15 YEARS OF EXPERIENCE WITH 100% GENERATOR STATOR GROUND FAULT PROTECTION – WHAT WORKS, WHAT DOESN'T AND WHY

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I. INTRODUCTION

This paper discusses the application of three different 100% stator ground fault protection schemes. Two third-harmonic methods and a low frequency-injection method are discussed. Third-harmonic schemes have been widely applied on generators within the U.S. to provide stator ground fault protection over the entire stator winding. In a number of cases, however, these schemes have been found not to be applicable. In many cases, these shortcomings were discovered during commissioning or when they operated improperly resulting in a false tripping of the generator. This paper discusses situations in which third-harmonic schemes will work and outlines the limitations of such schemes. It also discusses the use of low frequency injection subharmonic schemes which are gaining acceptance in the U.S.

II. BACKGROUND

A. Conventional Stator Ground Fault Protection

Until the late 1970s, almost all stator ground fault protection for unit-connected generators involved the use of only an overvoltage relay (59G) in the generator neutral that was tuned to the fundamental frequency. This detected faults over 90- 95% of the stator winding.

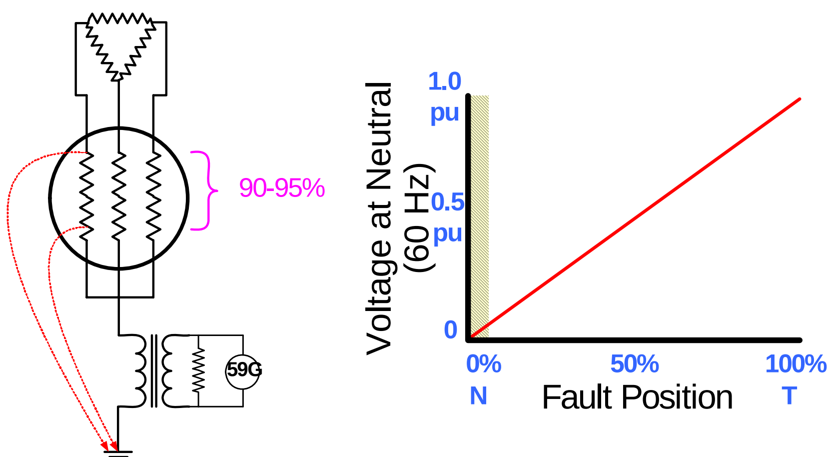


Fig. 1 Conventional Stator Ground Fault Protection

Fig. 1 illustrates this protection. There is a linear relationship between the voltage measured by the 59G relay and the fault location within the generator winding. For faults near the neutral (N), the voltage sensed by the 59G relay is diminished as illustrated in the graph in Fig. 1. The maximum voltage occurs for a fault at the generator terminals (T), where full line-to-neutral voltage occurs across the neutral grounding transformer. Typically, the last 5-10% of the winding is not protected by the 59G. Users accepted this lack of protection of the entire stator winding.

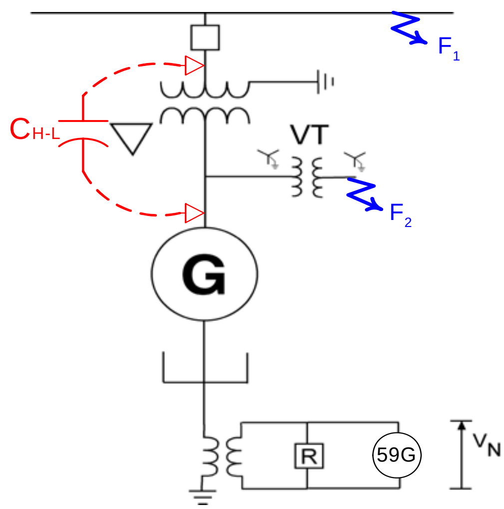


Fig. 2 Coordination Issues with the 59G Relay

In addition, the 59G relay must be coordinated so that it does not falsely operate for a system fault or secondary VT short circuits. Fig. 2 illustrates these two coordination issues. For transmission system ground faults (F1), the transformer capacitance (C_{H-L}) is large enough on many transformers to pick up the 59G relay. The 59G relay's setting is kept low (typically 5-6 V), so it is sensitive to faults as close as possible to the generator neutral. This low pickup setting can also result in 59G operations for short circuits (F_2) on the secondary of the generator VTs that are connected wye grounded – wye grounded.

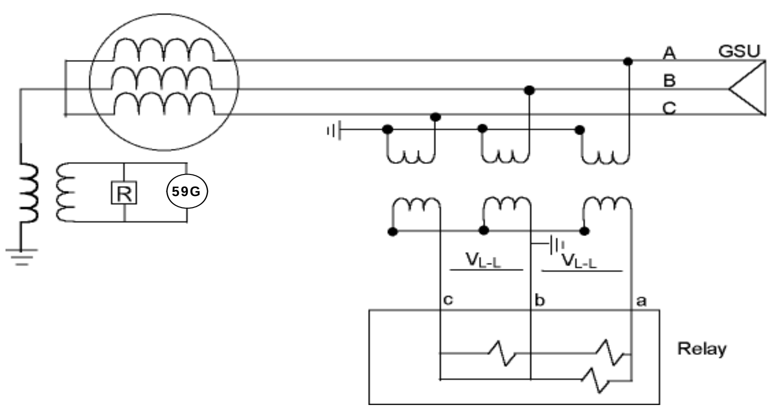
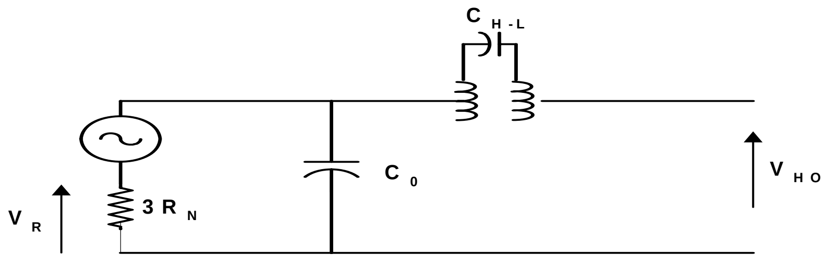


Fig. 3 VT Connection to Avoid 59G Coordination

Most all large generators with iso-phase bus work use wye grounded VT primary windings. Many users use a wye grounded - wye ungrounded VT connection with all relay voltage coils connected phase-to-phase. This provides an open circuit, zero sequence paths so the 59G will not respond to VT secondary ground faults. Fig. 3 illustrates such a connection. In both cases cited above coordination is provided by delaying the 59G tripping.

Modern digital relays have multiple 59G elements. One element is generally set with a low pickup and delayed for coordination. The second element is set with a pickup voltage higher than will occur for faults described above and set with a faster time to speed up fault detection.



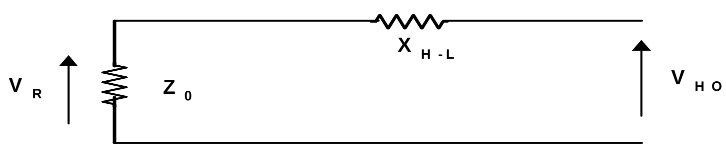
Where: V_R = Voltage across the neutral grounding transformer

V_{HO} = High side zero sequence voltage for a transmission system ground fault.

C_{H-L} = Generator step-up transformer high-to-low winding capacitance

C_0 = Generator system zero sequence capacitance per phase

$3R_N$ = Equivalent primary resistance in generator neutral



Circuit Reduction

Where:

X_{H-L} = Generator step-up transformer high-to-low winding capacitive reactance

Z_0 = parallel combination of $3R_N$ and X_{CO}

$$V_R = \frac{V_{HO} Z_O}{Z_0 - J X_{H-L}}$$

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Fig.4 Calculation of Generator Neutral Voltage for a Transmission System Ground Fault

The level of zero sequence voltage across the generator grounding transformer for transmission system ground faults can be calculated [1] using the equivalent circuits shown in Fig. 4. The second 59G element in a digital relay is then set higher than the calculated value with a faster time delay

B. Overview of 100% Stator Ground Fault Protection

<u>*Third Harmonic Neutral Undervoltage Scheme*</u>. In the late 1970's, a major European manufacturer [2] introduced a third-harmonic neutral undervoltage relay (27TN) that—in conjunction with the traditional 60Hz overvoltage protection (59G) —could provide stator ground fault protection over the entire stator winding. The third harmonic was measured across the generator neutral grounding resistor. Since that time, users have been upgrading generator

protection to provide 100% stator ground fault protection. The scheme's basic concept is that when a generator stator ground fault occurs near the generator neutral, the third-harmonic voltage goes to zero. If the generator has enough third harmonic neutral voltage present during normal operation to prevent the undervoltage relay from false operating, then such generators are candidates for 100% schemes using third-harmonic neutral detection.

Third-Harmonic Ratio Scheme. In the early 1980's, a second third-harmonic scheme was developed by an American manufacturer [3]. This scheme compared the third harmonic at the neutral and terminals of the generator. The major advantage of the scheme was that it was more secure than simply using third harmonic undervoltage measured at the generator neutral. It required a broken-delta potential connection on the generator terminals to measure the terminal value of third-harmonic voltage. This required the installation of a VT-—the primary winding of which needed to be wye-grounded. Many generators, especially smaller units, required the addition of this VT since these generators used open delta-phase VT connections. This additional cost and wiring complexity reduced the number of people that used the scheme.

The level of third harmonic voltage that is present on a given generator depends on a number of factors. These factors include:

- The construction of the generator itself The "pitch" of the stator windings (how the windings are laid into the stator core) is a key factor in determining the amount of third harmonic. There are generators that have very little third harmonic present and thus the third harmonic stator ground fault detection cannot be used.

- The MW and MVAR output of the generator The third-harmonic voltage generally increases with increasing MW load of the generator. At no-load or low loading of the generator, the third-harmonic voltage is generally at its lowest and, in many cases, the level will not allow a reliable setting. The MVAR or reactive generator output also affects the third harmonic and is more unpredictable. In some cases, it increases with MVAR loading, and in others (especially gas turbines), there are sudden drop-offs at specific MVAR outputs that make application of third harmonic schemes unreliable.

- Generator terminal capacitance also effects third-harmonic level The generator line-to-neutral winding capacitance as well as the capacitance of the bus and GSU low-voltage winding generally play a lesser role in the level of third harmonic present than the two items listed above. A greater addition of capacitance on the generator terminals has a positive influence on third harmonic.

Fig. 5 shows how the third-harmonic voltage measured at the generator neutral and terminals under normal no-fault conditions (a), for a stator ground fault at the generator neutral (b) and for a fault at the generator terminals (c). Note that the third-harmonic voltage goes to zero at the location of the fault.

There have been a number of papers written which discuss calculating third-harmonic voltages at both the generator neutral and the generator terminals. These calculations typically result in significant errors making relay setting that use such data unreliable. Today, field measurements have been recommend by most relay manufacturers as the method to obtain the necessary data to set third-harmonic relays. It is not uncommon that the data obtained for these field measurements will determine that third harmonic schemes for 100% stator ground fault protection simply will not work or have severe limitations—rendering them ineffective. Section III of this paper discusses these limitations in detail.

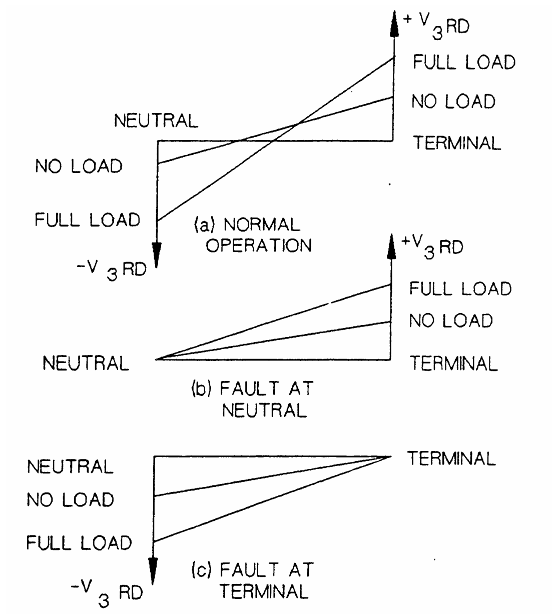


Fig. 5 Graphical Representation of Typical Third Harmonic

Sub-harmonic Voltage Injection Scheme An alternative to third harmonic 100% schemes was developed by a European manufacturer [4] and is widely used in Europe and other countries outside the U.S. This scheme injects a low frequency subharmonic into the generator stator windings. The injected frequency is 15-20 Hz. The signal is injected across the neutral grounding transformer neutral. The load that is presented to the injector in this scheme is the line-to-neutral capacitance of the generator windings, associated bus/cable that connects the generator to the GSU and the delta winding of the GSU and auxiliary transformer. The use of a low frequency subharmonic makes this capacitive reactance a high impedance. Thus, the KVA size of the injection transformer is reduced over what it would be if fundamental frequency were used. Under normal conditions, a small level of changing current will flow at the subharmonic frequency. When a ground fault occurs anywhere in the winding of the generator or its associated bus work, the capacitance is shorted in that phase and a higher current flows which is detected by an overcurrent relay. The scheme has the added advantage in that it can detect a stator ground fault in an off-line generator prior to it being put in-service.

The major problem with this scheme when it was developed in the 1960s and 1970s was that it was implemented with electronics that were very expensive. The injector and the filters were the main costs. As a result, not many U.S. users thought that it was not worth the high cost to protect the last 5-10% of the generator stator winding. The advent of digital technology has helped to reduce the scheme's costs and many U.S. users are giving this scheme a second look.

III. THIRD HARMONIC NEUTRAL UNDERVOLTAGE SCHEME

The most popular of all the 100% schemes used in the U.S. is the third-harmonic neutral undervoltage scheme. It is very inexpensive and is provided in almost every digital generator protection package. Fig. 6 illustrates this scheme and the trip logic that is typically used. A third-harmonic undervoltage relay (27TN) is installed across the grounding resistor in the secondary of the generator grounding transformer. The relay operates on the decrease in third harmonic voltage, which occurs during a stator ground fault near the generator neutral.

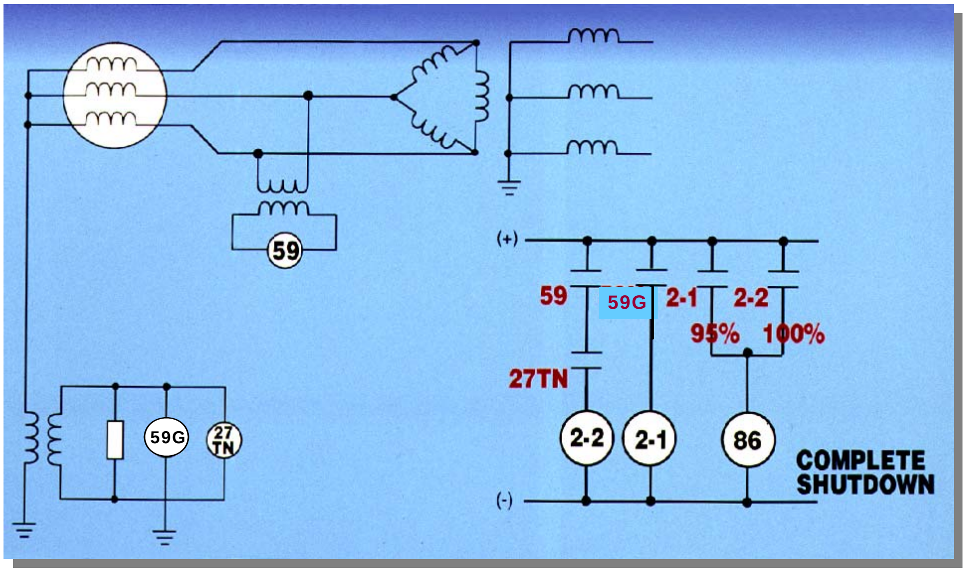


Fig. 6 Third-Harmonic Neutral Undervoltage Scheme

The 27TN relay is supervised by a phase overvoltage relay (59) that prevents false operation when the field is removed from the generator. This prevents false tripping when the generator is out of service. The 59 supervising relay will enable the scheme as soon as the field is applied prior to generator synchronizing to provide 100% ground fault protection.

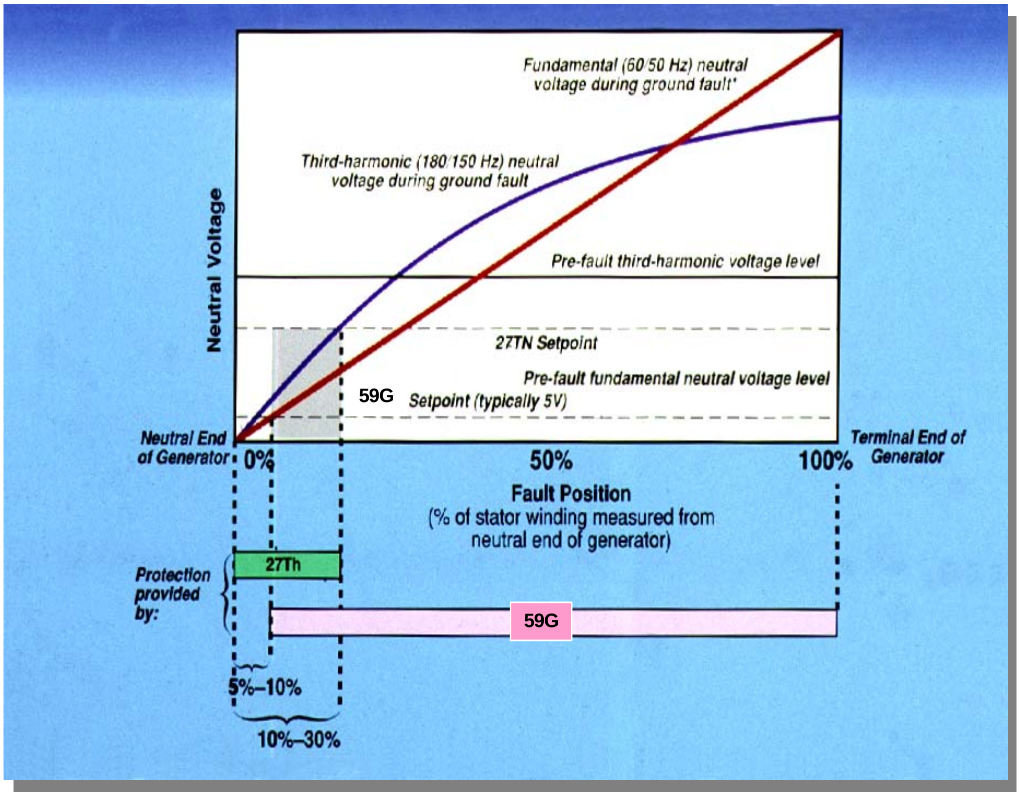


Fig. 7 Overlapping of 59G and Third Harmonic Undervolage (27TN) to Provide 100% Stator Ground Fault Coverage

Modern multifunction digital relays integrate the relay function described above into a single hardware platform. The 27TN, along with the conventional 59G, provide ground fault protection over the entire stator winding. They are typically overlapped to provide this protection. Fig. 7 illustrates this principle of overlapping the coverage with the convention 59G relay to provide 100% protection.

The lower the level of third harmonic on the generator, the less overlap. In some cases, the overlap cannot be maintained creating a "hole" in the coverage. To determine the level of third harmonic, field measurements are required. These measurements determine whether there is enough third harmonic to make the scheme work.

UNIT LOAD		180 HZ RMS VOLTAGE		VOLTAGE RATIO
MW	MVAR	NEUTRAL	TERMINAL	TERMINAL/NEUTRAL
0	0	2.8	2.7	1.08
7	0	2.5	3.7	1.48
35	5	2.7	3.8	1.41
105	5	4.2	5.0	1.19
175	25	5.5	6.2	1.13
340	25	8.0	8.0	1.00

Fig. 8 Field Measurements of the Magnitude of Third-Harmonic Voltage for a Generator

Fig. 8 illustrates typical third harmonic field measurements that are required to determine if there is sufficient third harmonic to make the scheme work. The generator in Fig. 8 is "well behaved" in terms of third harmonic neutral voltage. Note that it is necessary to vary the MVAR output as well as the MW output. Checking the level of third harmonic over the expected MVAR range of operation of the generator is generally not possible because of the voltage disruption it can cause on the power system. Therefore, the 27TN relay is set with a wide margin (generally at half the lowest third harmonic neutral voltage measured). Section V of this paper discusses the fact that there are many generators that do not have very well behaved third harmonic signatures with respect to both MW and MVAR output.

In an attempt to address some these generators, relay manufacturers have provided users with the ability to block 27TN tripping for various system operating conditions where the level is too low to prevent false tripping. Fig. 9 illustrates some of the choices of blocking that are available. Field testing has determined that on some generators the 27TN element would be blocked most of the time, thereby making the third harmonic undervoltage scheme a poor choice.

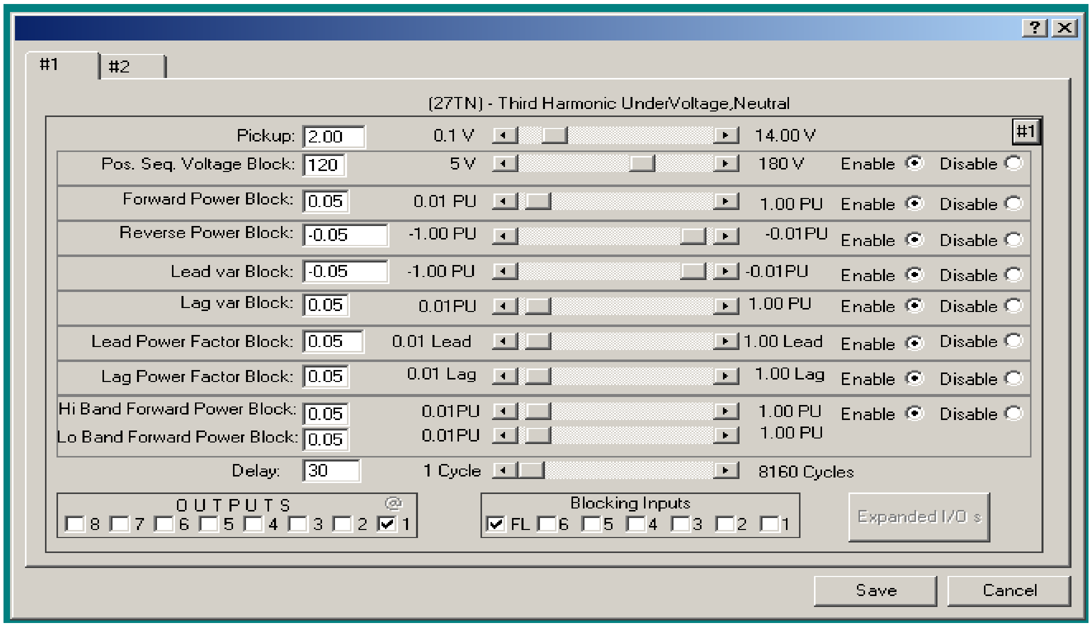


Fig. 9 Third Harmonic Neutral Undervoltage (27TN) Blocking

IV. THIRD HARMONIC RATIO SCHEME

This scheme requires the measurement of third harmonic voltage at both the neutral and terminals of the generator. Fig. 10 illustrates the third harmonic ratio scheme.

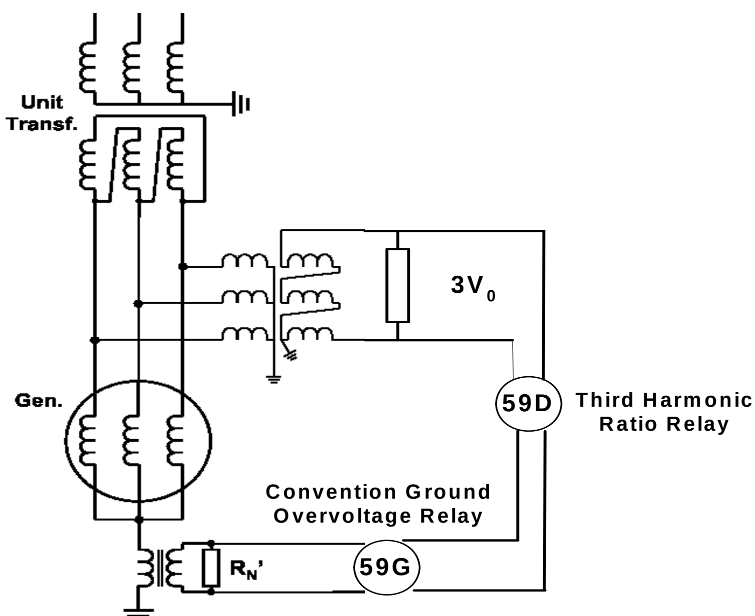


Fig. 10 Third Harmonic Ratio Scheme

The scheme compares the third harmonic voltage appearing at the generator terminals ($3V_{0)}$ to the third harmonic at the generator neutral. In some generators, this ratio remains fairly constant. In other generators, the ratio varies widely with MW and MVAR output. Fig. 8 illustrates this ratio for a relatively well-behaved generator. The ratio varied from a low of 1.0 to a high of 1.41.

The setting on this generator must be set greater than 1.41 ratio with a typical margin of 150%. A relatively wide margin is used over field measured values of third harmonic because all operating conditions can't be simulated due to system voltage restrictions.

The ratio of terminal-to-neutral third harmonic will increase for a stator ground fault near the generator neutral. The measurement of the third harmonic at the generator terminal generally requires a wye grounded–broken delta VT connection, which is typically not a standard VT connection on most generators. It usually has to be added specifically for this application, which adds to the cost of this scheme. Some digital relays can calculate the terminal third harmonic $3V_0$ if wye-grounded – wye-grounded VTs are used. The 59D element will detect stator ground faults at or near the generator neutral. It will not detect faults near the center of the generator winding or at the generator terminals. Thus, the conventional 59G element is necessary to detect these faults. The combinations of the 59D and 59G elements provide 100% coverage of the stator winding. The ratio scheme is generally more secure than the neutral undervoltage scheme described in Section III of this paper. However, if the machine does not have enough third harmonic, this scheme will not work.

V. LIMITATIONS OF THIRD-HARMONIC SCHEMES

Both the third harmonic schemes described above have some major limitations. First and foremost, many generators simply do not have enough third harmonic present to make the schemes work. It is very important to conduct field testing to measure the level of third harmonic prior to installation of the protection upgrade to ensure that the scheme described above will work. The author has been involved in a number of cases where there was not enough third harmonic for most operating conditions to use the schemes described above. In many cases, this shortcoming was discovered during commissioning or when the scheme operated improperly—resulting in a false tripping of the generator. This section of the paper outlines some of the applications where third harmonic schemes could not be use or must be modified.

A. Hydro Plant Applications

False Tripping during Load Rejection. When a hydro unit is full-load rejected (tripping of the generator breaker at full load), the generator can over-speed to180-200% of normal. Since hydro generators spin at a low RPM, this is not a serious condition and the closing of the runner valves will reduce the mechanical power and the RPM to normal levels in a few seconds. During this period, however, the generator terminal frequency is increased by 180-200%. Thus, the third harmonic that appears in the generator neutral is not the normal value of 180 Hz but 180-200% of this value. Since the neutral third harmonic undervoltage relays (27TN) are designed to detect third harmonic at normal 60 Hz frequency (180 Hz 3^{RD} harmonic), it will measure no 180 Hz voltage and will typically false-operate if the time delay setting is longer than the time it takes to reduce the generator speed to normal. Generally, supervising the 27TN element with an overfrequency relay (81O) will correct this problem. Many users are not aware of the need to provide such supervision and are surprised when they get an indication that the generator has sustained a stator-ground fault.

Synchronous Condenser Operation. Many hydro generators can, and do, operate as synchronous condensers. The unit is brought on-line and then the water is turned off to the turbine and the generator is operated as a VAR source. The generator AVR regulates the level of reactive power. Under this type of operation, the level of third harmonic neutral voltage can be substantially reduced over the level under normal generator operation. If the generator is to be operated as a synchronous condenser, the level of third harmonic must be determined through field measurements for this operating mode. In a number of cases, it was found that the 27TN element had to be blocked because the level of third harmonic was too low to make a secure setting for this operating mode. Thus, no 100% stator ground fault protection was provided during synchronous condenser operation.

Performance of Third Harmonic Scheme on Parallel Generators. It is not uncommon to parallel two or more hydro units on a common GSU step-up transformer. This practice is also sometimes used at other types of power plants. Fig. 11 illustrates this operating configuration. With the two generators operating in parallel, third harmonics can circulate between the two units. The MW and MVAR loading of unit G_1 affect the third harmonic neutral voltage of generator G_2. Similarly, the load level of generator G_2 affects the third harmonic neutral voltage of G_1. It is very difficult to make a secure 27TN setting and this protection may have to be blocked when both units are on-line.

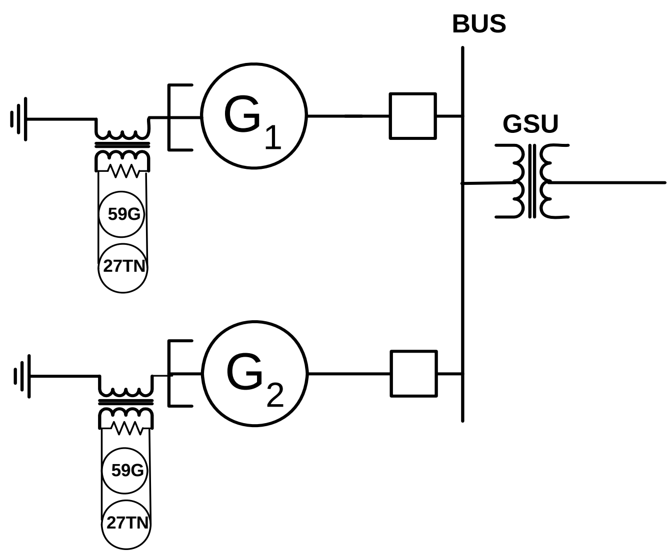


Fig. 11 Parallel Generators on a Common GSU

B. Cross Compound and Large Generators Applications

Cross compound and large steam units—especially those at nuclear plants—have parallel stator windings. Fig. 12 illustrates this type of winding configuration.

Only one winding on these units is typically grounded though a high impedance source to avoid circulating currents between ground sources. When the 27TN relay is used to detect ground faults in the last 5-10% of the stator winding, it will detect fault only in winding 1. The 27TN will not detect faults at the neutral end of winding 2, thereby leaving this zone unprotected.

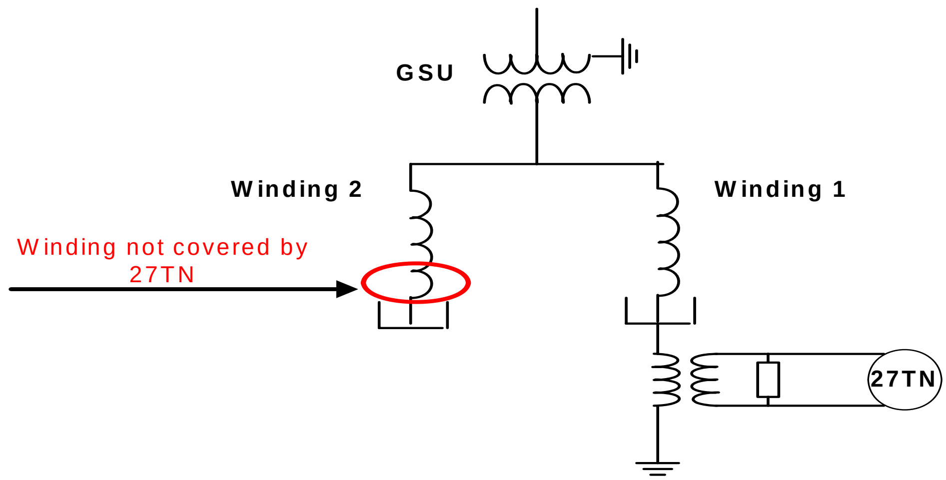


Fig. 12 Third Harmonic Relay Limitation for a Two-Winding Generator

C. Gas Turbines

Fig. 13 illustrates the variations of third harmonic with MW load on a 50 MW gas turbine. V3 is the terminal third harmonic voltage and VN3 is the third harmonic voltage measured at the generator neutral. The top two traces are the calculated values; the bottom two traces are the measured values.

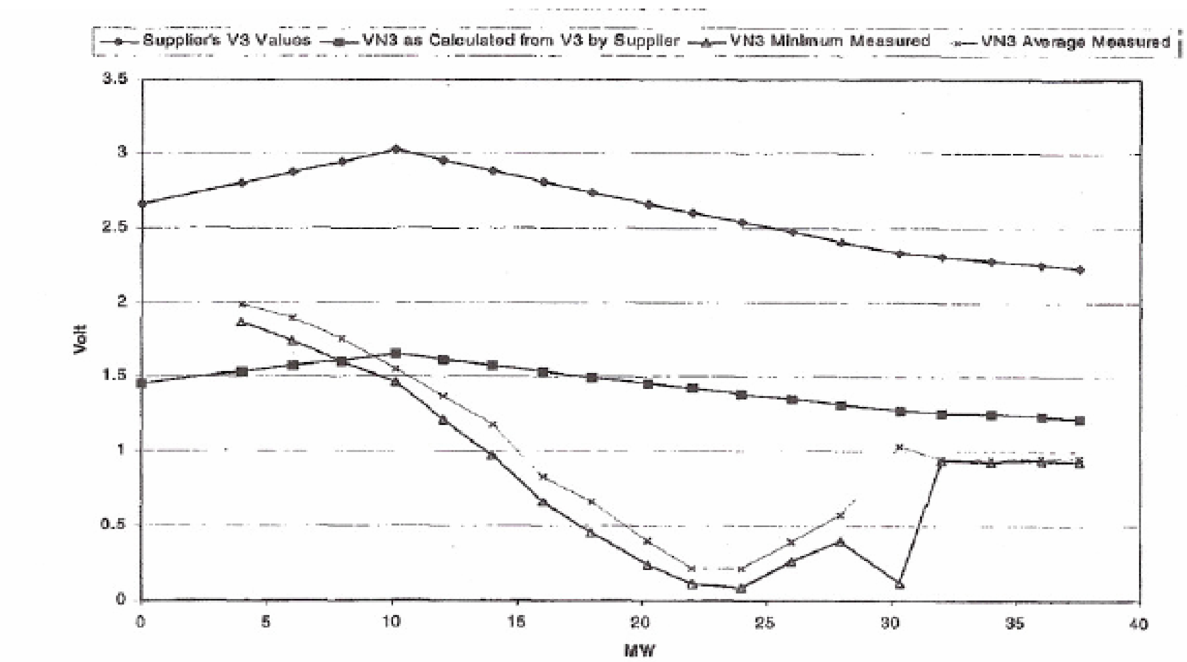


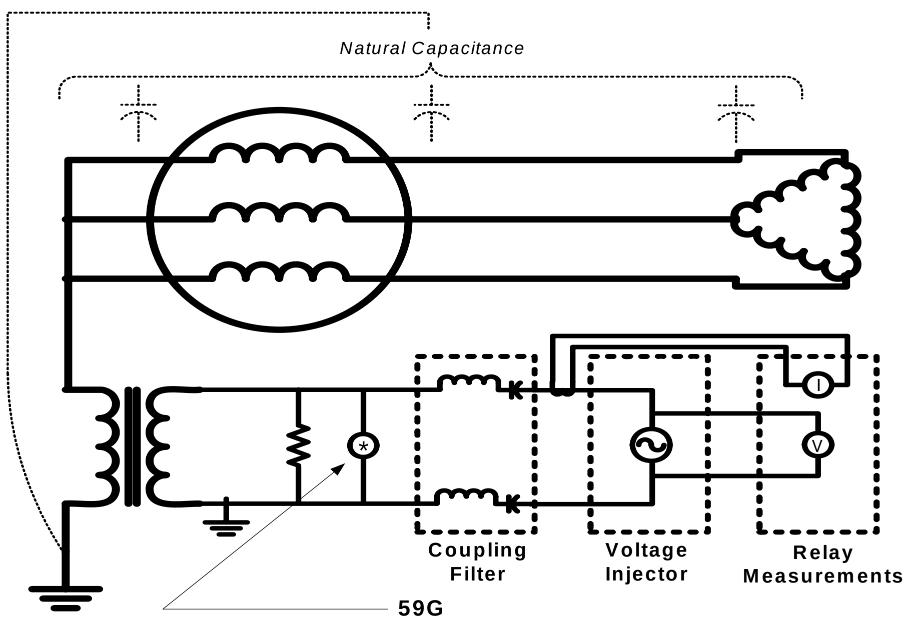
Fig. 13 Gas Turbine Third Harmonic Voltage Profile

As can be seen, there is a substantial error between calculated and measured values and this is one of the reasons that relay manufacturers recommend field measurements. For this particular gas turbine, there is a substantial drop in third harmonic neutral voltage, between 20 to 30 MW, which caused the 27TN to falsely operate. In other gas turbines, the third harmonic drops dramatically at certain generator VAR outputs—making the third harmonic schemes prone to false tripping. Field tests must be conducted on the gas turbine generators that are candidates for upgrade to 100% stator ground protection to determine if a third harmonic scheme can be applied.

VI. SUBHARMONIC VOLTAGE INJECTION SCHEME

An alternative to third harmonic schemes is the use of a subharmonic voltage injection scheme. These schemes are widely used in Europe and are just beginning to be used in the U.S. This scheme injected a low frequency subharmonic into the generator stator winding. The injected frequency ranges from 15-20 Hz. The signal is injected into the neutral grounding transformer.

Fig. 14 illustrates the subharmonic voltage injection scheme. The use of a low frequency subharmonic makes the generator and terminal bus capacitive reactance a high impedance. Thus, the KVA size of the injection transformer is reduced over what it would be if fundamental frequency were used.



Notes:
- Subharmonic injection typically at 15-20 Hz
- Coupling filter low pass or notch tuned for subharmonic frequency
- Measurement inputs tuned to respond to subharmonic frequency

Fig.14 Subharmonic Voltage Injection Scheme

Fig. 15 shows the coupling filter and voltage injector that is installed in the secondary of the generator grounding transformer. Typical subharmonic normal capacitive current is in the milli-amp range. Under normal conditions, a small level of changing current will flow at the subharmonic frequency. When a ground fault occurs anywhere in the winding of the generator or its associated bus work, the capacitance is shorted in that phase and a higher current flows which is detected by an overcurrent relay.

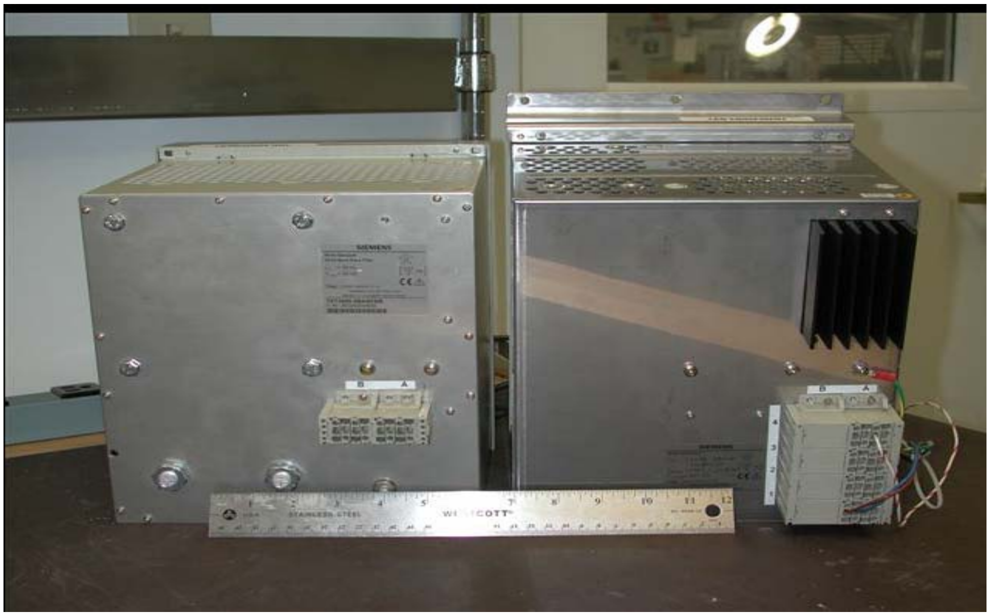


Fig. 15 Coupling Filter and Voltage Injector

The relay portion of the scheme in modern applications is usually in a digital multifunction generator protection package that typically includes all other generator protection functions. Integration of this function within a multifunction relay has reduced the scheme cost over separate relaying that was required in the older electronic versions of this scheme. The scheme is not affected by generator MW and MVAR loading and will detect ground faults at any location within the generator winding. It will also detect ground faults in both windings of a two-winding generator. Typically, the conventional 59G relay is used with this scheme to provide backup. Field measurements of the normal subharmonic capacitive current are required for commissioning. Digital relays typically measure this value and display it in a metering screen. This scheme's major feature is that it can detect stator ground faults when the generator is off-line, allowing the user to detect stator ground prior to putting the generator in-service.

VII. CONCLUSION

It is important to upgrade generator stator ground fault protection to provide protection for faults over the entire stator winding. This paper discusses the application of three different 100% stator ground fault protection schemes and the limitations that users have found with third harmonic schemes. When considering a third harmonic scheme, it is very important to first determine the third harmonic "signature" of the generator through field measurements. Ideally, these tests should determine the level of third harmonic over the MW and MVAR operating range of the generator. Many users have not done these tests and found, upon commissioning, that a third-harmonic scheme could not be used or its operation was so restrictive that it was only in-service a small percentage of the time. The subharmonic injection scheme provides an alternative to third-harmonic schemes and it can be applied on almost any unit-connected generator. Digital technology has substantially reduced its cost, making it a good choice for important generators. It offers the added advantage of being able to detect stator ground faults when the generator is off-line.

VIII. REFERENCES

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Chuck has a Bachelor of Science in Electrical Engineering from Purdue University and is a graduate of the eight-month G.E. Power System Engineering Course. He has authored a number of papers and magazine articles on protective relaying. He has over 25 years of experience as a protection engineer at Centerior Energy, a major investor-owned utility in Cleveland, Ohio where he was the manager of the system protection section. In that capacity, he was responsible for the electrical protection of the company's generating plants as well as the transmission and distribution system that served over 1.2 million customers. For ten years, he was employed by Beckwith Electric, a manufacturer of protective relays, as Application Manager for Protection Products. He is also a former instructor in the Graduate School of Electrical Engineering at Cleveland State University, as well as a registered Professional Engineer in Ohio.