Grounding and Ground Fault Protection for Generator

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Abstract— **This paper discusses typical grounding practices and ground fault protection methods for medium voltage generator stators, highlighting their merits and drawbacks. Particular attention is given to applications of multiple generators connected to a single bus. The paper also provides an overview of the generator damage mechanism during stator ground faults. Problem areas associated with each type of grounding are identified and solutions are discussed. The paper is intended as a guide to aid engineers in selecting adequate grounding and ground fault protection schemes for medium voltage industrial and commercial generators for new installations, for evaluating existing systems, and for future expansion of facilities, to minimize generator damage from stator ground faults.**

Index Terms—**Protection Schemes, Grounding, Ground Fault, Overcurrent Protection, Grounding Resistance**

I. INTRODUCTION

For internal generator ground faults, the generator should be shut down as quickly as possible. However, for an external ground fault such as a feeder fault, a time-delayed shut down is usually employed to permit selective isolation of the faulty circuit. Along with the time-delayed tripping, an instantaneous alarm will provide early warning for the operator to take necessary action to minimize generator damage from prolonged fault current flow. Generator Ground Protection provides a wide range of generator ground protection schemes for different generator grounding and system grounding configurations. Typical generator ground fault protection methods include:

- Percentage phase differential protection (device 87)
- Ground differential protection (device 87GN)
- Ground time-overcurrent protection (device 51G)
- Instantaneous ground overcurrent protection(device 50G)
- Wye-broken-delta vt ground overvoltage protection
- (device 59G)
- Stator winding zero-sequence neutral overvoltage
- protection (device 59GN)

All of the above protective functions should initiate a complete shutdown of the generator, including tripping of the generator main and field circuit breakers and closing of the prime mover throttle valve.

II. PERCENTAGE PHASE DIFFERENTIAL PROTECTION (DEVICE 87)

Conventional percentage differential protection for phase-to- phase winding faults (Figure 1) will provide the ability to detect most internal ground faults, depending on the available ground fault current. If the maximum ground fault current is below the phase percentage differential pick-up, the phase differential relays will not provide any ground fault protection. In such cases a ground differential scheme as discussed below may be needed to provide adequate protection of the generator.
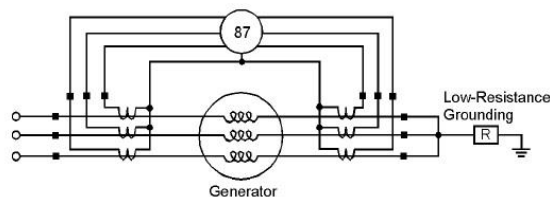

Figure1. Generator Percentage Phase Differential Protection
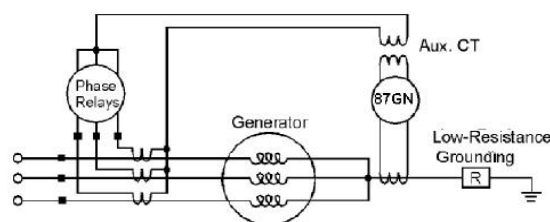
III. GROUND DIFFERENTIAL PROTECTION (DEVICE 87GN)

Figure 3.Generator Ground Differential Protection

Due to the high fault currents associated with low-resistance grounded systems, it is important to provide sensitive, high speed ground differential protection for generators. As discussed above, with low-resistance grounding, the phase differential relays may not be sensitive enough to detect ground faults internal to the generator, especially, since the maximum ground fault current may be limited to values below the phase differential pick-up. In such cases, a ground differential protection scheme as shown in Figure 2 would be desirable. When properly applied a ground differential scheme may be able to detect ground

faults to within 10% of the generator's neutral without the risk of false tripping on external faults. A ground directional overcurrent relay is generally used in this application with differential current as the operating quantity and neutral current as the polarizing quantity. The differential comparison is biased such that a positive restraint exists for an external fault. Depending upon the rating of, and the burden presented to the phase transformers, this scheme provides excellent security against misoperation for external faults while providing sensitive detection of internal ground faults.

IV. GROUND TIME-OVERCURRENT PROTECTION (DEVICE 51G)

As previously mentioned one of the most important advantages of low-resistance grounding is the ability to selectively coordinate ground overcurrent protection for downstream faults; thereby tripping only the faulted part of the system. For example, consider a ground fault occurring on a load feeder supplied from a generator bus, as shown in Figure 3. The load feeders will be protected using sensitive instantaneous ground overcurrent relays (device 50G) on each feeder, permitting high speed clearing of the fault. In the event of an uncleared feeder fault, an inverse time overcurrent relay (device 51G) on the bus tie breaker will provide back-up protection, isolating the faulted bus section. Further back-up protection will be provided by the inverse time-overcurrent relays (device 51G) on the grounded neutrals of the sources. Although, time-overcurrent ground relays provide sensitive, high-speed protection for ground faults, coordination can be difficult with multiple sources since the ground current magnitude will vary with addition or removal of sources.
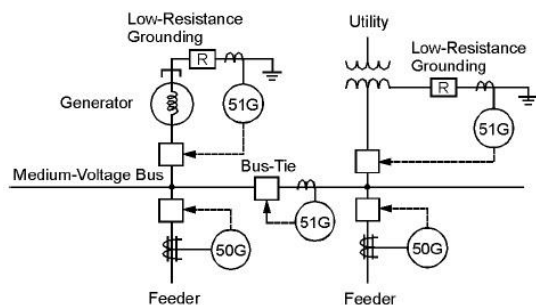
Figure 3. Generator Ground Time Overcurrent Protection

However, there is a possibility of serious generator damage from the prolonged high fault currents, especially when a ground fault occurs near the terminals of the generator. This damage may be reduced by using an instantaneous ground-overcurrent relay (device 50G) in conjunction with the time overcurrent relay. The instantaneous relay will detect faults near the generator neutrals. It may also provide backup protection for feeder faults.

V. INSTANTANEOUS GROUND OVERCURRENT PROTECTION (DEVICE 50G)

This is also called a generator self-balancing differential ground relay scheme and is shown in Figure 4. A window (toroidal) type (also called core-balance or zero-sequence) current transformer that surrounds the generator phase and neutral leads measures the ground current coming from the generator and the system for a ground fault in the generator. The current transformer output operates an instantaneous overcurrent relay to trip the generator. For a ground fault in the system external to the generator, the current transformer output will be zero. Therefore, the relay can be safely set to a low value for optimum protection of the generator. The limit of sensitivity can be affected by having to energize a large block of transformer load and by the physical position of leads in the window of the toroid.
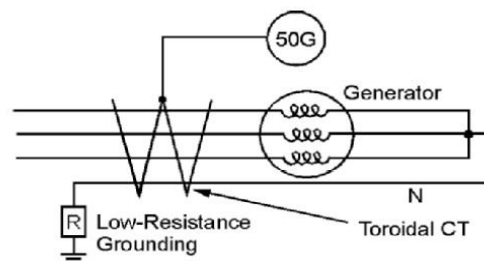
Figure 4. Instantaneous Ground Overcurrent (Self-Balancing Differential Ground Current) Protection

VI. WYE-BROKEN-DELTA VT, GROUND OVERVOLTAGE PROTECTION (DEVICE 59G)

This protection system is generally used for the high resistance grounded generators. This protection scheme is a variation of the stator winding zero-sequence neutral overvoltage protection scheme that is described below. In this scheme as shown in Figure 5, an overvoltage device (device 59G) is connected to a separate set of broken-delta secondary windings of the voltage transformer (vt), whose primaries are connected to the generator terminals in grounded wye configuration. A ground fault in the generator stator winding is detected by measuring the voltage across the broken delta secondary windings of the voltage transformer. For example, during a single-phase-to-ground fault in the generator, the vectorial sum of the phase-to-ground voltages applied to the primary windings of the three voltage transformers will be equal to three times the phase-to- neutral voltage of the generator. The voltage appearing across the terminals of the 59G device operating circuit will be the vectorial sum voltage divided by the voltage transformer ratio. It should be noted that full line-to-line voltage appears across each voltage transformer during a ground fault; therefore, they should be rated accordingly. A loading resistor may be placed across the broken delta to control possible ferroresonance.
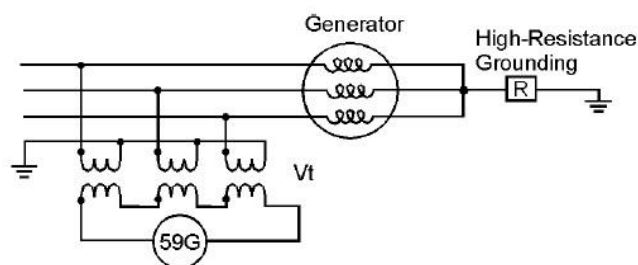
Figure 5. Wye-Broken-Delta Vt, Ground Overcurrent Protection

VII. STATOR WINDING ZERO-SEQUENCE NEUTRAL OVERVOLTAGE PROTECTION (DEVICE 59GN)

The most conventional and widely used protection scheme for high-resistance grounded systems is a time delayed overvoltage relay (device 59GN) connected across the grounding resistor, as shown in Figure 6. The relay used for this application should be tuned to fundamental frequency voltage and be insensitive to third-harmonic voltages that are present at the generator neutral under normal operating conditions.
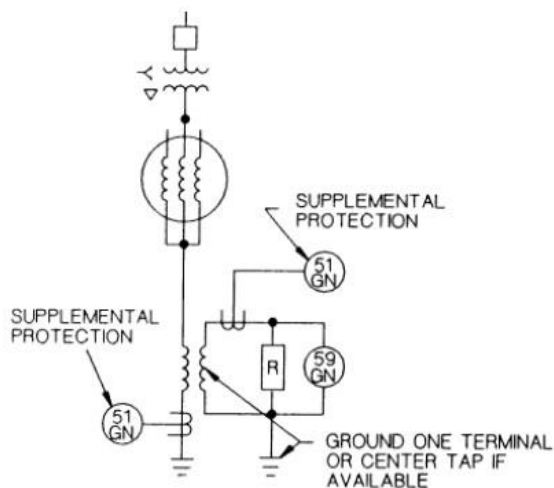
51GN Neutral Overvoltage Relay
59GN Neutral Overvoltage Relay Tuned to the Fundamental (60Hz) Frequency

Figure 6. High-Resistance Grounded, Unit-connected Generator, Zero-Sequence Voltage Protection

Since the grounding resistance is large compared to the generator impedance and other impedance in the circuit, the full phase-to-neutral voltage will be impressed across the grounding device for a phase-to-ground fault at the generator terminals. The voltage at the relay is a function of the distribution transformer ratio and the location of the fault. The voltage will be a maximum for a terminal fault and will decrease in magnitude as the fault location moves towards the generator neutral. Typically, the overvoltage relay has a minimum pickup setting of approximately 5 V. With this setting and with typical distribution transformer ratios, this scheme is capable of detecting faults to within about 2-5% of the stator neutral. The time setting for the overvoltage relay is selected to provide coordination with other system protective devices. Specific areas of concern are:

1) When grounded wye-grounded wye voltage transformers (vt) are connected at the generator terminals, the neutral ground overvoltage relay should be coordinated with the vt fuses to prevent tripping the generator for vt secondary ground faults. This would require very careful selection of vt fuses.

2) The ground voltage relay (device 59GN) may have to be coordinated with system relaying for system ground faults. System phase-to-ground faults will induce zero sequence voltages at the generator neutral due to capacitive coupling between the windings of the unit transformer. This induced voltage will appear on the secondary of the grounding

distribution transformer and can cause operation of the 59GN voltage relay. A time overcurrent ground relay (device 51GN) can be used as backup protection when the generator is grounded through a distribution transformer with a secondary resistor as shown in Figure 6. The current transformer supplying the overcurrent relay may be located either in the primary neutral circuit or in the secondary circuit of the distribution transformer.

VIII. ADDITIONAL PROTECTION METHOD

Additional protection methods are used to provide more sensitive protection against ground faults in generators that are high-resistance grounded. These include 100% stator winding ground fault protection and the use of a generator neutral breaker.

A. 100% Stator Winding Ground Fault Protection

Conventional protection for stator ground fault detection on high-resistance grounded systems has been discussed in the previous section. These protective schemes are straightforward and dependable. However, these relays would typically provide sensitive protection for only about 95% of the stator winding. This is because the fault in the remaining 5% of the winding, near the neutral, does not cause sufficient 60 Hz residual voltage and residual current to operate these relays. Even if fault current magnitudes for ground faults close to the neutral point are negligible in causing any immediate damage, potential severe damage can be caused from a second fault, especially when the first fault is near the neutral.

Furthermore, if the second fault occurs in the same winding, the generator differential relay may not operate at all since this condition can be regarded as an internal turn-to-turn fault. Therefore, complete winding protection should be considered for large generators. Special protection schemes based on detection or absence of third-harmonic voltages or neutral/residual voltage injection techniques are available to detect ground faults in the generator stator close to the neutral points that may otherwise go undetected using the typical protection schemes mentioned above.

However, these are only applicable on high-resistance grounded, unit-connected generators. Third harmonic voltage based techniques are widely used to provide such protection. They are applicable where there is sufficient third-harmonic neutral voltage to apply such schemes.

The techniques based on the use of third-harmonic voltage can be divided as follows:

i) Third-harmonic neutral undervoltage technique

ii) Third-harmonic residual terminal overvoltage technique

iii) Third-harmonic comparator technique

i) Third-harmonic neutral undervoltage technique

This technique uses the fact that for a fault near the neutral, the level of third-harmonic voltage at the neutral decreases. Therefore, an undervoltage relay (device 27) operating from third-harmonic voltage measured at the generator neutral can be used to detect ground faults near the neutral.

The ground faults in the remaining portion of the windings can be detected by conventional ground fault protection such as an overvoltage relay (device 59GN) which operates on the 60 Hz neutral voltage. The combination of both relays can provide 100% stator winding protection. A protection scheme using this technique is shown in Figure7.

ii) Third-harmonic residual terminal overvoltage technique

This technique is based on the fact that for a fault near the neutral, the level of third-harmonic voltage at the generator terminals increases. Therefore, an overvoltage relay using third-harmonic voltage at the terminals of a generator can be used for detecting faults near the neutral. As before, the ground faults in the remaining portion of the windings can be detected by the conventional 95% protection, e.g., an overvoltage relay which operates on 60 Hz neutral voltage. Both of these relays can provide 100% protection of stator windings by covering different portions of the windings. A protection scheme using this technique is shown in Figure 8.
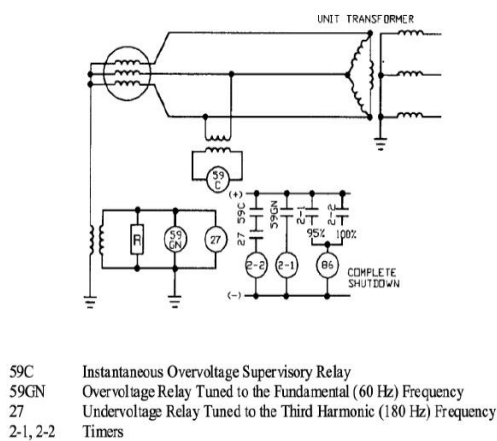

59C	Instantaneous Overvoltage Supervisory Relay
59GN	Overvoltage Relay Tuned to the Fundamental (60 Hz) Frequency
27	Undervoltage Relay Tuned to the Third Harmonic (180 Hz) Frequency
2-1, 2-2	Timers

Figure 7. High-Resistance Generator, Third-Harmonic Undervoltage Ground Fault Protection Scheme

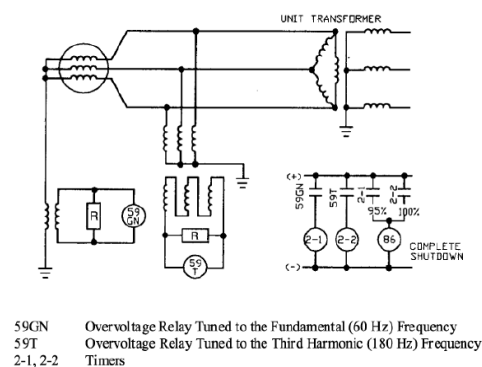|	
59GN	Overvoltage Relay Tuned to the Fundamental (60 Hz) Frequency
59T	Overvoltage Relay Tuned to the Third Harmonic (180 Hz) Frequency
2-1, 2-2	Timers

Figure 8. High-Resistance Grounded Generator, Third-Harmonic Residual Terminal Voltage Based Ground Fault Protection Scheme

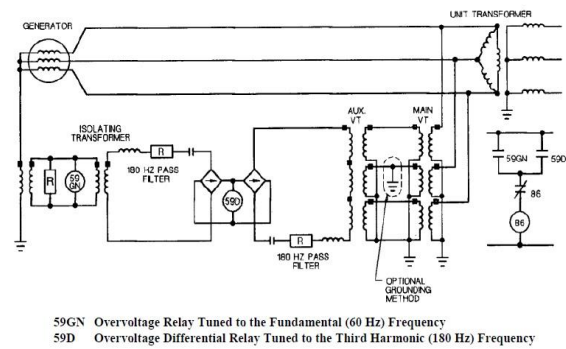|	
59GN	Overvoltage Relay Tuned to the Fundamental (60 Hz) Frequency
59D	Overvoltage Differential Relay Tuned to the Third Harmonic (180 Hz) Frequency

Figure 9. High-Resistance Grounded Generator, Third-Harmonic Comparator Based Ground Fault Protection Scheme

iii) Third-harmonic comparator technique

This scheme compares the magnitude of the third harmonic voltage at the generator neutral to that at the generator terminals. The scheme is based on the premise that the ratio of the third-harmonic voltage at the generator terminals to that at the generator neutral is almost constant during the normal operation of a generator. This ratio is upset for a ground fault near the neutral or near the terminals of a generator, and this fact is used to detect these faults. The ground faults in the remaining portion of the windings are detected by the conventional 95% ground fault protection such as 60 Hz overvoltage or overcurrent relay operating from the neutral voltage or current respectively. Figure. 9 show a diagram of the comparator scheme.

B. Generator Neutral Breaker

While this is a possible aid in minimizing stator ground fault damage, the cost and potential risks of using a neutral breaker result in few applications of these devices.

Under damage mechanism for a stator ground fault, tripping the generator main breaker alone does not interrupt the current from the faulted generator. Providing a generator neutral breaker will minimize stator damage (iron burning) from internal faults. If a neutral breaker cannot be justified, stator damage can be significantly reduced by accelerating decay of field flux by field forcing to zero using de-excitation circuits.

IX. GENERATOR GROUNDING CONSIDERATIONS

Grounding systems are generally classified as ungrounded, effectively grounded, low impedance, or high-impedance grounded. Ungrounded systems have no physical connection between the generator neutral and ground. But a small ground fault current will flow as a result of shunt system capacitance. Effectively grounded systems have a direct connection from the generator neutral to system ground. The phase-to-ground fault current on an effectively grounded system is very high, in many cases higher than that of a three-phase fault.

A low-impedance grounded system has minimal impedance connected between the generator neutral and ground. This impedance limits the ground fault current to a value typically between 100 A and the magnitude of a three-phase fault. In a high-impedance grounded system, the ground-to-neutral impedance is large enough to limit the ground fault current to a value between 2 and 15 A.

4

A. Ground Fault Current Limitation

At the heart of the differences between generator and transmission grounding is the difficulty in designing a generator to withstand the thermal and mechanical forces associated with a fault. Although the same constraints are placed on T&D system components, they are more difficult to satisfy for generator. Generator fault current does not cease immediately following the operation of a protective relay. The generator fault current will require anywhere from 1 to 10 sec to decay to zero as the magnetic energy stored in the generator dissipates onto the fault. Also, the X/R ratio for a fault at the generator terminals is much higher than at substations. The higher ratio prolongs the mechanical and electrical stress produced by the DC component of the fault current. Another factor is the low zero-sequence impedance of a generator. Typically, a generator's zero-sequence impedance is much less than its subtransient or negative-sequence reactance. As a result, the magnitude of an unrestricted phase-to-ground fault at the generator terminals is significantly higher than that of a three-phase fault. Both heating and mechanical force vary as the square of the fault current. Therefore, a small reduction in fault current significantly reduces thermal and bracing requirements for the generator.

B. Overvoltage Concerns

Ungrounded operation would eliminate concerns relating to excessive ground fault current, because the only current flow would be the minimal current sustained by the system shunt capacitance. Unfortunately, this solution is unacceptable because this capacitance can cause damaging overvoltages. A primary requirement of any grounding scheme is that it limits overvoltages to non damaging levels. Overvoltages can be steady state, caused by ground faults, or transient, caused by switching or arcing ground faults. The magnitude of these overvoltages is a function of the ground path impedance. When a generator neutral is connected solidly to system ground, the low ground path impedance will permit very high fault currents, but it will also prevent significant overvoltages.

The addition of impedance into the neutral to limit fault current increases the overvoltages imposed on the system. The neutral impedance must be chosen using specific criteria to eliminate the possibility of damaging overvoltages.

X. DESIGN CONSIDERATION FOR GROUNDING RESISTANCE

$$R_S = \frac{10^6}{N^2 \times 2\pi f C} \, ohms$$

Where, N=distribution transformer turns ratio
   C=microfarads capacitance to ground of all three phase
   R_S=Secondary resistance

The maximum generator ohmic rating has been determined the maximum generator ground fault may be calculated as follows:

$$I_P = \frac{E_P}{R_S (V_r)^2}$$

Where, I_P=maximum generator ground fault amperes
   E_P=generator phase-to-neutral volts
   R_S=Secondary resistor rating in ohms
   V_r=transformer voltage ratio

The maximum voltage applied to the relays:

$$V_R = \frac{V_{L-N}}{N \times \frac{220}{110}}$$

XI. CONCLUSIONS

Ground faults of only a few amperes contain the seeds of destruction of any piece of equipment. This is particularly true of generators where a second fault can result in large fault currents. These cannot be quickly removed because of the stored energy in the field and significant damage generally results. All generators develop some harmonics. In substantially all cases there is enough third harmonic on the generator neutral bus to use in a protective system. Third harmonic voltages as low as 1/2 % of line to neutral voltage are sufficient. The reduction of third-harmonic is an indication of an abnormality at or near the neutral end of a generator.

REFERENCES

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