Understanding Generator Stator Ground Faults and Their Protection Schemes

Nathan Klingerman
Duke Energy

Dale Finney, Satish Samineni, Normann Fischer, and Derrick Haas
Schweitzer Engineering Laboratories, Inc.

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Understanding Generator Stator Ground Faults and Their Protection Schemes

Nathan Klingerman, *Duke Energy*
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***Abstract*—Because of stator winding construction, an insulation failure is more likely to result in a winding-to-ground fault than in a phase-to-phase fault. Other failures, such as a broken conductor or turn-to-turn fault, may not be detected until the fault develops into a winding-to-ground fault. Consequently, stator ground fault protection is one of the indispensable schemes for protecting a generator stator winding. Dedicated stator ground fault protection is required for high-impedance-grounded machines.**

Neutral overvoltage protection is the simplest method for detecting a stator winding-to-ground fault, but this method does not detect faults over the entire winding. Therefore, additional protection is required in the form of third-harmonic undervoltage, third-harmonic voltage balance, or subharmonic injection. Each of these protection schemes is available in several alternatives.

I. INTRODUCTION

This paper provides an overview of winding insulation failure modes related to ground faults and discusses all common ground fault protection schemes in detail. The paper contrasts the following aspects of these schemes: sensitivity, speed, security, availability, complexity, and setting considerations.

II. HIGH-IMPEDANCE GROUNDING OF GENERATORS

This paper is primarily concerned with synchronous generators connected via a generator step-up transformer (GSU) to a power system. The zero-sequence impedance of a synchronous generator is typically about half of the positive-sequence subtransient reactance of the machine. This means that a single-phase-to-ground fault generates a per-phase fault current greater than the per-phase fault current generated by a three-phase fault [1] [2].

However, National Electrical Manufacturers Association (NEMA) standards do not require that standard generators be braced for the stress associated with nonsymmetrical fault currents in excess of a three-phase fault at the terminal of the generator [3]. Therefore, to maintain the mechanical integrity (rigidity) of the stator windings of a generator, the neutral terminal of a standard generator should be grounded via an impedance. Doing so limits the per-phase fault current magnitude for a single-phase-to-ground fault to be no greater than the per-phase fault current during a three-phase fault. Another aspect to consider is that, at such high fault currents, not only are the stator windings damaged, but burning of the stator core also occurs, which leads to expensive repairs if not the scrapping of the generator.

So why not leave the neutral terminal of the synchronous generator ungrounded? This would ensure that the fault current for a single-phase-to-ground fault at the terminals would be no greater than the charging current of the generator stator windings plus the associated cabling and surge capacitors. If the ground fault is bolted and not intermittent, then the potential difference of the unfaulted phases increases from a line-to-neutral voltage to a line-to-line voltage, an increase of 73 percent. The rating of the stator winding insulation could be selected so as to take this into account. However, most ground faults begin as intermittent faults, and, as a result of this arcing phenomena or restriking, large transient voltages are generated on the unfaulted phases that can lead to insulation breakdown [4] [5].

From this information, it can be deduced that the solution for the grounding of a standard generator lies between the two extremes of being solidly grounded or being ungrounded.

High-resistance grounding of a generator limits the fault current magnitude of a single-line-to-ground fault so that the integrity of the stator winding bracing is not compromised and at the same time ensures that the stator core is not damaged. A further advantage of high-resistance grounding of a generator is that the transient overvoltages are substantially reduced when compared with those of an ungrounded generator.

High-resistance grounding of a generator is usually achieved by using a distribution transformer and having the primary winding of the distribution transformer connected between the neutral terminal of the generator and ground. A resistor is connected across the secondary winding of the transformer. This method of high-resistance grounding is shown in Fig. 1.

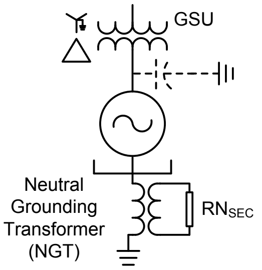

Fig. 1. Implementation of a Generator High-Resistance Grounding Scheme Using a Distribution Transformer

Note that in Fig. 1 the GSU is delta-connected. The high-voltage side of the unit auxiliary transformer (if present) is also delta-connected at the output of the generator. There is a small coupling between other zero-sequence networks due to capacitance between transformer windings. However, generally, there is very little system contribution to ground faults on the stator. Similarly, the generator makes very little contribution to system ground faults. In addition, the voltage displacement that occurs for a generator ground fault is not seen in the power system. Section IV in this paper looks at the impact of interwinding capacitance in more detail.

The voltage rating of the primary winding of the distribution transformer is typically equal to the line-to-ground voltage rating of the generator, with the secondary rating of the distribution transformer being in the range of 120–480 V. This arrangement allows for the resistor to be of a low ohmic value and of rugged construction compared with inserting a high-ohmic resistor directly between the generator ground and neutral. The sole purpose of the distribution transformer in this arrangement is to transform a low-ohmic resistor in the secondary winding to a high-ohmic value in the primary winding (between the generator neutral and ground), which in turn limits the magnitude of the fault current during a single-phase-to-ground condition. The kVA rating of the transformer and resistor is related to the capacitive current to ground during a single-phase-to-ground fault. In practice, the resistor is selected so that the fault current in the primary winding of the distribution transformer is matched to the capacitive fault current during a single-phase-to-ground fault. The resistor is selected so that the active power (kW) loss of the resistor is equal to the reactive power dissipated by the equivalent capacitance of the generator (this is the sum of the generator winding capacitance, cabling, and generator surge capacitors) during a single-line-to-ground fault. This is done either by setting RN equal to the capacitive reactance of all three phases or by setting it equal to one-third of the per-phase value. Either way, the result is the same. Selecting the value of the resistor so that the above conditions are satisfied also ensures that ferroresonance between the generator potential transformer (PT) and equivalent capacitance is avoided.

Calculation of the values of the neutral grounding resistance and the resulting available fault current is illustrated in Appendix A.

III. STATOR WINDING CONSTRUCTION AND FAILURE MODES

A. *Winding Construction*

The following three basic types of stator winding structures are used in machines today, ranging from 200 kW to more than 1,000 MW:

- Random-wound stators. These are used in generators from 200–300 kW.
- Form-wound stators using multiturn coils. These are used in generators up to about 100 MW.
- Form-wound stators using Roebel bars. These are used in generators with ratings larger than 100 MW [6].

This paper mainly concentrates on the two types of form-wound windings.

B. *Coil-Type Form-Wound Stator*

At terminal voltages larger than 1 kV, the voltage between adjacent turns in random wound stators becomes significant. This problem is addressed through the use of form-wound coils. The coils are made from one continuous piece of insulated copper wire with additional insulation applied over each coil. Typically, a coil consists of two or more series turns. Several of these coils are connected in series and in parallel to produce the rated current and voltage of the machine.

Fig. 2 is a picture of a typical form-wound stator coil.

Fig. 2. Example of a Form-Wound Stator Coil

Careful design and machine manufacturing are employed to ensure that during assembly each turn of a coil is placed next to an adjacent turn so as to create the lowest potential difference between two adjacent turns. By doing this, thinner insulation can be used to separate the turns.

C. *Roebel Bar Form-Wound Stator*

As the machine rating increases above about 100 MW, the form-wound coils become so stiff that it is nearly impossible to insert them into the narrow stator slots without damaging the coils. Therefore, most large generator coils today are not constructed using multiturn coils but rather are constructed with what are known as half-turn coils, also referred to as Roebel bars (see Fig. 3).

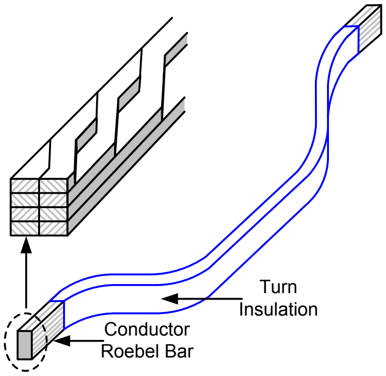

Fig. 3. Sketch of a Half-Turn Coil, or Roebel Bar, Commonly Used in Large (greater than 100 MW) Generators

Referring to Fig. 4, which demonstrates the insertion of a form-wound coil, it becomes clear that when winding large machines with sizable coils, it is easier to insert a half-turn coil (Fig. 3) into a stator slot than to insert two sides of a form-wound coil (Fig. 2) into two slots simultaneously.

Fig. 4. Insertion of a Form-Wound Coil Winding Into a Small Synchronous Motor

Although both ends of a half-turn coil require an electrical connection, this effort is insignificant when compared with the effort of inserting two sides of a coil into two slots simultaneously without causing mechanical damage to the coil.

D. Insertion of Coils Into Stator Slots

Large machines are usually wound using single-turn coils that are made of double-layer bar windings. Windings are categorized as lap-connected (where each coil is lapped over the next to form the winding) or wave-connected (where coil sides are located under alternating poles around the stator). A lap connection is preferred over a wave-connected winding because it is easier to connect the coils. The turns that make up a coil must be insulated, not only from ground (the stator core is typically grounded) but also from one another. A turn of a coil used on a large machine is constructed with a number of individual strands. This is done to negate the skin effect and circulating currents and to optimize the conductor area. Each strand and each turn is insulated. The turns are then formed into coils and insulated in what is known as the groundwall insulation. The groundwall insulation not only provides insulation for the coil but also ensures there is no void between the coil and the stator wall. Before the coil is embedded into a stator slot, the stator slot is lined with semi-conductive insulating paint. This semi-conductive coating aids in heat dissipation.

Fig. 5 is a diagram of a form-wound stator coil in a stator slot. The figure shows the different components, including the insulation material, that make up a stator coil.

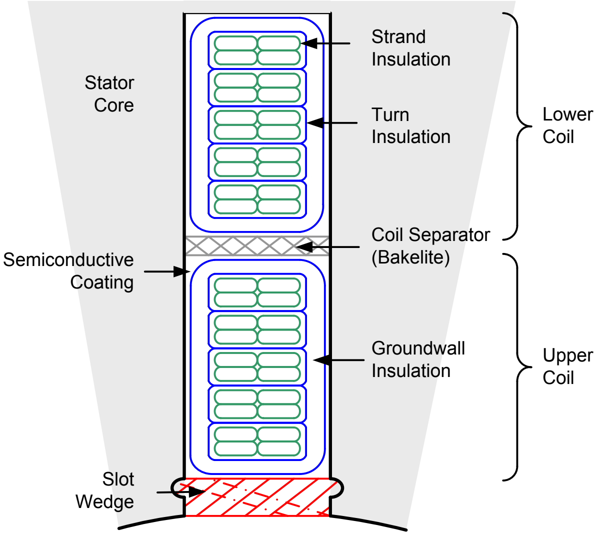

Fig. 5. Form-Wound Stator Coil in a Double-Layer Stator Winding With Four Strands and Five Turns Per Coil

E. Failure Modes

A winding failure is often the result of gradual deterioration of the insulation system followed by an event, such as an external fault or voltage surge, that stresses the already weakened insulation beyond its reduced capability. A number of processes can produce deterioration. These include thermal, electrical, mechanical, and environmental factors [7].

1) Thermal Deterioration

Thermal deterioration occurs when insulation is heated beyond its design temperature. This causes the breakdown of chemical bonds in the insulation material. This, in turn, makes the insulation brittle and increases the possibility of cracking. Overheating of the insulation can be caused by overloading or by a cooling system failure. Overheating can also be localized and usually occurs due to a high-resistance electrical connection in the winding. Such a problem can be created by a loose mechanical connection within the stator or by high-resistance electrical conditions from soldering defects or conductive material contamination.

2) Electrical Deterioration

Electrical deterioration results from partial or slot discharges. Partial discharge refers to the arcing that occurs within small voids in the insulation. Often these voids are preexisting defects created during the construction of the winding. We can consider the insulation and the void as two capacitors connected in series. The application of voltage to the conductor produces a capacitive voltage divider. The resulting voltage across the void can exceed the electrical breakdown strength, leading to arcing within the void. The arcing causes a decomposition of the insulation on the interior surface of the void, gradually causing the void to grow and weakening the insulation over time [7]. Partial discharge can also occur in the end windings. This can happen when inadequate clearances create voltage gradients that exceed the breakdown strength of the insulation.

A slot discharge is similar to a partial discharge. Slot discharges can occur in generators that are subjected to high thermal cycling (heating and cooling due to rapid load changes or frequent starting and stopping). When high thermal cycling occurs in generators with long stators, the differing thermal expansion coefficients of the various components (conductor, insulation, and core) produce shear forces. These forces result in the separation of the ground wall insulation from the stator core, producing a void. The voltage at the surface of the insulation where the void occurs rises to the phase-to-ground value. This results in an arc, which breaks down the insulation at the surface, eventually causing the insulation to fail.

3) Mechanical Deterioration

Mechanical deterioration occurs when excessive movement or vibration leads to insulation wear or cracking. In water-cooled stators, vibration can also create leaks, which lead to environmental deterioration.

Within the stator slot, loose coils or bars can occur due to insulation shrinkage or poor construction. Magnetic forces at twice the line frequency cause the bars to vibrate, which can cause the insulation to wear and/or separate from the stator core. As with the case of thermal cycling, separation of the ground wall insulation from the core results in a slot discharge.

In the end winding, inadequate bracing can lead to excessive vibration. The bracing may also loosen due to the high transient torque produced by an out-of-phase synchronization event or a close-in fault. The impact of repeated events is cumulative. Excessive vibration leads to wearing or cracking of the insulation.

4) Environmental Deterioration

Contamination is the penetration of water, oil, or dust (coal, brush gear sediment, and so on) into the insulation. Contamination degrades the insulation in two ways. First, it causes a reduction in the electrical or mechanical strength of the insulation. Some types of insulation are more susceptible than others. For example, insulation made from organic compounds suffers more from water ingress than insulation made from inorganic compounds. Secondly, contamination provides a medium for surface tracking, primarily in the end winding. Surface contamination creates a path for small capacitive currents driven by potential differences within a phase or between phases. These currents lead to surface discharge in the air adjacent to the surface and the formation of carbon tracking. The low-impedance paths formed by these tracks can lead to a fault.

Interactions between the different deterioration processes described can accelerate the deterioration of the winding. For example, insulation that has become more brittle due to thermal degradation is more susceptible to mechanical effects.

IV. FUNDAMENTAL NEUTRAL OVERVOLTAGE

A. Principle of Operation

The primary method to detect ground faults in a large portion of the generator windings is to connect an overvoltage relay to monitor the voltage impressed across the neutral grounding resistor, as shown in Fig. 6. As described in the next section, there are significant harmonic components produced by the generator. Therefore, this element should be designed to measure only the fundamental component of the voltage and to attenuate or filter out any harmonic voltages.

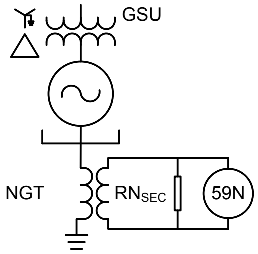

Fig. 6. Generator With Fundamental Neutral Overvoltage (59N) Protection

High-impedance-grounded machines are connected to the power system via a delta-connected GSU. Therefore, under normal operating conditions, no fundamental current flows through the NGT and the fundamental voltage across the grounding resistor and 59N relay is zero. During a ground fault on the stator winding, the ground fault current flowing through the NGT causes a voltage to be impressed across the grounding resistor. The function of the overvoltage relay is to measure the fundamental voltage magnitude and thereby detect a ground fault in the stator winding. A complete treatment of a stator winding ground fault in the sequence domain is given in [1].

Fig. 7 illustrates the relationship between the location of the stator winding ground fault and the voltage across the grounding resistor, with a ground fault on the A-phase stator terminal. We perform our analysis in the phase domain using this diagram. From Appendix A, we know that the effective neutral primary resistance (RN_{PRI}) is in the kilohm range. Therefore, we can neglect the series impedance of the stator because it is much smaller. In addition, when considering only the generator fault contribution, we can neglect the line-to-neutral capacitance of the generator.

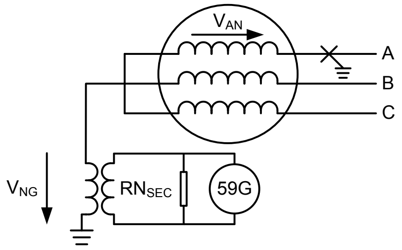

Fig. 7. Simplified Three-Line Diagram Showing a Fault on the A-Phase Stator Terminal and Equivalent Circuit

Applying Kirchhoff's voltage law and considering the loop created by the fault in the A-phase, we can see that the voltage across the NGT (V_{NG}) is equal to the phase-to-neutral voltage generated by the machine (V_{AN}). Stated differently, a bolted phase-to-ground fault on the stator terminals of the generator produces rated generator line-to-neutral voltage across the primary side of the NGT.

To generalize our analysis, we can consider a fault anywhere on the stator of generator. In Fig. 8, consider a fault at *x*, where *x* is the location of the fault measured from the neutral point (N) in per unit. The voltage from the generator neutral point (N) to the fault point (x) is equal to $x \bullet V_{PN}$, and this voltage is impressed across the NGT. Therefore, the voltage impressed across the NGT is directly proportional to the distance that the fault is located from the neutral point.

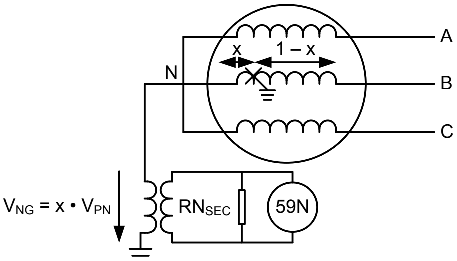

Fig. 8. Simplified Three-Line Diagram Showing Fault on B-Phase Stator at *n* and the Equivalent Circuit

It is evident that this scheme will not operate for faults in the vicinity of the generator neutral (i.e., $x \approx 0$).

B. Settings and Coordination

As mentioned previously, this paper primarily focuses on generators connected to the power system through a GSU. The GSU generator-side windings are connected in delta. Any ground current on the load side of the GSU or auxiliary transformers is circulated in the delta windings of the GSU and auxiliary transformers, respectively, and does not flow through the generator. However, due to the parasitic capacitance between the transformer windings, a small percentage of ground or zero-sequence current flows through the generator during a ground fault on the load side of the GSU or auxiliary transformer.

We can make some assumptions about the network impedances in order to create a useful sequence network for analysis purposes. The interwinding capacitance is typically in the nanofarad (nF) range, resulting in hundreds of kilohms of impedance. In the positive- and negative-sequence networks, the leakage reactance of the GSU effectively short-circuits the interwinding capacitance, but in the zero-sequence network, the GSU delta creates an open circuit, leaving the interwinding capacitance as the only path between the system and the generator. This results in the equivalent zero-sequence network for a solid ground fault on the load side of the GSU shown in Fig. 9.

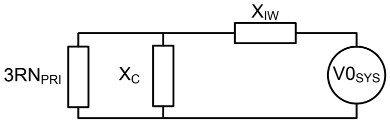

Fig. 9. Zero-Sequence Network for a Ground Fault at the GSU High-Voltage Terminals

We build on the example in Appendix A in Appendix B. These calculations result in a pickup setting of 10 V.

Selecting a pickup setting of 5–15 V secondary for the 59N element is typical because a setting in this range provides a balance between sensitivity and security and avoids tripping for ground faults outside of the generator zone.

Due to the sensitivity of the 59N relay, a ground fault inside the PT or a ground fault on the secondary side of the PT could very likely cause the 59N element to operate. To avoid tripping the unit for these cases, care must be taken to coordinate the 59N element with the operating time of the PT's high-voltage (F1) and low-voltage (F2) fuses, as shown in Fig. 10.

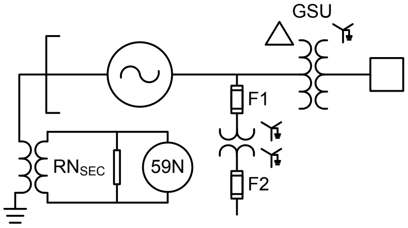

Fig. 10. Simplified One-Line Diagram Showing PT and PT Fuses

C. Sensitivity and Coverage

The percentage of the winding that is covered by the 59N element can be calculated as follows:

$$59N\ \%\ \text{Coverage} = \frac{VG_{RATED} - \text{Pickup}_{59N} \bullet n_{NGT}}{VG_{RATED}} \bullet 100\% \qquad (1)$$

From Appendix A, these calculations yield a coverage of 95.8 percent. Therefore, the 59N will not detect faults in the first 4.2 percent of the winding. For some smaller machines, this level of coverage may be acceptable. It is sometimes the case that the 59N is the sole element applied for stator ground fault protection and is supplemented by performing extensive testing of the windings during outage times to detect faults in the bottom portion of the winding. However, it should be noted again that this practice is predicated on the assumption that a fault occurring in the bottom portion of the winding will not cause appreciable damage to the machine. As described in the previous discussion of failure modes, stator winding insulation deteriorates over time, which can lead to catastrophic damage if not detected and corrected quickly. For this reason, the fundamental neutral overvoltage is typically combined with the methods discussed in the following sections so that full coverage of the stator winding is achieved.

D. Other Considerations

Another area of concern is that during startup and shutdown the unit is energized and so should be monitored for ground faults on the stator. However, with certain types of prime movers, the unit may be operating at a frequency well below its nominal rated frequency. For these conditions, care must be taken to ensure that the 59N relay uses frequency tracking in order to correctly measure fundamental voltage when the unit is operating at lower speeds (i.e., the fundamental frequency is not 50 or 60 Hz). Note that in these generators we can expect that the terminal voltage will be reduced proportionally with speed in order to prevent overexcitation. Since this element is an overvoltage function, security is not impacted, but a loss of coverage is anticipated. For example if the element provides 90 percent coverage at 60 Hz, we expect 45 percent coverage at 30 Hz due to the decrease in terminal voltage. More detailed treatment of the responses of different protective relays, including 59N relaying, to off-nominal frequencies is provided in [8].

V. THIRD-HARMONIC NEUTRAL UNDERVOLTAGE

A. Principle of Operation

As discussed in the previous section, the fundamental neutral overvoltage protection scheme detects ground faults located in 90–95 percent of the stator windings, but leaves the 5–10 percent nearest the neutral point vulnerable. Additional protection is required to cover 100 percent of the stator. Third-harmonic voltage schemes (see Fig. 11) can be used in high-impedance grounded generators to complement the 59N element.

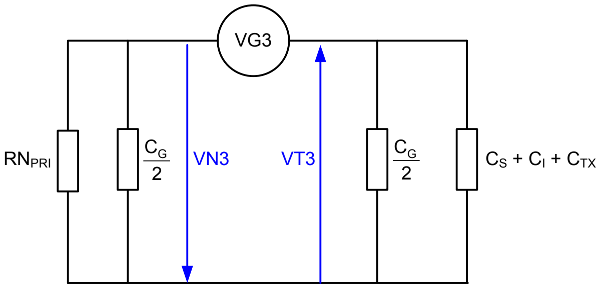

Fig. 11. Third-Harmonic Network

Harmonic voltages are generated during the normal operation of generators. This is chiefly due to physical limitations in the design of the machines. The triplen harmonics (e.g., third, ninth, and fifteenth) are each produced in equal magnitude and phase on all three phases. The result is that the triplen harmonic voltages are zero-sequence voltages, with the third-harmonic voltage being the largest harmonic. The stator capacitance, the system capacitance, and the grounding resistance all act to create a voltage divider circuit in the zero-sequence network. This causes the third-harmonic voltage to split across the stator windings and creates a voltage characteristic similar to the one seen in Fig. 12. Due to the selection criteria for the neutral grounding resistor, the third-harmonic voltage produced by the generator is split almost equally across the stator windings such that at some point in the stator (X1 or X2 in Fig. 12), the third-harmonic voltage magnitude is zero.

The magnitude of third-harmonic voltage found at the generator neutral widely varies from generator to generator, depending on a number of factors including the generator construction, loading conditions, and system configuration.

The third-harmonic voltage drop within the stator is shown in Fig. 12. The *Y* axes on the left and right sides represent the voltage drops at the neutral and the terminal, respectively. The *X* axis represents the position, in percent, measured from the stator neutral. The dotted lines represent typical third-harmonic distributions on a healthy machine at various load conditions. A linear distribution of voltage is assumed.

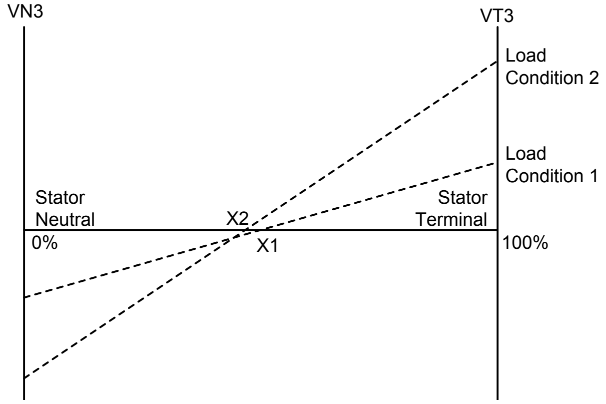

Fig. 12. Typical Third-Harmonic Voltage Distribution at Various Load Conditions

Fig. 13 shows the third-harmonic voltage distribution during faulted conditions when the generator is at a given load. A ground fault at the neutral creates an upward shift in the curve (top line). Similarly, a ground fault at the terminals creates a downward shift in the curve (bottom line).

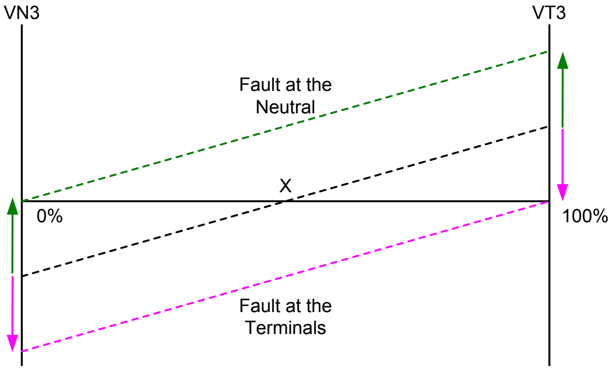

Fig. 13. Shift in Third-Harmonic Voltage Due to Faults at the Neutral and at the Terminals

A drop in the third-harmonic voltage across the grounding resistor (VN3) can therefore be used to detect ground faults near the neutral of the generator, as shown in Fig. 14.

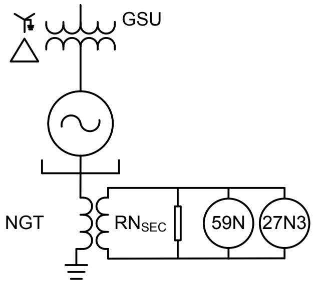

Fig. 14. Generator With Fundamental Neutral Overvoltage (59N) and Third-Harmonic Neutral Undervoltage (27N3) Protection

B. Settings and Coordination

Assume that at a given load condition the unfaulted third-harmonic voltage distribution is as shown in Fig. 15.

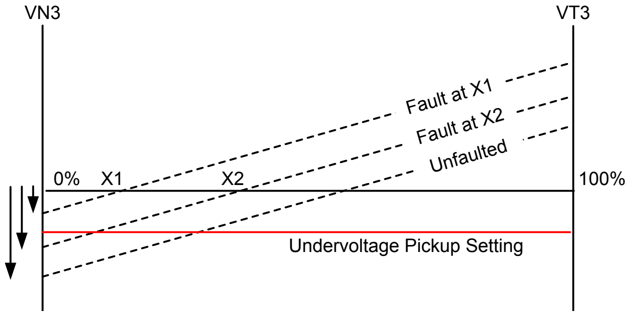

Fig. 15. Shift in Third-Harmonic Voltage Faults at Two Points Close to the Neutral

The pickup setting must be set at a safe margin below the level of VN3 for the unfaulted case. Now assume that a solid fault occurs at X1. VN3 will drop below the pickup setting and the scheme will operate. Now assume that the fault is moved to X2. VN3 is still greater than the pickup setting for this case, so coverage is not provided for this fault. We can conclude that the best sensitivity is achieved when the pickup setting is as high as possible. Note that plotting the harmonic distribution shown in Fig. 15 requires a knowledge of VT3 as well. Normally this measurement is not known (see Section VI of this paper for more details). We can estimate a slope based on a knowledge of the voltage divider network of Fig. 11. However, it is generally not possible to accurately determine the coverage of this function.

From Fig. 15 it is clear that the setting must be set low enough that the scheme remains secure when the third-harmonic voltage levels for an unfaulted generator are at a minimum. However, it must be set high enough that the scheme can detect ground faults in the entire range required to provide 100 percent coverage in conjunction with the fundamental neutral overvoltage element. A conservative approach is to set the 27N3 pickup at 50 percent of the lowest value of VN3 measured during testing. However, because a generator may produce a very small third harmonic at a particular operating point, application of this setting may not result in sufficient overlap with the 59N.

One strategy to improve coverage is to block the element in the region when the unfaulted third harmonic is very small. For example, if the third harmonic is very low when the generator is at no-load, then the element could be torque-controlled using a low forward power element. This would allow a higher undervoltage setting to be applied. The element would provide no protection at no-load. However, this may be acceptable for a generator that is not expected to operate in this region for an extended duration. Other possibilities include supervision using reactive power or power-factor elements.

Before setting a 27N3 element, it is crucial to measure the third-harmonic voltage in as many different operating conditions as possible in order to confirm that the element can be securely set. Tested operating conditions should include no-load and disconnected, no-load and synchronized, and the entire operating range of power levels and power factors. Fig. 16 shows an example taken from an in-service generator.

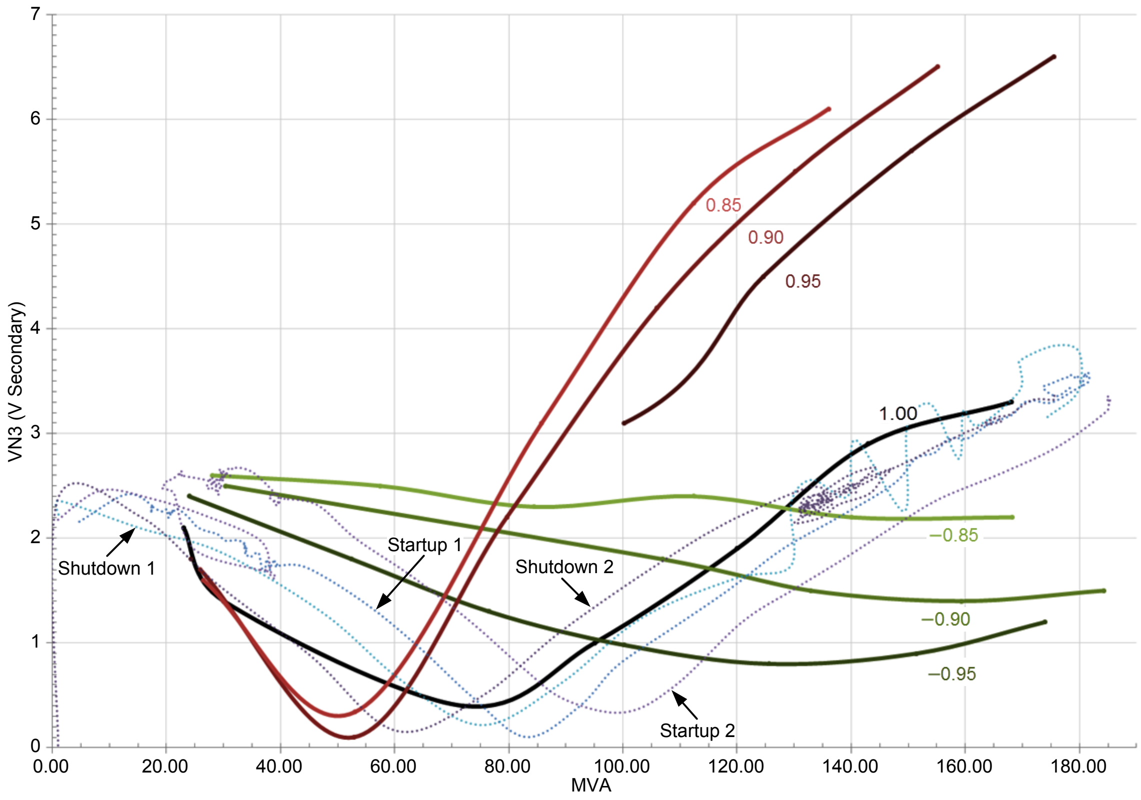

Fig. 16. Third-Harmonic Neutral Voltage Survey for Various Values of Real Power and Power Factor

C. Sensitivity and Coverage

The sensitivity of the 27N3 element is dependent on the voltage characteristics of the machine. A general guideline for setting the pickup of this element is as follows [9]:

$$\text{Pickup}_{27\text{N3}} = \frac{\text{VN3}_{\text{MIN}}}{2} \qquad (2)$$

where:

VN3_{MIN} is the minimum third-harmonic voltage produced by the generator.

$\text{Pickup}_{27\text{N3}}$ is the pickup of the third-harmonic undervoltage element.

In Fig. 12, Fig. 13, and Fig. 15 we saw the distribution of the third harmonic throughout the machine. Note that drawing these plots requires a knowledge of the third harmonic at the terminals. In the large majority of cases where the third-harmonic undervoltage is applied, it is not possible to measure the third harmonic at the terminals. This is addressed in the following section. However, we can estimate this value from our knowledge of the generator capacitances and our selection of the neutral resistor. Based on Fig. 11 and the quantities in Appendix A, we can calculate the third-harmonic impedances at the neutral and terminals and then compute the voltage drops as shown in Appendix C. These calculations show that the third-harmonic voltage drops are approximately equal.

Proceeding with these values, we can make the plot shown in Fig. 17. Applying a setting of one-half of VN3_{MIN}, we can estimate the element coverage as 25 percent measured from the neutral based on the geometry shown in Fig. 17. Because the 59N is covering 90–95 percent of the winding (measured from the terminals), the two elements provide a good overlap.

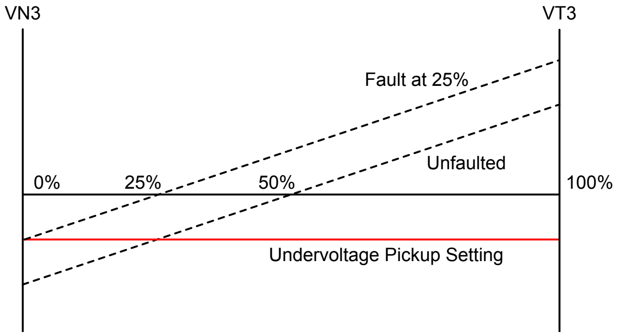

Fig. 17. Coverage of 27N3 for a Pickup Setting of One-Half of VN3_{MIN}

However, it is important to point out that this coverage estimate is for the case that the generator third harmonic is at a minimum. If we carry out a similar exercise for the maximum generator third harmonic, we will find that the coverage is reduced. For machines that exhibit large variations in the third harmonic, it is possible that overlap with the fundamental neutral overvoltage element could be lost. In these cases, the supervision schemes described in the previous subsection should be considered.

D. Other Considerations

Because the third harmonic is generated by the machine, we expect that it will vary with the fundamental terminal voltage. The same assumption was made in Section IV of this paper for the 59N, but because we are dealing with an undervoltage function in this case, security is an issue. As a result, this element is normally supervised by positive-sequence terminal voltage. Accordingly, for machines that operate at reduced frequencies during starting, this element is not expected to provide coverage.

In addition, and especially in the case of a synchronizing breaker on the low-voltage side of the GSU, the neutral third harmonic might change significantly when the generator is offline. Consequently, the level should be checked for this operating mode. The element may be dynamically disabled from a generator-offline indication, or a setting group change may be implemented for the offline mode.

VI. THIRD-HARMONIC VOLTAGE DIFFERENTIAL

A. Principle of Operation

It is clearly evident in the previous section that the third-harmonic undervoltage can be a challenge to set. As we will see in this section, a voltage differential is a better method in terms of ease of setting and dependability.

A simplified circuit showing the generator as a third-harmonic source (VG3) is shown in Fig. 18. The current that flows due to this component is confined by the delta connections of the GSU and auxiliary transformers. It flows through shunt capacitance paths to ground and returns through the neutral. The neutral impedance (ZN3) is formed from one-half of the stator capacitance in parallel with the neutral grounding resistance. The other half of stator capacitance is combined with the additional terminal capacitances (surge, isophase bus, and GSU) to form the terminal impedance (ZT3).

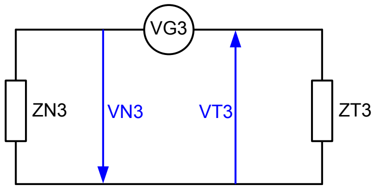

Fig. 18. Third-Harmonic Voltage Distribution

Although the generator third harmonic can vary significantly, the ratio of the voltage drops (VT3 and VN3) is determined by ZN3 and ZT3, and these are not expected to change during normal operation. Taking advantage of the fixed relationship between the third-harmonic voltages, differential schemes have been designed to operate on the ratio of the third-harmonic voltage drops rather than on absolute values, as shown in Fig. 19. Because the third harmonic behaves like a zero-sequence component, differential schemes require a grounded-wye PT at the terminals to measure VT3. Electromagnetic relays require an open-corner delta PT connection. Static and digital relays usually summate the line-to-neutral voltages internally.

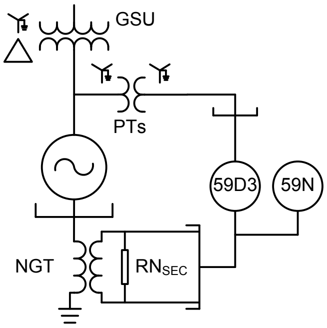

Fig. 19. Generator With Fundamental Neutral Overvoltage (59N) and Third-Harmonic Voltage Differential (59D3) Protection

One common implementation uses the following operating equation:

$$OP = \left\| VN3 \right| - RAT \left| VT3 \right\| > PKP \tag{3}$$

where:

RAT is a setting chosen to zero the left side of the equation under normal operation.

PKP is a pickup setting.

Referring back to Fig. 13, a fault at the neutral causes VN3 to decrease and VT3 to increase. A fault at the terminals causes VN3 to increase and VT3 to decrease. In either case, the left-hand side of the inequality in the previous equation is no longer zero and the element operates. In the unfaulted state, ||VN3| – RAT|VT3|| is less than PKP due to the voltage divider effect.

B. Settings and Coordination

Due to the variations in the third harmonic, it is recommended to carry out a survey of VN3 and VT3 while the generator MW and MVAR output varies. At a minimum, these measurements must be taken at no-load and full-load conditions. It is recommended that measurements be taken at a number of intermediate loads as well to ensure that the data include the full range of variation of third-harmonic quantities.

The optimal setting for RAT is the ratio of the average values of VN3 and VT3, calculated as follows:

$$RAT = \frac{\sum_{n=1}^{N} \frac{VN3\_SEC_n}{N}}{\sum_{n=1}^{N} \frac{VT3\_SEC_n}{N}} = \frac{\sum_{n=1}^{N} VN3\_SEC_n}{\sum_{n=1}^{N} VT3\_SEC_n} \tag{4}$$

where:

$VN3\_SEC_n$ and $VT3\_SEC_n$ are sets of secondary measurements taken at particular loads.

N is the number of measurement sets.

Once RAT is determined, the pickup can be calculated. This value should be greater, with margin, than the largest value of ||VN3_SEC| – RAT|VT3_SEC|| to ensure that the element does not pick up during normal operation. This criterion results in the $Pickup_{59D3}$ equation (5). In this equation, the constants 1.1 and 0.1 have been chosen to ensure an adequate margin for the pickup setting.

C. Sensitivity and Coverage

The coverage of 59D3 is given by the 59D3 % Coverage equation (6), where PTR is the terminal PT ratio. PTRN includes the turns ratio of the NGT and any auxiliary PTs that may be used to derive the neutral secondary voltage.

The setting process and sensitivity calculation are illustrated in Appendix D. Assume that the online measurements are taken for the example system.

D. Other Considerations

Ideally, the ratio of the third harmonics will be constant over the operating range of the machine. However, this distribution can be impacted by an external third-harmonic source (VX3), as illustrated in Fig. 20. For example, the GSU itself can be an external source of third harmonics [10]. GSU harmonics will appear as phase-neutral quantities at the generator terminals and neutral by coupling across the GSU interwinding parasitic capacitance (C_{IW}).

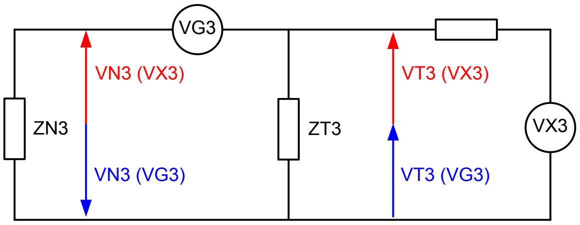

Fig. 20. Impact of an External Source on the Third-Harmonic Distribution

$$Pickup_{59D3} = 1.1\left(0.1 + MAX_n\left\{\left\| VN3\_SEC_n \right| - RAT\left| VT3\_SEC_n \right\|\right\}\right) \tag{5}$$

$$59D3\ \%\ Coverage = \left(\frac{RAT}{RAT + \frac{PTR}{PTRN}} - \frac{PKP}{\left(RAT + \frac{PTR}{PTRN}\right) \bullet \left(VN3\_SEC \bullet \frac{PTRN}{PTR} + VT3\_SEC\right)} \right) \bullet 100\% \tag{6}$$

Because the voltage drops created by an external source are limited by the interwinding capacitance, its influence is usually small. However, examination of Fig. 20 shows that its influence increases if the generator third harmonic (VG3) drops to a low magnitude.

Generators with synchronizing breakers on the low-voltage side of the GSU can have a significantly different third-harmonic distribution prior to synchronizing. The reason for this can be seen in Fig. 21.

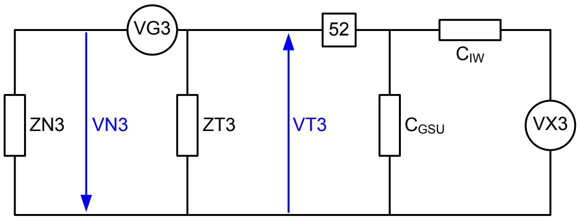

Fig. 21. Impact of a Low-Voltage Breaker on the Third-Harmonic Distribution

When the breaker (52) is open, the GSU capacitance is no longer in parallel with other terminal impedances. In addition, the scheme does not respond to the external third-harmonic source (if present) when the breaker is open. In such cases, calculating separate settings for the offline and online modes of operation can be an optimal solution. These settings can be entered into separate setting groups in the relay and the setting group change can be driven by the breaker status.

VII. SUBHARMONIC INJECTION

A. Principle of Operation

The subharmonic injection scheme detects ground faults by injecting a known signal into the stator of the generator and measuring the resulting current. The injected signal is ac, so it can be coupled through a transformer to the primary circuit. The signal must be zero sequence, such that it is confined by the delta windings of the GSU. Unlike other stator ground protection schemes, the subharmonic injection scheme can provide 100 percent stator winding protection even when the generator is at standstill or on turning gear. The injection scheme can only be applied to high-impedance grounded systems such as the one shown in Fig. 22. The generator neutral is grounded through a distribution transformer with a low-voltage neutral grounding resistor (RN) in the secondary. Consequently, the subharmonic injection scheme does not require a grounded-wye PT at the terminals as the 59D3 does. The method is also applicable to machines that are high-impedance grounded using a grounding transformer at the terminals.

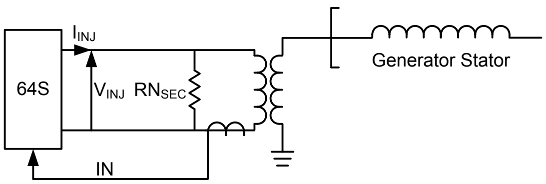

Fig. 22. Subharmonic Injection Applied to a High-Impedance Grounded System

The basic operating principle of the protection scheme is to detect a change in measured stator circuit leakage (insulation) resistance by injecting a subharmonic frequency voltage across the neutral grounding resistor [11]. Fig. 23 shows various load components seen by the injection source for the high-impedance grounded system shown in Fig. 22.

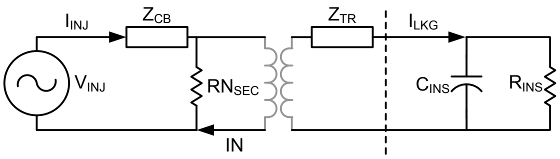

Fig. 23. Third-Harmonic Voltage Distribution

Z_{CB} is cable impedance from the injection source to the neutral grounding resistor. Z_{TR} is the distribution transformer impedance. C_{INS} is the equivalent insulation capacitance in the stator circuit that includes the line-to-neutral capacitance of the generator windings, surge arrestor, delta winding of the GSU, auxiliary transformer, and any other connected equipment. R_{INS} is the equivalent insulation resistance in the stator circuit. The injection scheme measures the injected voltage (V_{INJ}) and current (I_{ING}) and calculates R_{INS} and C_{INS}.

In order to improve the accuracy of the calculated R_{INS}, the capacitive leakage current needs to be decreased and neutral current in the transformer secondary needs to be directly measured. The capacitive leakage current can be decreased by injecting a subharmonic signal.

One implementation of the 64S element uses a multi-sine signal as the injected signal in order to make the calculated R_{INS} immune to interference. The multi-sine signal consists of four subharmonic frequency sinusoids combined such that the individual frequency sinusoids can be easily extracted using a simple Fourier transformation, resulting in four R_{INS} and C_{INS} calculated values. Having four independently calculated R_{INS} values greatly increases the reliability of the protection scheme.

B. Settings and Coordination

The normal insulation resistance for newer generators is generally above 100 kΩ. The insulation resistance degrades as the generator becomes older. Many factors contribute to the degradation, such as thermal loading, overvoltage transients, moisture ingress, and so on. The 64S element can be set to any value below the measured insulation resistance value, so following normal utility practices is recommended. This usually entails taking a survey of resistance measurements under normal generator operation and using these values to determine an optimal setting. Monitoring R_{INS} helps detect possible insulation degradation. Monitoring C_{INS} helps detect the grounding problems in the stator circuit.

C. Sensitivity and Coverage

Unlike third-harmonic schemes, the subharmonic injection scheme is insensitive to changing system conditions such as voltage, current, and speed. It operates with the same sensitivity for stator ground faults over 100 percent of the winding.

Certain types of generators are started with their fields energized. These include gas turbines and cross-compound generators. Usually, the 64S is blocked during starting because at some point the frequency generated by the machine is in the same range as the injected frequency. For schemes that employ the multisine signal, only one of the constituent frequency components is impacted as the generator frequency ramps-up. As a result, this scheme can provide protection throughout the starting period.

D. Other Considerations

The subharmonic injection scheme can be applied to several high-impedance grounded systems where a conventional third-harmonic scheme is ineffective.

Fig. 24 shows a cross-compound machine that has two stator windings. One stator winding is high-impedance grounded and the other is ungrounded. At the neutral of G1, 59N and 27N3 elements can be applied. The 59N sees faults over 90–95 percent of G1 and G2. The 27N3 sees faults near the neutral of G1. The neutral region of G2 is unprotected [12]. Setting of the 27N3 faces the same challenges as those described in Section V of this paper. Application of a 59N3 is not recommended because G2 upsets the voltage distribution. However, the subharmonic injection scheme applied as shown provides 100 percent stator ground protection for both of the stator windings.

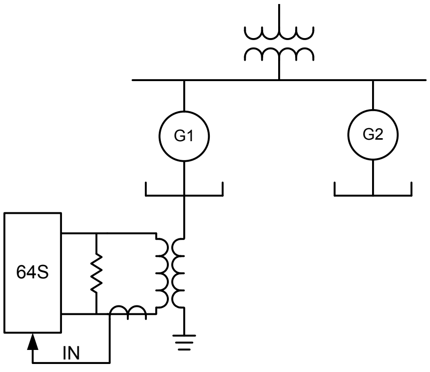

Fig. 24. Subharmonic Injection Applied to a Cross-Compound High-Impedance Grounded System

Fig. 25 shows a common configuration consisting of two parallel generators sharing the same GSU. This configuration is sometimes found in hydroelectric installations. As was the case with the previous example, it is challenging to set the third-harmonic protection scheme for this system.

The subharmonic injection scheme can be applied with the combined neutral current measurement, as shown in Fig. 25. The 64S1 element measures the current it injects into the neutral of G1 and the injected current flowing out of the neutral at G2. Without the G2 measurement, the accuracy of the impedance measurement would be degraded. By measuring the G2 current, the 64S1 can provide effective coverage for both machines. However, because each generator has its own breaker, G2 is not covered unless both breakers are closed.

Each generator can also be equipped with its own 64S. In this application, each subharmonic injection scheme injects two unique frequency sinusoids. In this scheme as well, each 64S measures its own injected current and the current in the neutral of the opposite machine. Each 64S sees faults over 100 percent of both G1 and G2, providing redundant protection for both machines when both breakers are closed.

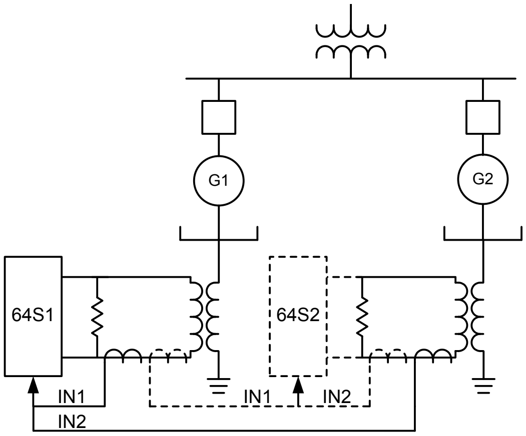

Fig. 25. Subharmonic Injection Scheme Applied to Two Parallel High-Impedance Grounded Systems Sharing a GSU and Using Either One or Two Injection Units

VIII. CONCLUSION

This paper reviewed stator ground faults and the schemes for their detection. Guidelines for settings and general application considerations were also presented.

The 59N has the simplest operating principle and can detect faults over most of the stator winding. It is relatively straightforward to set.

Third-harmonic schemes can protect the portion of the winding left uncovered by the 59N. These may be viewed as injection schemes in which the injection source is provided by the generator itself. The 27N3 is sensitive to variations in the available third harmonic. However, it does not require grounded-wye PTs at the generator terminals. The 59D3 is insensitive to variations in the available third harmonic, responding instead to changes in the distribution of this voltage. It is more secure and simpler to set than the 27N3, and the coverage of this function can be easily determined. As a result, this is the preferred third-harmonic scheme if a grounded-wye PT is available.

The subharmonic injection scheme detects ground faults by directly measuring the shunt impedance of the stator. The only disadvantage of this scheme is the need for an additional piece of hardware. On the plus side, this scheme is very straightforward to set. Unlike other functions, its coverage is not dependent on the location of the fault within the winding. It is also unaffected by variations in the generator voltage, frequency, or loading. It works equally well when the machine is online, offline, starting, or at a standstill.

IX. APPENDIX A – NEUTRAL RESISTOR SIZING

TABLE I
SYSTEM PARAMETERS

Generator rated voltage	22 kV_{LL}, 12.7 kV_{LN}
NGT rated secondary voltage	240 V
Nominal frequency	60 Hz
Capacitances (per phase)	Generator stator (C_G): 0.297 µF Isophase bus (C_I): 0.003 µF Surge capacitor (C_S): 0.056 µF GSU (C_{TX}): 0.002 µF **Total: 0.358 µF**

Referring to Fig. 1 and Table I, the per-phase capacitive reactance is as follows:

$$X_C = \frac{1}{2\pi \bullet 60 \bullet 0.358\,\mu F} = 7.407\,k\Omega \tag{7}$$

The generator neutral primary resistance is as follows:

$$RN_{PRI} = \frac{X_C}{3} = 2.469\,k\Omega \tag{8}$$

The NGT ratio is as follows:

$$n_{NGT} = \frac{12.7\,kV}{240\,V} = 53 \tag{9}$$

The maximum generator primary fault current is as follows:

$$IFG_{PRI} = \frac{12.7\,kV}{2.469\,k\Omega} = 5.1\,A \tag{10}$$

The generator neutral secondary resistance is as follows:

$$RN_{SEC} = \frac{2.469\,k\Omega}{53^2} = 0.88\,\Omega \tag{11}$$

The maximum generator secondary ground fault current is as follows:

$$IFG_{SEC} = \frac{240\,V}{0.88\,k\Omega} = 272\,A \tag{12}$$

The power dissipation during a fault is as follows:

$$P_{FAULT} = 240\,V \bullet 272\,A = 65\,kW \tag{13}$$

X. APPENDIX B – SYSTEM FAULT COORDINATION AND 59N COVERAGE

TABLE II
SYSTEM PARAMETERS

Primary system voltage (V_{SYS})	230 kV_{LL}, 132 kV_{LN}
Interwinding capacitance (C_{IW})	5 nF

Referring to Fig. 9 and Table II, the GSU interwinding capacitive reactance is as follows:

$$X_{IW} = \frac{1}{2 \bullet \pi \bullet 60 \bullet 5\,nF} = 531\,k\Omega \tag{14}$$

The generator equivalent impedance is as follows:

$$Z_N = \frac{-jX_C \bullet 3 \bullet RN_{PRI}}{3 \bullet RN_{PRI} - jX_C} = 5.239\,k\Omega\angle{-45^\circ} \tag{15}$$

We assume a worst-case, zero-sequence voltage equal to one-third of the nominal phase-neutral system voltage. The secondary neutral voltage for a high-voltage ground fault is as follows:

$$VN_{SEC} = \frac{V_{SYS}}{3} \bullet \left|\frac{Z_N}{Z_N - j \bullet X_{IW}}\right| \bullet \frac{1}{n_{NGT}} = 8.2\,V \tag{16}$$

Choosing a setting of 10 V, the element coverage is as follows:

$$59N\ \%\ Coverage = \frac{12.7\,kV - 10\,V \bullet 53}{12.7\,kV} \bullet 100\% = 95.8\% \tag{17}$$

XI. APPENDIX C – THIRD-HARMONIC VOLTAGE DISTRIBUTION

Referring to Fig. 11, the terminal third-harmonic capacitive reactance is as follows:

$$\begin{aligned} X_{3T} &= \frac{1}{2 \bullet \pi \bullet 180 \bullet \left(\frac{0.297}{2} + 0.003 + 0.056 + 0.002\right)\mu F} \\ &= 5.954\,k\Omega \end{aligned} \tag{18}$$

The neutral third-harmonic capacitive reactance is as follows:

$$X_{3N} = \frac{1}{2 \bullet \pi \bullet 180 \bullet \left(\frac{0.297}{2}\right)\mu F} = 4.22\,k\Omega \tag{19}$$

The neutral third-harmonic impedance is as follows:

$$Z_{3N} = \frac{-jX_{3N} \bullet 3RN_{PRI}}{3RN_{PRI} - j \bullet X_{3N}} = 4.641\,k\Omega\angle{-51.2^\circ} \tag{20}$$

The per-unit voltage drop at the neutral is as follows:

$$VN3_{PU} = \left|\frac{Z_{3N}}{Z_{3N} - j \bullet X_{3T}}\right| = 0.555 \tag{21}$$

The per-unit voltage drop at the terminals is as follows:

$$VT3_{PU} = \left|\frac{-j \bullet X_{3T}}{Z_{3N} - j \bullet X_{3T}}\right| = 0.505 \tag{22}$$

Because we are dealing with complex values, the per-unit magnitudes do not add up to 1. The magnitudes of the voltage drops are approximately equal.

XII. APPENDIX D – 59D3 SETTINGS AND COVERAGE

TABLE III
SYSTEM PARAMETERS

PTRN	183.3
PTR	239

The values in Table IV are used to calculate the ratio setting.

TABLE IV
THIRD-HARMONIC SURVEY

Load (per unit)	VN3_PRI (V)	VT3_PRI (V)	VN3_SEC (V)	VT3_SEC (V)
0.0	193.0	428.9	1.678	2.859
0.1	180.5	515.7	1.570	3.438
0.3	150.8	348.3	1.311	2.322
0.5	136.7	487.4	1.189	3.249
0.6	163.5	582.0	1.422	3.880
0.7	171.1	609.6	1.488	4.064
0.8	189.6	674.3	1.649	4.495
0.9	201.2	717.3	1.749	4.782
1.0	200.6	715.9	1.744	4.773

The ratio setting is as follows:

$$\text{RAT} = \left(\frac{1.678 + 1.570 + 1.311 + 1.189 + 1.422 + 1.488 + 1.649 + 1.749 + 1.744}{2.859 + 3.438 + 2.322 + 3.249 + 3.880 + 4.064 + 4.495 + 4.782 + 4.773} \right) \approx 0.4 \quad (23)$$

The pickup setting is as follows:

$$\text{Pickup}_{59\text{D}3} = 1.1\left(0.1 + 0.147\right) = 0.17 \quad (24)$$

TABLE V
CALCULATION OF PICKUP

Load (per unit)	VN3_SEC (V)	VT3_SEC (V)	||VN3_SEC| – RAT|VT3_SEC||
0.0	1.678	2.859	0.143
0.1	1.570	3.438	0.137
0.3	1.311	2.322	0.118
0.5	1.189	3.249	0.106
0.6	1.422	3.880	0.127
0.7	1.488	4.064	0.132
0.8	1.649	4.495	0.142
0.9	1.749	4.782	0.147
1.0	1.744	4.773	0.147

Using the values from Table III, the coverage at no load (Row 1 of Table V) is as follows:

$$\text{59D3 \% Coverage} = \left(\frac{0.4}{0.4 + \dfrac{239}{183.3}} - \frac{0.17}{\left(0.4 + \dfrac{239}{183.3}\right) \bullet \left(1.678 \bullet \dfrac{183.3}{239} + 2.859\right)} \right) \bullet 100\% = 21.1\% \quad (25)$$

The coverage at no-load value produces a good overlap with the 59N. Calculations at other load levels yield similar results.

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XIV. BIOGRAPHIES

Nathan Klingerman received a BS in Electrical Engineering in 2012 from North Carolina State University. He has worked for Duke Energy since 2009 and has been a member of the Fossil/Hydro Generation System Protection Engineering group since 2010. Nathan's responsibilities include generator, transformer, and motor protection design, engineering, and field support. Nathan is a member of multiple IEEE PSRC working groups.

Dale Finney received his bachelor of engineering degree from Lakehead University and his master of engineering degree from the University of Toronto. He began his career with Ontario Hydro, where he worked as a protection and control engineer. Currently, Dale is employed as a senior power engineer with Schweitzer Engineering Laboratories, Inc. His areas of interest include generator protection, line protection, and substation automation. Dale holds several patents and has authored more than 20 papers in the area of power system protection. He is a member of the main committee and the rotating machinery subcommittee of the IEEE PSRC. He is a senior member of the IEEE and a registered professional engineer in the province of Nova Scotia.

Satish Samineni received his bachelor of engineering degree in electrical and electronics engineering from Andhra University, Visakhapatnam, India, in 2000. He received his master's degree in electrical engineering from the University of Idaho in 2003. Since 2003, he has been with Schweitzer Engineering Laboratories, Inc. in Pullman, Washington, where he is a senior power engineer in the research and development division. He has authored or coauthored several technical papers and holds a United States patent. His research interests include power electronics and drives, power system protection, synchrophasor-based control applications, and power system stability. He is a registered professional engineer in the state of Washington and a senior member of IEEE.

Normann Fischer received a Higher Diploma in Technology, with honors, from Technikon Witwatersrand, Johannesburg, South Africa, in 1988; a B.S.E.E., with honors, from the University of Cape Town in 1993; an M.S.E.E. from the University of Idaho in 2005; and a Ph.D. from the University of Idaho in 2014. He joined Eskom as a protection technician in 1984 and was a senior design engineer in the Eskom protection design department for three years. He then joined IST Energy as a senior design engineer in 1996. In 1999, Normann joined Schweitzer Engineering Laboratories, Inc., where he is currently a fellow engineer in the research and development division. He was a registered professional engineer in South Africa and a member of the South African Institute of Electrical Engineers. He is currently a senior member of IEEE and a member of ASEE.

Derrick Haas graduated from Texas A&M University in 2002 with a B.S.E.E.. He worked as a distribution engineer for CenterPoint Energy in Houston, Texas, from 2002 to 2006. In April 2006, Derrick joined Schweitzer Engineering Laboratories, Inc., where he works as a field application engineer. He is a member of IEEE

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