A Practical Improvement to Stator Ground Fault Protection Using Negative Sequence Current

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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.

Index Terms – Relaying, generators, high-impedance, negative sequence, interwinding capacitance.

I. 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.

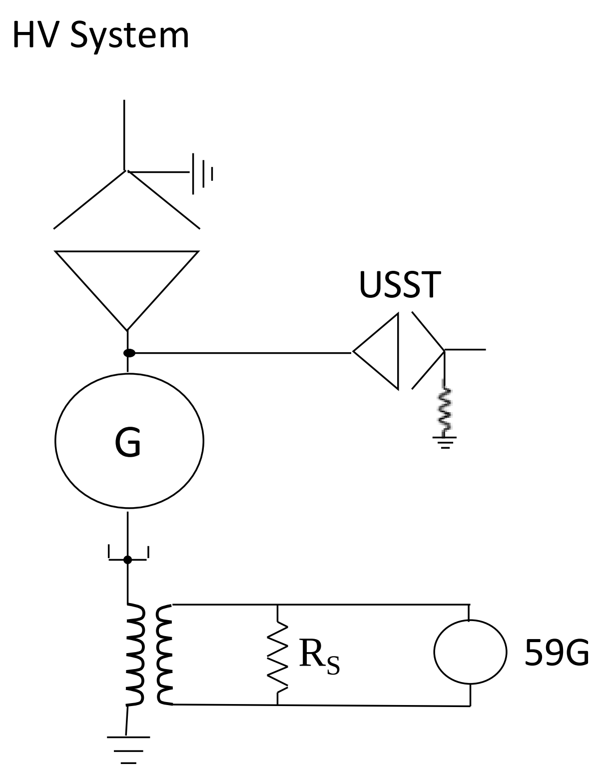

Figure 1: *Typical high-impedance grounded synchronous generator.*

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.

II. 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.

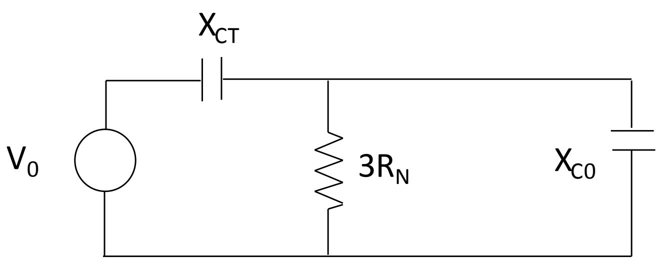

Figure 2: *Circuit producing zero sequence fundamental frequency voltage across the neutral of the generator.*

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 common). 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. One USST familiar to the author has an interwinding capacitance of 9,400 pF resulting in an X_{CT} of 282 kΩ at 60Hz. The worst case V_N presented to the generator neutral for a USST low-side ground fault would thus be less than 100V primary, well below the typical 59G pickup. The interwinding capacitance can be obtained from USST test data and evaluated easily as described above. In the unlikely event that the USST interwinding capacitance is large enough to allow low-voltage bus faults to produce generator neutral voltage above the 59G set point then the approach described as follows in this paper would need to be modified or simply not used.

III. 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
ZT = 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

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.

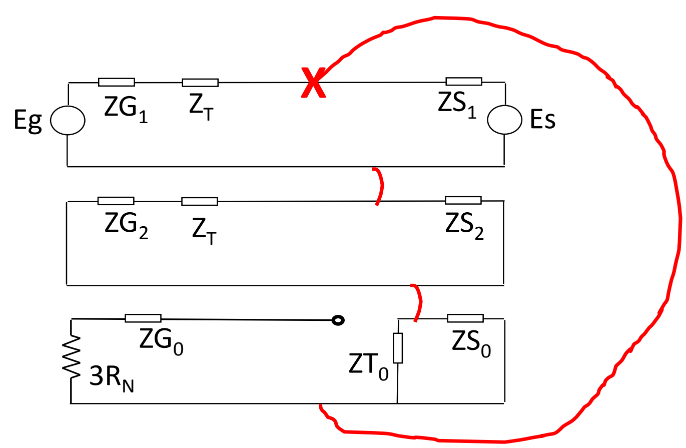

Figure 3: *Circuit to determine negative sequence current in the generator during HV system phase-ground faults.*

IV. FACTORS EFFECTING SPEED OF 59G

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

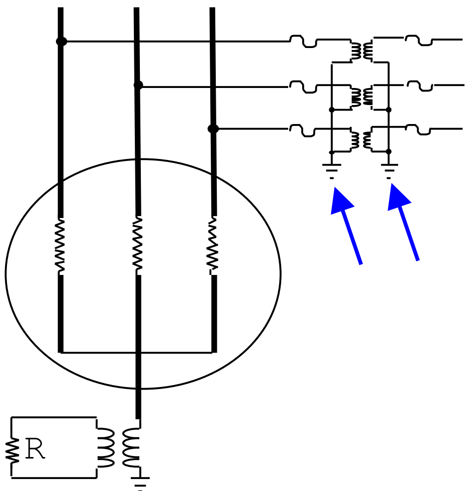

Figure 4: *PTs on generator bus with both primary and secondary windings connected wye-grounded.*

In this configuration PT secondary phase-ground faults will be detected by the 59G. As such, its time delay must be coordinated with the PT 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 PT 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.

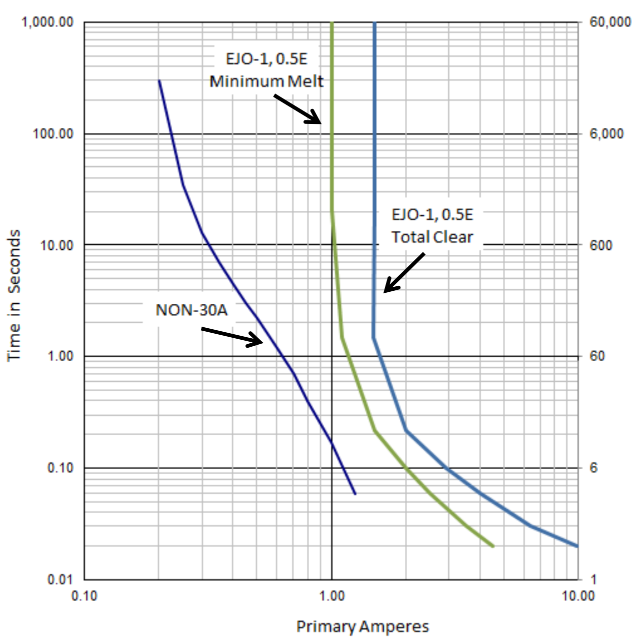

Figure 5: *PT primary side fuse (0.5E, EJO-1 current limiting) and secondary fuse (NON-30A).*

It can be seen that in the range of normal ground fault current afforded 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).

It is recommended to break the zero sequence path of the wye-grounded primary and wye-grounded secondary by simply removing the ground connection on the secondary wye point and placing it on one of the phase conductors (typically b-phase). This breaks the zero sequence path through the PTs while maintaining a ground reference for safety as shown in Figure 6. By removing the ground on the neutral and by not running a neutral conductor out with the phase conductors the chances of a phase-neutral fault occurring and risking a unit trip are eliminated. Placing the safety ground on a phase (e.g. b-phase) is an acceptable and preferable approach as long as the protection and control devices fed from the secondary of the PTs do not require zero sequence quantities for operation (such as a 3rd harmonic voltage differential). Note that it is still possible to ground a phase conductor and run a conductor from the secondary neutral point to relays that require zero sequence quantities allowing them to properly operate (such as 3rd harmonic voltage differential). Doing so simply reduces some of the benefit of b-phase grounding due to the neutral conductor being exposed with the phase conductors along the run and available to allow a secondary phase-neutral fault which will appear as a phase-ground fault to the 59G protection.

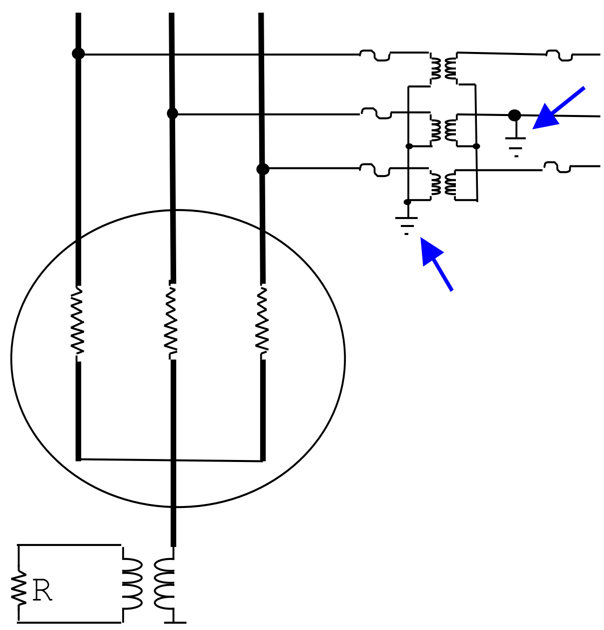

Figure 6: *PTs on generator bus with primary wye-grounded and secondary winding b-phase grounded.*

In configurations with PTs being wye-grounded on both primary and secondary there will be no negative sequence generator current during the secondary phase-ground faults.

As such, coordination with the PT fuses must be ensured. This has been shown to be a minor point only requiring minimal delay for the 59G. This is an acceptable delay as it is also required if it is desired to prevent operation of the 59G for stator turn-turn faults that produce brief neutral shifts detected by this relay.

An additional interesting point is that secondary phase-ground faults for the configuration shown in Figure 4 may produce fault current that is higher than that for a phase-phase or three-phase secondary fault. Further, the voltage impressed across the 59G for this fault may be higher than that seen by the 59G for a bolted phase-ground fault on the terminals of the generator. This is due to the inductive reactance of the PTs in series with the parallel combination of the neutral resistance and the phase-ground capacitance in the zero sequence network.

V. 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.

VI. REFERENCES

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VIII. BIOGRAPHY

Russell W. Patterson (SM 2002) received his BSEE degree in 1991 from Mississippi State University in Starkville, MS. He began his career as a field test engineer for TVA and has 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. Russell owns Patterson Power Engineers, a consulting firm headquartered in Chattanooga, TN with six full time protection engineers. He is a member of the IEEE Power System Relaying Committee where he is chairman of the Line Protection Subcommittee and a member of the Rotating Machinery Subcommittee. He is a senior member of IEEE, a member of CIGRÉ, and a registered professional engineer in multiple states and with NCEES. He is also an adjunct lecturer at the University of Tennessee at Chattanooga in the electrical engineering department where he teaches graduate classes and short courses on power system protection. Russ has authored/co-authored over a dozen conference papers on protective relaying. http://PattersonPowerEngineers.com

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