding failures

It is of interest to determine the direct losses associated with non-functioning ground relay systems. Looking only at the four largest incidents, and based on the author’s engineering judgment and input from the plant personnel, the following values result:

Actual costs of the four incidents:

- Repair costs, $104 million.
- Realistic estimate of loss-of-generation costs, $378 million.
- **Total, $482 million.**

Estimated costs, if the ground relay systems had been functional:

- Repair costs, $30 million.
- Loss-of-generation costs, $128 million.
- **Total, $158 million.**

Estimated net savings if a functioning ground relay system had been in place:

- Repair costs, $74 million.

- Loss-of-generation costs, $250 million.
- **Total, $324 million.**

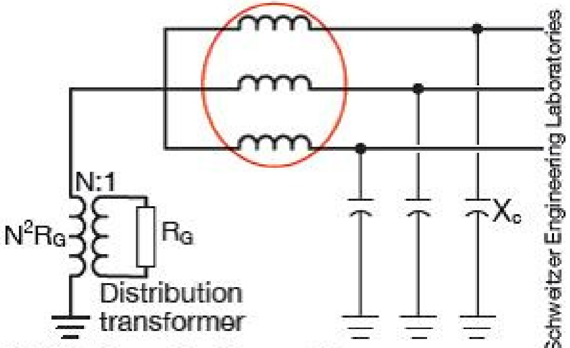
The $324 million is an incredibly large number. For comparison purposes, there have been numerous stator-winding failures in the higher-voltage portions of windings where the ground relay trip operated correctly. Two such failures are shown in Figs 10 and 11. Following each incident, repairs were relatively minor. In one case, the contamination was sufficient to require a field rewind. In both cases, the stator repair was accomplished without a rewind. Outage time was in the order of one month for each failure.

10, 11. Numerous stator-winding failures have occurred in the higher-voltage portions of windings where the ground relay successfully tripped the generator. Repairs to correct the failed phase connection above and the failed series connection at the right were relatively minor

Obviously, it is not possible to accurately estimate the savings of having a functioning ground relay system. But $324 million is a huge sum. A saving of an order of magnitude less would still be $32 million—a non-trivial amount of money.

Stator-winding ground relay systems

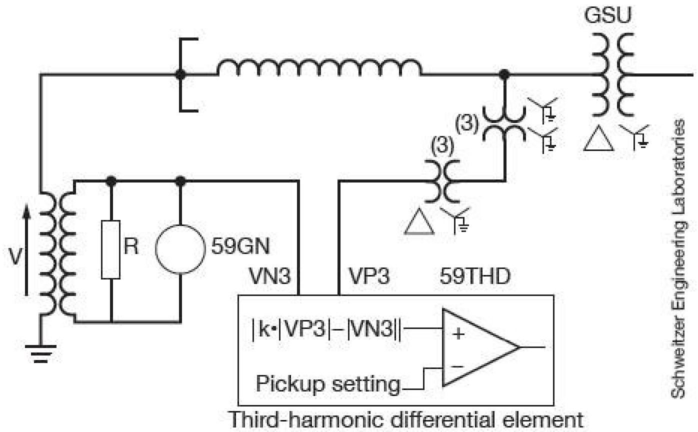
The stator windings of power station generators are typically Y-connected, and high-impedance grounded through a distribution transformer. The impedance is controlled by the magnitude of the resistor connected across the transformer. This impedance is selected to allow a maximum of about 3-10 amps to flow in the event of a ground at the high-voltage end of the stator winding (Fig 12).



12. Stator windings of large generators typically are wye-connected and high-impedance-grounded through a distribution transformer

Historically, an electromechanical relay (59GN) is placed across the resistor, which is powered by the voltage of the stator winding. The characteristics of this electrical circuit and relay are such that the relay does not respond to the voltage of the bottom 5% of the stator winding.

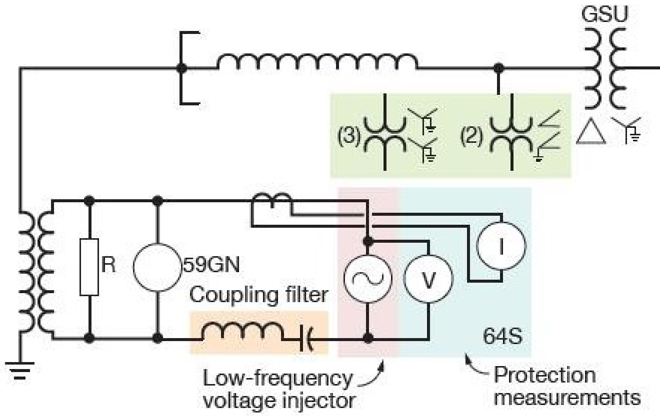
This weakness of the electromechanical relay has been recognized for many years. By the early 1970s, in Europe, most generators larger than 100 MW also were protected by a third-harmonic relay (59THD). Third-harmonic relay protection was first applied in the US in 1980. The combined relay system protects 100% of the winding (Fig 13). But most generators in North America apparently are still protected only by the 59GN relay.



13. Combining electromechanical (59GN) and third-harmonic (59THD) relays protects 100% of the winding

A third-harmonic relay system requires initial calibration with the generator operating offline and online to properly set the relay responses; this calibration work can involve significant cost and inconvenience to the plant. Furthermore, some generator designs may not produce sufficient third-harmonic voltages to allow reliable ground-fault protection schemes based on third- harmonic signals. Finally, the third-harmonic relay system has been found to occasionally perform unreliably due to subtle changes over time in the power-system third-harmonic voltages.

Because of these concerns, there is a trend toward developing and installing voltage-injection relay systems (64S). With the injection relay system, ground-fault protection can be functional when the generator is shut down (at standstill or turning gear), during startup, and at-speed offline or online (Fig 14).



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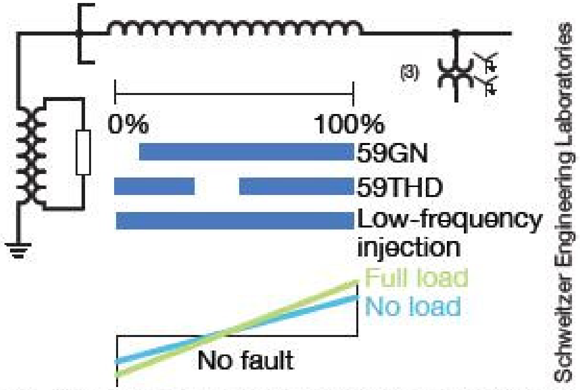
14. Voltage-injection ground protection can be functional when the generator is shut down (standstill or turning gear), during startup, and at speed offline or online

A subharmonic sinusoidal voltage is injected continuously, typically at 15 or 20 Hz on 60-Hz systems. The resultant sub-harmonic current is measured via the 64S relay and, if a ground fault occurs anywhere in the three phases of the stator winding, the current in the relay increases and causes the relay to operate.

The injection relay system is self-monitoring and the sensitivity is independent of the power- system voltage, load current, or frequency. This system has improved sensitivity (compared to the 59GN or 59THD relay systems) because of the higher impedance path of the generator capacitances at these lower frequencies. Also, because the 64S relay system integrates over a half cycle of the subharmonic frequency, there is no contribution from the signals of system base frequency and harmonics—that is, 60, 120, and 180 Hz. Thus these frequencies do not influence the 64S relay performance.

The cost associated with providing and maintaining a reliable injection source is a disadvantage, but this may be small compared to the costs associated with calibration efforts required on the third-harmonic relay system.

Coverage of the stator winding provided by the three relay systems is shown graphically in Fig 15. The 59GN relay gives reliable protection, but only on the top 95% of the winding. The bottom 5% remains completely unprotected. In some cases, this has proven to be a near-fatal deficiency, based on the experience discussed earlier.



15. Coverage of the stator winding is provided by the three relay systems described in Figs 12-14

The 59THD relay does not protect a mid-portion of the winding and must be used in conjunction with an additional relay system. Thus even if fully reliable, the third-harmonic system could not be considered as adequate protection by itself.

The cost of the signal generator is a disadvantage of the injection relay system (64S), but this system can reliably protect the entire winding, by itself. It has these further advantages: It can detect open circuits in the grounding transformer primary or secondary and is self-protecting for a grounding-relay system problem or loss-of-injection voltage source.

Concluding recommendations

Because of the hazards associated with either rotor or stator winding grounds, the ground protection systems for both components should be reviewed and any deficiencies found and corrected.

The ground protection systems for rotors are relatively uncomplicated, but the alarm/trip decision may not be uncomplicated. If a rotor is known to have marginal or suspect ground insulation, and if the generator is important to the power system, a ground should not be allowed to exist for more than a brief period—that is, minutes, hours, or a few days at most.

On stators, the historic stator-winding ground protection relay (59GN) should not remain as the sole protection system on any generator of importance to the power system. Based on the industry experience reported here, it is advisable to upgrade the ground protection to include 100% of the stator winding.

Unfortunately, the third-harmonic relay (59THD) has proven to occasionally perform unreliably, because of insufficient or changing third-harmonic voltages. It can also cause a false positive trip—thereby incorrectly removing a turbine/generator from power production. These concerns would seem to make the third-harmonic relay unattractive, unless the reliability issues can be resolved.

Based on operating experience and the current state-of-the-art for relay systems, it appears that an injection stator winding relay system (64S) should be installed on any generator where high reliability and low cost exposure are considered important.

Finally, IEEE Standards C37.101 and 102, relative to ground protection of rotor and stator windings, should be revised to reflect the broken conductor failure mechanism.

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