100% Stator Ground Fault Detection Implementation at Hibbard Renewable Energy Center

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Introduction

An undetected stator ground fault on a large turbine generator can cause millions of dollars in damage and a larger amount of lost operating revenue during the time the generator is out of service being repaired. As Minnesota Power has been upgrading the protection on their generating units the grounding has been being upgraded from low impedance grounding to high impedance grounding. 100% stator ground protection has been being implemented. From a past project of relay upgrades at Minnesota Power's Laskin Energy Center the two generators do not have 100% stator ground fault detection. Due to the design of the generators, the use of third harmonic voltage to detect the stator ground fault is not reliable. When it was time to upgrade Minnesota Power's Hibbard Energy Center Unit 3 and Unit 4 generators, which are similar in design and size as the units at Laskin Energy Center, it was decided that different options needed to be explored to achieve 100% stator ground protection.

Minnesota Power services 143,000 retail customers in northeastern Minnesota and wholesale electric service to 16 municipalities and some of the largest industrial customers in the country. MP operates five thermal power plants, and eleven Hydro Stations for a total production of 1500 Megawatts net

Generator Grounding

To understand the issue of ground fault protection for a generator, it's necessary to know the effect of grounding of the generator has on the amount of ground fault current available. There are several ways to ground a generator; Ungrounded, low impedance grounding, low impedance grounding, high impedance grounding, and solidly grounded.

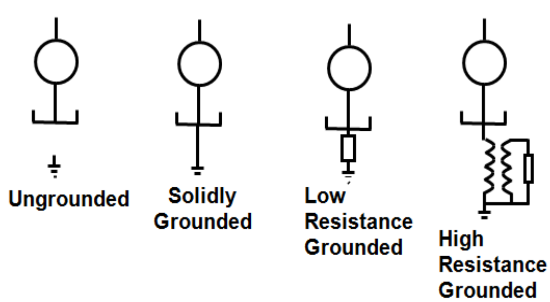

Fig 1 Types of Grounding

Ungrounded

Generator is grounded through the winding and cable capacitance. Fault current is negligible. This type grounding rarely used for generators since neutral of generator must be insulated for full phase to phase voltage. On small generators this may not be problem. This grounding method is used in some industrial applications where the generator can still operate with a ground fault.

Solidly grounded

Generator neutral is directly tied to ground The high magnitude of fault current which results from solidly grounding a generator is unacceptable because of the fault damage it can cause. Shutting down the generator through tripping the generator breaker, field, and prime mover does not cause the fault current to immediately go to zero. The flux trapped in the field will result in the fault current slowly decaying over a number of seconds after the generator is tripped which substantially increases damage. This type connection is not commonly used.

Stator windings on major generators are grounded in a manner that will reduce the fault current and overvoltages and provide a means of detecting the ground fault condition quickly enough to prevent iron burning. Two methods to accomplish this are low impedance and high impedance grounding.

Low impedance grounding

The grounding resistor or reactor is chosen to limit the generator contribution to a single line to ground fault current to between 200 amps and 150% of rated load current. The phase differential relaying can provide some ground fault protection for higher level ground faults, but additional protection is needed for lower level ground faults closer to the generator neutral.

High Impedance grounding

This grounding method is mainly used on unit connected generators. A distribution transformer is utilized whose primary voltage is chosen to be slightly greater than the line to neutral rating of the generator so it doesn't saturate on single line to ground faults with the machine operating at 105% of rated voltage. The secondary rating is 120 or 240v. The secondary resistor is selected so that the fault current for a single line to ground fault at the terminals of the generator is limited to 3 – 25 primary amps. This level of fault current is not sufficient to pick up the generator differential relay for ground faults. Additional protection is needed to detect ground faults.

Those generators that use low impedance or high impedance grounding will need to supplement the generator differential relay with some other protection to detect stator ground faults. There are several methods to detect stator ground faults

The classical method to provide generator ground fault protection is a neutral overvoltage scheme. (59GN). A time delayed overvoltage relay is connected across the grounding resistor to sense zero sequence voltage. The relay is sensitive to fundamental frequency voltage and not sensitive to third harmonic voltage that is present at the generator neutral.

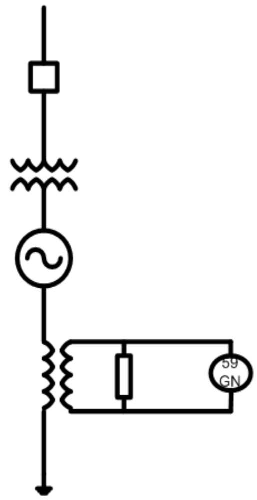

Fig 2. 59GN

For a single line to ground fault on the generator terminals, full phase to neutral voltage will impressed on the generator neutral. The voltage across the resistor will be a function of the transformer turns ratio and the location of the fault within the winding. As the fault moves from the terminal to the generator neutral, the voltage across the resistor becomes smaller. Typically, the minimum pick up setting for this relay is 5v. This limits the sensitivity of the relay, so it can detect faults only down to within 5% of the generator neutral.

A time overcurrent relay can also be used for providing ground fault protection when using a distribution transformer grounding scheme with a secondary resistor. The current transformer can either be located in the generator neutral or in the secondary of the distribution transformer. An inverse of very inverse overcurrent curve is used for this application. The relay must be set above the normal unbalance currents and the zero sequence harmonic currents that appear in the neutral. The pickup setting of the overcurrent relay should be greater than 135% of the maximum current in the neutral under non fault conditions. The time overcurrent relay provides less sensitive protection than the overvoltage relay that detects zero sequence voltage.

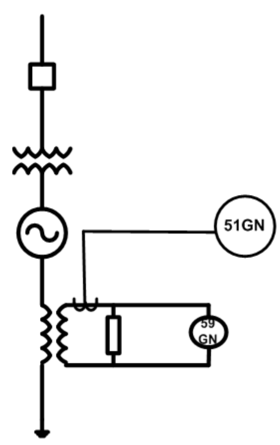

Fig. 3 51GN

The relaying described above does not yield 100% stator ground fault protection, only 95%. This is because faults near the neutral do not cause sufficient residual voltage and residual current to operate these relays. To achieve 100% ground fault protection two methods are used; third harmonic voltage, and neutral injection.

Third harmonic voltages are present at the terminals of nearly every generator in some degree. They exist due to differences in generator design and manufacture. If there is adequate amount of third harmonic voltage, this voltage can be used to detect ground faults near the neutral. The third harmonic voltages measured at the generator terminals, or neutral, or both can be used to detect ground faults.

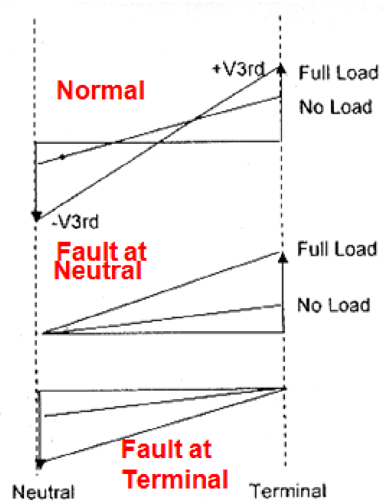

Fig. 4

3rd Harmonic Profile

Figure 4 shows the third harmonic voltage at the terminal of the generator and the neutral of the generator during different load conditions, for a fault at the generator neutral, and a fault at the generator terminals. Several observations can be made from the voltage profile. The level of third harmonic voltage at the neutral and generator terminals is dependent of the operating conditions of the generator. The voltage is higher at full load than no load, although this could change with generator design. There is a point in the winding, depending on the generator design, where the third harmonic voltage is zero. For a fault at the generator neutral, the third harmonic voltage at the neutral is zero. For the same fault, the third harmonic voltage on the generator terminals is high and varies with load. For a fault at the generator terminal, the third harmonic voltage is zero, and the third harmonic voltage at the neutral is high. As the ground fault moves from the generator terminal toward the neutral, the third harmonic voltage at the generator terminal increases, and the third harmonic voltage at the neutral decreases. The amount of increase or decrease is a function of the generator operating conditions. The third harmonic voltage levels vary from one generator to another.

There are three types of third harmonic voltage schemes employed for 100% stator ground fault protection; Third harmonic neutral overvoltage, third harmonic terminal voltage, and third harmonic comparator.

Third Harmonic Undervoltage

This method uses the fact that for a fault near the neutral of a generator the third harmonic voltage decreases. An Undervoltage relay operating from third harmonic voltage at the neutral could detect a fault at the neutral.

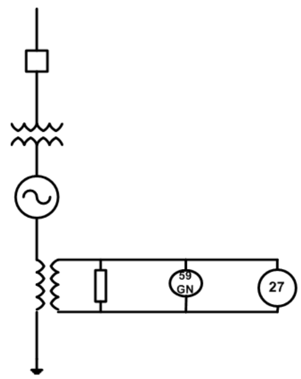

Fig. 5 Third Harmonic Undervoltage Relay

An Undervoltage relay tunes to 180HZ is used in this application. The relay is placed across the resistor in the secondary of the neutral grounding transformer scheme. Generally, the third harmonic undervoltage relay can detect faults from 0 – 30% of stator winding as view from the neutral towards the machine terminals. This relay in combination with the overvoltage relay tuned to fundamental frequency will overlap in protection and give 100% ground fault protection for the stator.

Third Harmonic Residual voltage

This method relies on the fact that the third harmonic generator terminal voltage increases at the ground fault approaches the generator neutral. Therefore, an overvoltage relay at the generator terminal using third harmonic voltage can detect fault at the generator neutral. Residual voltage at the generator terminal is supplied by a wye grounded – broken delta transformer. This voltage is passed to an overvoltage relay tuned to 180HZ. As the fault approaches the generator neutral the voltage received by the relay increases and operated the relay. For faults near the generator terminal, the third harmonic voltage as seen by the relay decreases and this protection does not operate. Thus, this relay needs to be sued in conjunction with the 59GN scheme to yield 100% protection of the stator winding for ground faults.

Third harmonic comparator

The third harmonic comparator relies on the fact that under normal conditions the ratio of the magnitude of the third harmonic voltage at the generator neutral to the magnitude of the third harmonic generator voltage at the generator terminals is almost constant. This ratio is upset for fault near the generator neutral or near the generator terminals. Ground fault midway in the stator winding are detected by the 59GN relay since the third harmonic differential relay sensitivity is minimal for these faults. For these faults the third harmonic voltage at the neutral and at the terminal is very near the relay setting. The setting for the relay is determined during field tests.

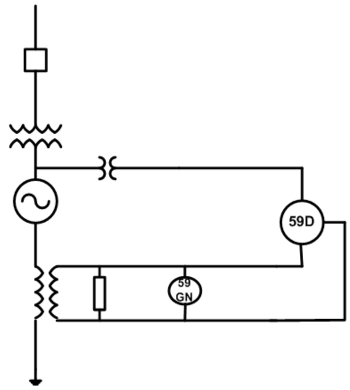

Fig 6. Third Harmonic Comparator

Voltage injection

In this method, an independent signal with a certain frequency, different from the generator rated frequency is injected into the stator circuit. The response of this injected signal is used to detect stator ground faults. To implement this, a separate injection box is required. The injection box generates a square wave which can be injected into a voltage transformer in the neutral of the generator, or grounding transformer. This signal propagates through the transformer into the stator circuit. The magnitude of the injected voltage signal is measured on the secondary of the grounding transformer. In addition, the injected current is measured via a resistive shunt located in the injection box. Based on these two measured quantities, the stator winding resistance to ground is calculated. The calculated resistance value is compared to a setting for alarm or trip.

This technique not only measures the resistance to the generator neutral but also along the stator winding and at the generator terminals including connected components such as voltage transformers, excitation transformers, circuit breakers, and other equipment. The measuring principle is not influenced by the generator operating condition and is fully functional even when the generator is on turning gear, or at standstill.

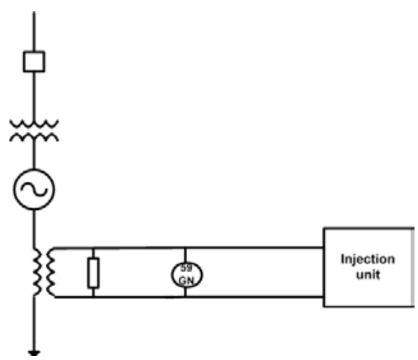

Fig 7. Stator Injection

Grounding Upgrade at Hibbard

The existing grounding on Unit 3 and 4 at Hibbard was low impedance. With the relay upgrade it is MP's standard to upgrade the grounding of the unit to high impedance. The high impedance grounding was implemented by using a distribution transformer with a resistor connected on the low side. The transformer used is a 13,800V to 240V with a 6A primary. The resistor bank is 1.664A, 8154W this setup limits the fault current for a line to ground fault to 6A primary.

Stator ground protection at Hibbard

Traditionally to achieve 100% stator ground protection on MP's generators a neutral overvoltage scheme (59N) along with a third harmonic comparator (59D). When Laskin Units one and two were upgraded it was discovered that the machines did not produce enough third harmonic voltages, due to the pitch of the windings, to implement a third harmonic comparator scheme. The two Units at Hibbard are of the same vintage and design as Laskin, so it was decided that in the design it should be assumed that the machines would not produce enough third harmonics. Table 1 shows third harmonic reading from the metering after the new relaying was installed. The 59N overvoltage element covers 95% of the stator, and the third harmonic differential only covers the first 15% of the winding so there is 5% of the winding not covered as shown in Figure 8.

GENREATOR LOAD	3RD HARMONIC SECONDARY VOLTAGE TERMINAL SIDE	3RD HARMONIC SECONDARY VOLTAGE NEUTRAL SIDE
Off Line	1.753V	2.010V
0.364 MW	1.865V	2.154V
1.052 MW	1.943V	2.249V
5.163 MW	2.960V	3.609
8.679 MW	3.914V	4.801V

Table 1 Third Harmonic Voltage Readings

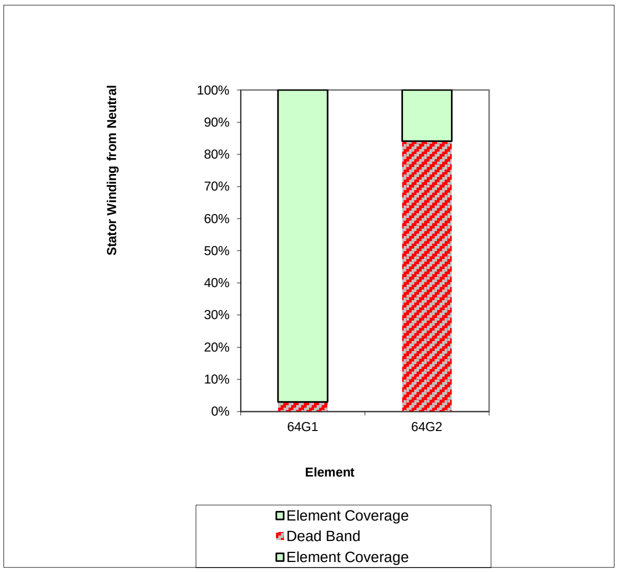

Figure 8 Element Coverage.

Achieving 100% Stator Ground Protect

To achieve 100% stator ground protection an overvoltage scheme (59N) was implemented along with injection through the secondary side of the grounding transformer see figure 9. The 59N element was set to 4% of the nominal primary line to ground voltage, 319V primary, and is only sensitive to the fundamental frequency. This value provides approx 95% of the stator protection while being secure enough not to trip on unbalanced currents. A time delay of 1 second is used to make the element more secure and allow for external system faults to be cleared. Due to there not being enough third harmonics produced to set a third harmonic voltage differential, injection through the grounding transformer was used as shown in figure 9.

There are three main parts to the injection unit; the generator protection relay, the injection unit, and a shunt resistor. The injection unit injects a square wave voltage in to the secondary side of the grounding transformer at a frequency of 106 Hz and measures the resulting 106HZ current. The injection unit outputs two voltages to the generator relay which represent the voltage and measured current. The generator relay uses these values to calculate a reference resistance from the winding to ground. This measured value is then compared to predetermined values that are set during commissioning. The shunt resistor is installed in to the circuit to protect the injection unit which is designed to handle voltages of 120V not 240V which is present on the secondary side of the grounding transformer.

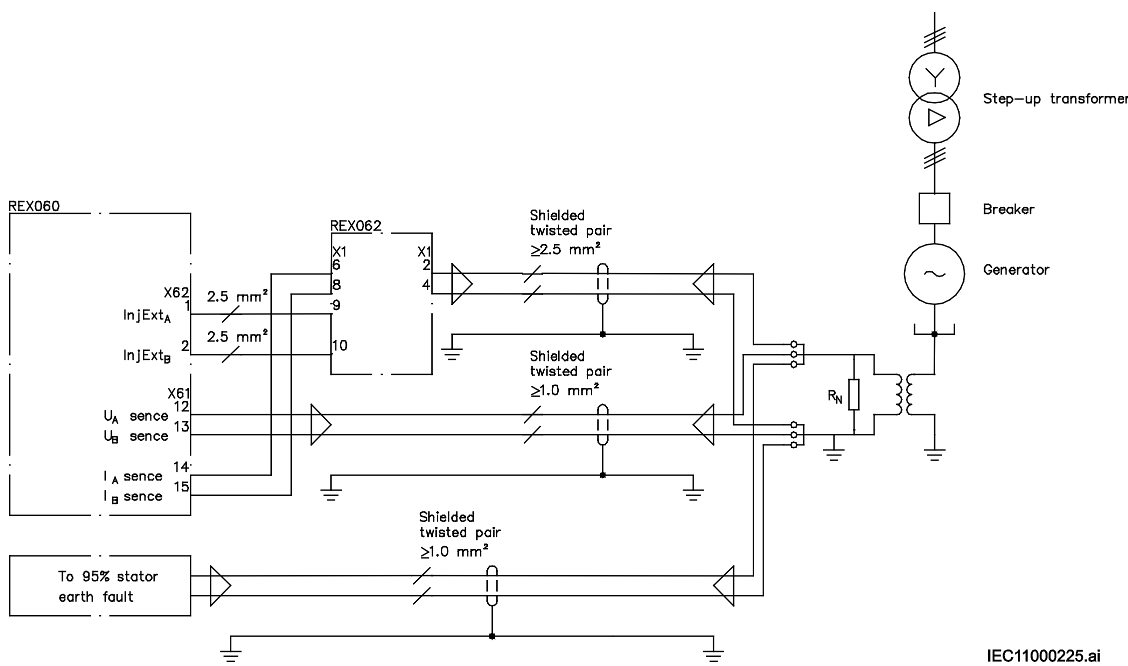

Fig 9. 100% Stator Connection

To implement the injection protection the unit needed to be calibrated. The resistance of the stator is being measured at the generator relay which led to approximately 250’ of cable to the grounding transformer of the generator. So the circuit has to be calibrated to account for the resistance in the cable.

To calibrate the unit three steps need to be followed; a measurement with the injection circuit in its final configuration, injection with a know resistance from the star of the generator to the ground, and injection with the neutral of the generator grounded. The three steps were done using the commissioning tool, a K1 value and K2 value was established. The K1 value is used to compensate for the transformer ratio and K2 compensates for series impedance from the cabling in the circuitry. See figure 10 and eq. 1 and eq 2 for further explanation of K1 and K2.

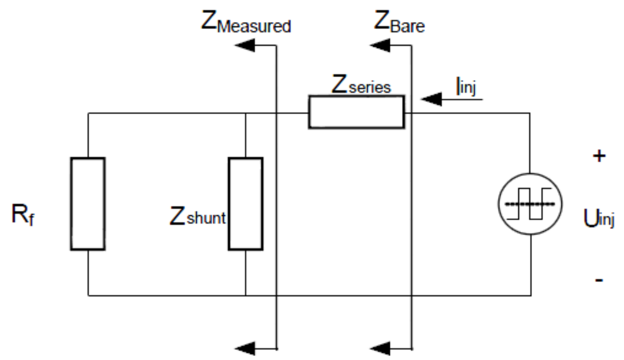

Figure 10 Equivalent circuit for impedance measurement

Where :

$$Z_{Bare} = V_{inj} / I_{inj}... \qquad \text{eq. 1}$$

$$Z_{measured} = Z_{Bare} \cdot K_1 + K2 \qquad \text{eq 2}$$

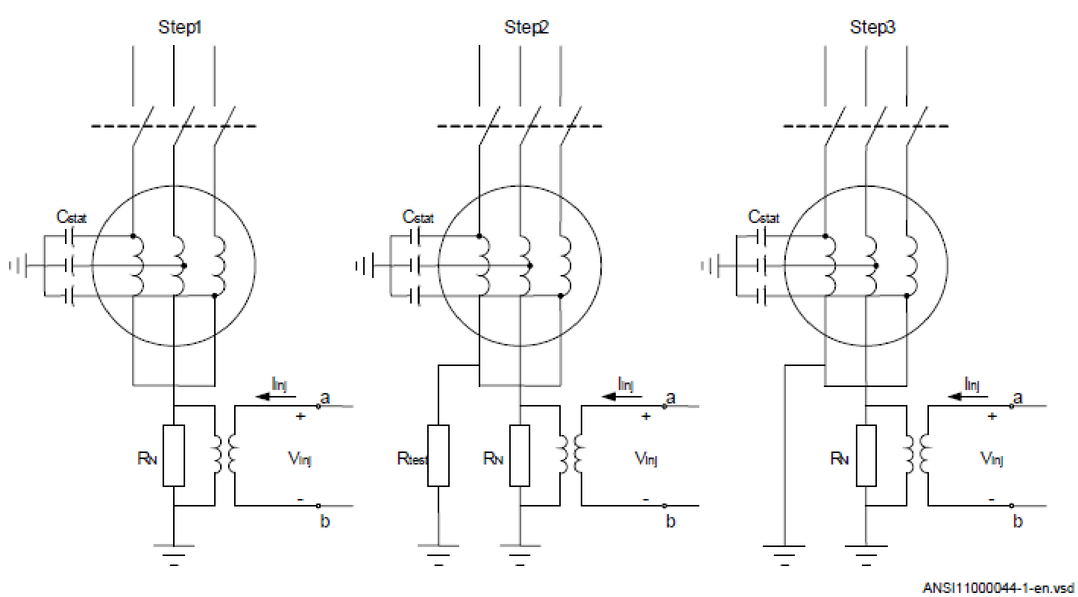

Fig 11. Three steps for Calibration

With the injection unit calibrated reference values need to be established. This was done as the unit was brought on line. Various operating conditions were observed. Measurements were taken with the generator at stand still, with the voltage regulator on and the unit up to speed, and then at various loads. Table 2 shows the various values. The measured resistance stayed very constant through the loading of the generator. This was expected since the generator parameters stay constant throughout the loading

STATOR READINGS		
LOAD (MW)	**REAL (OHM)**	**IMAGINARY (OHM)**
VR OFF	1224.244	-945.448
VR ON OFF LINE	1313.83	-1020.388
3	1310.125	-1023
10	1299.284	-1022.067
15	1302.019	-1023.031
19.5	1294.789	-1024.84
27.7	1279.789	-1026.547
32.9	1277.404	-1028.37
37.5	1272.637	-1029.127

A setting of 1000 ohm was set for tripping the unit off line. The logic for tripping the generator if a ground fault is detected by injection is to perform a soft shut down if the unit is online followed by tripping the unit lockout. If the unit is not online the lockout is tripped immediately. This tripping logic allows the unit be taken off line without stressing the turbine. If the overvoltage (59N) scheme picks up and times out the lock out is trip instantly even if the unit is online being the fault is not within the last 5% of the stator winding and more damaged can be caused the farther away from the neutral of the generator the fault is.

Conclusion

By using an overvoltage scheme and injection 100% stator protection was able to be achieved using injection. With the installation of high impedance grounding and 100% stator ground protection, the risk of causing costly damage to Hibbard Energy Center’s Unit 3 and 4 due to a stator ground fault was greatly reduced.

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