# Accelerated Stator Ground Fault Tripping Using Negative Sequence Current

**Russell W. Patterson**
Patterson Power Engineers, LLC

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## Abstract

This paper discusses the phenomenon of zero sequence voltage coupling from the high-voltage system to the high-impedance grounded low-voltage bus for a synchronous generator and a simple improvement to accelerate stator ground fault protection (59G) using negative sequence current.


## Introduction

Figure 1 shows a typical one-line diagram for a unit connected synchronous generator. The machine is high-resistance grounded via a neutral transformer and secondary resistance [1]. The step-up transformer is delta connected on the generator side and wye connected on the HV system side. Likewise, the unit station service transformer (USST) is also connected delta on the generator side.

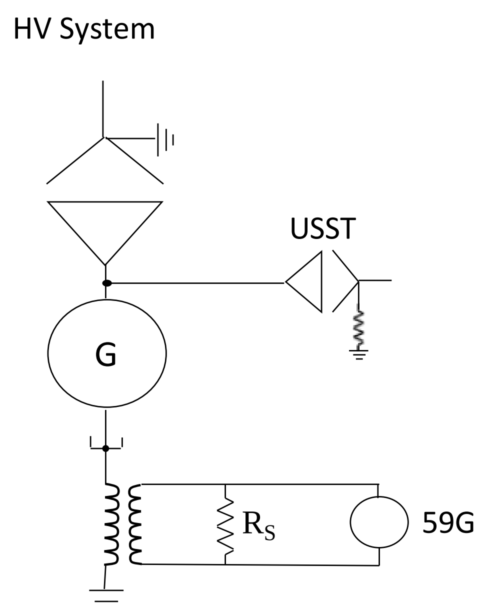


Figure 1: Typical high-impedance grounded synchronous generator.

An almost universally used method of detecting phase to ground faults in the generator stator winding is to use a voltage relay (59G) to measure the fundamental frequency voltage across the grounding resistance as shown in Figure 1. This relay will typically be set to detect ground faults in the upper 90-95% of the stator winding as described in section 7.18.1 of [1]. This relay will be complemented with other protection (e.g. third-harmonic neutral undervoltage, 27TH) to provide for 100% coverage of the stator for ground faults.

Due to the sensitive setting of the 59G (around 5% of generator rated phase-ground voltage) this relay is susceptible to operation during phase-ground faults on the HV side of the step-up transformer. When ground faults occur on the HV system a zero sequence voltage will be present as shown in Figure 3.40 of [2]. Due to the inherent interwinding capacitance between the HV and LV windings of the step-up transformer a portion of this HV zero sequence voltage will be impressed across the neutral grounding transformer. This phenomenon happens for ground faults on the low-voltage side of the USST as well but typically to a negligible degree.

This paper recommends a new simple approach to prevent operation of the 59G for HV system phase-ground faults that securely allows for much faster operation of the 59G for stator ground faults in the machine thus affording improved protection.

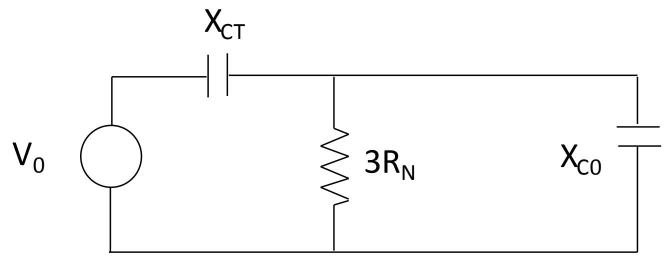


Figure 2: Circuit producing zero sequence fundamental frequency voltage across the neutral of the generator.

## Generator Neutral Voltage During HV System Ground Faults

The circuit to determine this voltage is a simple series voltage drop circuit comprised of the interwinding capacitance in series with the parallel combination of the generator neutral resistance and the phase-ground capacitance of the generator bus system (usually dominated by the stator phase-ground capacitance). This circuit is shown in Figure 2. $V_0$ is the zero sequence voltage at the HV terminals of the step-up transformer during the HV system ground fault, $X_{CT}$ is the capacitive reactance of the HV to LV interwinding capacitance, $3R_N$ is the effective resistance in the zero sequence of the high-impedance resistor grounding, and $X_{C0}$ is the total zero sequence phase-ground capacitive reactance of the generator bus system (includes stator phase-ground capacitance, any TRV capacitors, etc). This circuit is easily arrived at by applying symmetrical component theory and neglecting insignificant impedances.

The interwinding capacitance, $X_{CT}$, is typically much larger than the parallel combination of $3R_N$ and $X_{CO}$. However, a small percentage of the $V_0$ voltage will be impressed across $3R_N$ nonetheless. Due to the sensitive setting of the 59G it can operate during this HV phase-ground fault. The typical practice to prevent this protection from misoperating for this fault is to simply time delay its operation (delays of 1 to 5 seconds being typical). A common belief is that due to the fact that the phase-ground fault current in the generator is relatively small (10-25A) that damage is not occurring during this long delay. That may not always be the case and if the core of the generator is damaged significant down-time may be required for repairs, resulting in loss of opportunity as well as repair costs. Further, if a second ground occurs on one of the unfaulted phases with elevated voltage the resulting phase-phase-ground fault would most likely be catastrophic to the machine. The sooner the first ground fault can securely be cleared the better.

Actual data from [3] can be used to calculate the voltage ($V_N$) impressed across the neutral grounding transformer of a real machine during an actual HV system ground fault as follows with $Z_0$ being the parallel combination of $3R_N$ with $X_{CO}$.

$V_0 = 147\text{kV}$
$X_{CT} = 0.012\ \mu\text{F} = 221.0\ \text{k}\Omega$ (at 60Hz)
$X_{C0} = 0.254\ \mu\text{F} = 10.4\ \text{k}\Omega$
$3R_N = 8.4\ \text{k}\Omega$
$Z_0 = (6.5\ @\ {-39}°)\ \text{k}\Omega$
$V_N = (V_0 \times Z_0) / (Z_0 + X_{CT}) = 4.2\ \text{kV}$

With a neutral PT ratio of 120:1 this would impress 35.0 V across the 59G relay (normally set around 6.0 V secondary).

This same phenomenon occurs for ground faults on the low-voltage side of the USST but the driving zero sequence voltage on the low-voltage side of the USST is much smaller than the zero sequence voltage available on the HV side of the generator step-up transformer. For example, a typical auxiliary board voltage might be 6.9kV or less. Since the USST low-voltage side is commonly wye-grounded through a resistor the maximum available $V_0$ during a 6.9kV board ground fault might be 6.9kV x 1.73 ÷ 3 ≈ 4kV.

## Generator Negative Sequence Current During HV System Ground Faults

When phase-ground faults occur in the HV system the generator will feed fault current to the fault. This fault current from the machine will be comprised of positive and negative sequence current as can be seen from the symmetrical component network for this fault shown in Figure 3 where,

Eg = generator emf
Es = system positive sequence voltage
$ZG_1$ = generator positive sequence impedance
$ZG_2$ = generator negative sequence impedance
$ZG_0$ = generator zero sequence impedance
$Z_T$ = step-up transformer positive sequence impedance
$ZT_0$ = step-up transformer zero sequence impedance
$ZS_1$ = system equivalent positive sequence impedance
$ZS_2$ = system equivalent negative sequence impedance
$ZS_0$ = system equivalent zero sequence impedance

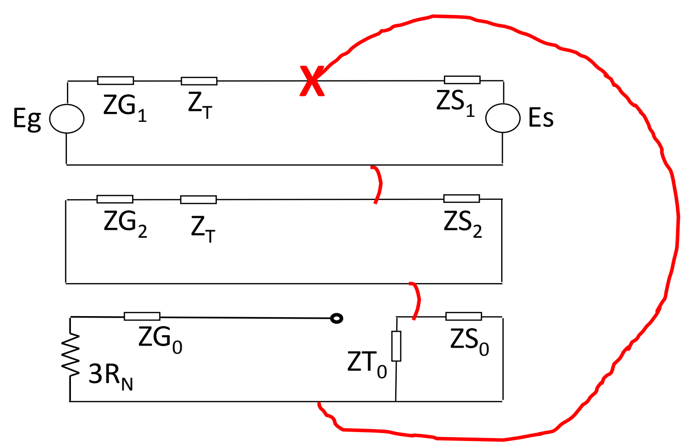


Figure 3: Circuit to determine negative sequence current in the generator during HV system phase-ground faults.

In this case the interwinding capacitance can be neglected and the networks connected in series as shown. During this fault significant negative sequence current will flow through the left-hand side of the negative sequence network through the generator ($ZG_2$). This quantity can be used as a "torque control" to block fast operation of the 59G when the operating voltage it experiences is due to the zero sequence voltage coupled across the interwinding capacitance of the step-up transformer during an HV system ground fault. If the 59G experiences operating quantity above its pickup in the absence of this negative sequence current it can be allowed to operate significantly faster than the typical 1 to 5 seconds. It can securely operate in as fast as 5-10 cycles depending on a few other aspects that are discussed in the following section.

## Factors Effecting 59G Accelerated Time Delay

A minor complication for 59G protection is the use of VTs on the generator bus that are connected wye-grounded on both the primary and secondary windings.

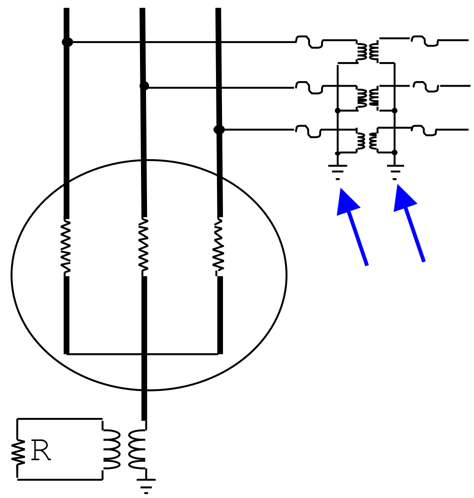


Figure 4: VTs on generator bus with both primary and secondary windings connected wye-grounded.

In this configuration VT secondary phase-ground faults will be detected by the 59G. As such, the 59G time delay must be coordinated with the VT primary and secondary fuses to prevent erroneous tripping of the generator for secondary wiring ground faults. Figure 5 shows coordination curves for two commonly used primary and secondary VT fuses in this configuration with the secondary fuse curve reflected to a primary ampere base and adjusted since the total fuse current is a combination of current from the generator neutral and from the phase-ground capacitance.

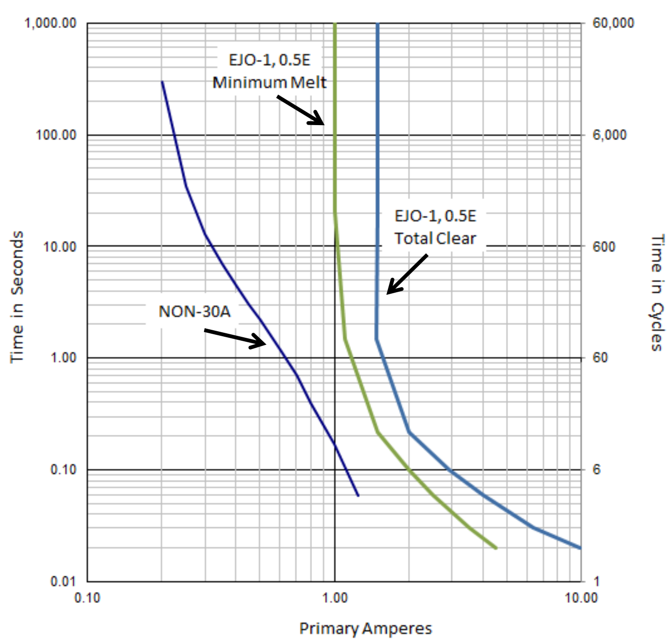


Figure 5: PT primary side fuse (0.5E, EJO-1 current limiting) and secondary fuse (NON-30A).

It can be seen that in the range of normal ground fault current presented by a high-resistance grounding method (10-25A typically) the fuses operate relatively fast (faster than 6 cycles). Note that the presence of current limiting resistors in series with the PT primary fuses (used when the available fault current exceeds the capability of the current limiting fuses) have a negligible effect on the phase-ground fault current as they are swamped by the other circuit parameters (e.g. 65Ω is used for current limiting resistance in one installation).

## Summary

This paper outlines a simple method to allow accelerated tripping of the 59G for stator ground faults in the absence of negative sequence current as would be present in the generator during HV system phase-ground faults. This method is simple and secure and easily implemented in most modern digital protection relays. One common approach used by the author is to simply use the pickup of the negative sequence unbalance protection (46Q) as the torque control used to prevent accelerated tripping of the 59G. The 46Q is typically set in the range of 5-10% of the generators full load current providing good sensitivity when used in this additional role. Fast tripping (e.g. 5-15 cycles) can be achieved securely with the negative sequence torque control suggested in this paper.

# References

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3. C.H. Griffin, J.W. Pope, "Generator Ground Fault Protection Using Overcurrent, Overvoltage, and Undervoltage Relays", IEEE Transactions on Power Apparatus and Systems, PAS-101, no. 12, pp. 4490-4501, 1982.

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## Biographical Sketch

**Russell W. Patterson** (SM 2002) received his BSEE in 1991 from Mississippi State University in Starkville, MS and his MSEE in 2013 from the University of Tennessee at Chattanooga, TN. He began his career as a field test engineer for TVA and has over twenty years' experience in utility generator and transmission protection and managed the system protection department for TVA until his retirement in 2008 to enter full time consulting. Russ owns Patterson Power Engineers (PPE), a consulting firm headquartered in Chattanooga, TN. He is a member of the IEEE Power System Relaying Committee where he is Secretary, a past chairman of the Line Protection Subcommittee, and an active member of the Rotating Machinery Subcommittee. He is an active member of CIGRÉ and a registered professional engineer. http://PattersonPowerEngineers.com