A Case Study of Implementing a Stator Ground Protection Scheme at Long Spruce Generating Station

Kris Manchur, P.E.
Manitoba Hydro
Canada

Gilberto Maioli
Hitachi Energy
Sweden

***Abstract*—Traditional injection-based stator ground fault protection uses a signal lower than the 60 Hz power system operating frequency and have been applied at Manitoba Hydro since 2011.**

This paper presents and discusses the implementation of an advanced injection-based stator ground protection scheme on a high-impedance grounded generator at Long Spruce Generating Station that utilizes a dedicated injecting transformer for improved sensitivity at an injection frequency above 60 Hz. The evaluation, design, and implementation of the protective scheme as well as the comprehensive software-assisted calibration and commissioning of the scheme in service is discussed along with highlighted relay field data to corroborate the results and confirm the applied settings.

I. Introduction

Manitoba Hydro is an electric and gas utility with over 4,900 employees that serve 608,554 electric customers in Central Canada in the province of Manitoba. It operates sixteen hydroelectric generating stations on the Nelson, Winnipeg, Saskatchewan, Burntwood and Laurie rivers supplying up to 6,100 megawatts. Manitoba Hydro operates on alternating current (AC) and direct current (DC) transmission systems and serve the entire province where most of the load is in the southern Manitoba in the city of Winnipeg.

Long Spruce Generating Station is located on the Nelson River in the northern part of Manitoba and along with Kettle, Limestone and Keeyask Generating Stations form an AC network that supplies the southern load through three HVdc bipoles. Long Spruce consists of 10 hydraulic turbine generators with an aggregate capacity of 1,010 MW.

Historically, Manitoba Hydro has used a neutral ground overvoltage (59G) protection function on its high-impedance grounded synchronous generators to provide stator ground fault protection; however, this protection function only provided 95% coverage of the stator winding. With multi-function digital relay packages, it allowed Manitoba Hydro to provide redundant 100% stator ground protection coverage through third harmonic voltage and sub-harmonic injection-based protection functions to complement the 59G protection function. Manitoba Hydro has been using various sub-harmonic injection-based protection since 2011 as its primary 100% stator ground protection function and it currently resides on 27 synchronous generators and 5 synchronous condensers.

II. Generator Neutral Grounding Considerations

Unit-connected generator configurations are commonly high-impedance grounded through neutral grounding equipment that consist of a neutral grounding transformer (NGT) with a secondary neutral ground resistor (NGR). The objective of generator grounding is the following:

- Reduce damage for internal ground-faults.
- Limit mechanical stress in the generator for external ground-faults.
- Limit temporary and transient overvoltages on the generator insulation.

The energy generated during a stator ground fault is equal to $I_f^2 * R_f * t$, where I_f is the fault current, R_f is the fault resistance and t is the fault duration. This relationship indicates that a reduction in current will have a greater reduction of the fault damage and iron burnings than a proportional reduction in time and fast fault clearing [1].

The equivalent resistance of the generator neutral grounding equipment reduces the ground fault current and the related mechanical stress. A minimum value of impedance, either a resistance or a reactance, shall be installed in the neutral of all wye-connected grounded generators where the zero-sequence reactance is less than the positive-sequence subtransient reactance. If sufficient neutral impedance is used to make the phase-to-ground fault current less than or equal to the three-phase fault current with the machine isolated from the system, the winding currents for any fault will be less than or equal to the winding current for a three-phase fault [2].

The design of generator neutral grounding equipment is based on the total capacitance to ground of generator stator windings and equipment connected to its terminals: if the value of the equivalent primary resistance of the generator neutral grounding equipment is equal, or not higher, than the three-phase reactance of the total capacitance to ground of generator stator windings and equipment connected to its terminals, then peak transient overvoltages at the healthy phases of the generator during ground faults are limited to values that are lower than the generator test voltage [2]. The generator neutral grounding equipment limits the single-phase to ground fault current to a value in the range between 3A and 25A primary [3].

A high-impedance generator neutral grounding configuration, such as the one found at Long Spruce is illustrated in Fig. 1. The neutral grounding equipment used at Long Spruce consists of a 13.8kV to 240V distribution transformer and a 0.3Ω resistor connected to its low voltage side. This limits the maximum fundamental fault current to approximately 11.37A for a ground fault located at the generator terminal of the stator winding and within the range of IEEE standards C37.101-2006 and C62.92.2-2017.

III. Generator Stator Ground Fault Protections

Typical protective functions independently used in a high-impedance grounded configuration to detect single-phase to ground faults are:

- A time delayed overvoltage protection (59G) that is connected across the grounding resistor on the secondary of the NGT to sense the residual voltage at the generator neutral.
- A time delayed overcurrent protection (51G) that measures the generator neutral current that can be connected at either the primary or secondary side of the NGT.
- A time delayed overvoltage protection (59G) that is wired to the broken delta connected secondary windings of a three-phase voltage transformer (VT) at the generator terminal to sense the residual voltage.

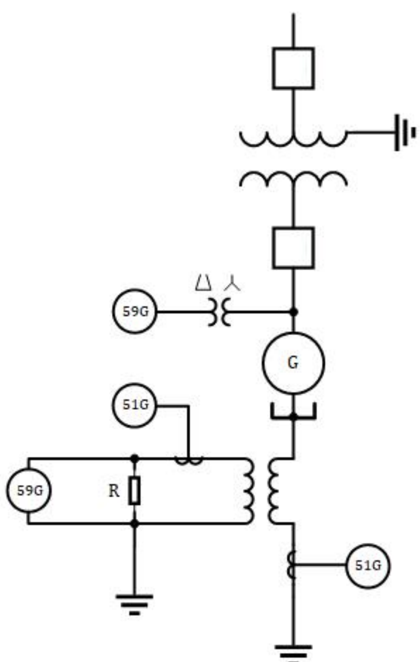


Fig. 1: High-Impedance Grounded Generator Configuration

These protection functions are called 95% stator ground fault protection and shown in Fig. 1 as they must account for the small amount of zero-sequence voltage and current that are present due to the generator construction imperfections under normal operating conditions. These functions are designed to operate on fundamental-frequency voltage (or current) and filter out third harmonic voltage (or current) and other triplen harmonics present at the generator neutral to gain sensitivity. The 95% stator ground fault protection has a blind zone that corresponds typically to about 5% of the stator windings close to the generator neutral point.

To achieve 100% stator ground fault protection, the protection scheme requires an additional protection function to extend the coverage of the 95% stator ground fault protection to the complete stator winding and to the generator neutral itself. This function should also provide an overlap area to ensure no blind zones exist in the stator winding. The 100% stator ground fault protection schemes can be grouped into two families:

- Stator ground fault protection schemes based on the third harmonic voltage which can be up to several percent of the generator's nominal voltage. This scheme involves the third harmonic undervoltage (27TH), the third harmonic overvoltage (59TH) or the third harmonic differential (59THD) protection function. Third harmonic-based protection can protect up to 30% of winding from the neutral point.
- Stator ground fault protection schemes based on the sub-harmonic injection principle (64S).

IV. Principles Of Operation Of Sub-Harmonic Injection-Based Stator Ground Protection

Traditional injection-based stator ground fault protection schemes inject a subharmonic voltage signal, with a fixed frequency into the generator neutral grounding equipment for the purpose of applying standard digital filtering techniques. This enables the algorithm to filter out interfering power system and harmonic components to obtain the resultant sub-harmonic injection current signal.

In healthy conditions, subharmonic current signal flows through distributed capacitance to ground of the generator stator windings and the capacitances to ground of equipment connected to the generator terminals. A ground fault is a resistive path in parallel to these shunt capacitances and will cause the measured subharmonic current to rise and the relay to operate [3].

The injection-based stator ground fault protection has some limitations:

- Capacitive current may limit the fault detection sensitivity of those systems that only measure the current magnitude.

- Traditional digital filtering affects the behavior and performances of the protection function when the generator deviates from nominal frequency.
- The largest detectable ground fault resistance depends on:
    - Low frequency signals propagate poorly through a transformer that is designed for 50 Hz or 60 Hz. For low frequencies the magnetizing current of the transformer will also influence the maximum relay sensitivity.
    - The capacitive reactance of the stator windings.
    - The impedance of the generator neutral grounding equipment.
    - Any other impedance to ground inside the reach of the protection function.

An injection-based stator ground fault protection that estimates the resistance to ground (and, therefore, the resistance of an eventual ground fault) injecting a signal slightly higher than the power system nominal frequency with advanced numerical filtering techniques can mitigate the above limitations [4].

V. Evaluation Of The Advanced Injection-Based Solution At Long Spruce

Due to the nature of the layout of the generating station and the inherent characteristics and construction of the generator, an evaluation of the advanced injection-based solution was performed using a simplified model to ensure the protection scheme would be able to acquire proper signal strength to detect stator ground faults at the neutral of the generator.

The evaluation of the simplified model was based on the absolute value of the total equivalent impedance to ground (Z_{tot}) on which the injection is performed. This equivalent impedance is equal to the parallel connection of the total equivalent capacitance C_{tot} and the primary equivalent resistance R_n(pri) of the generator neutral grounding equipment as shown in Fig. 2.

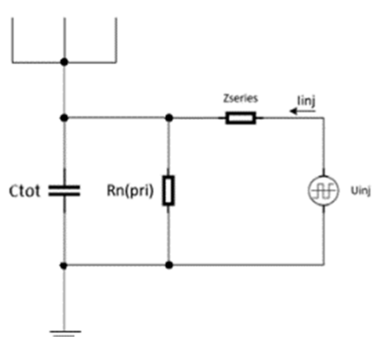


Fig. 2: Equivalent Circuit Impedance

The equivalent capacitance C_{tot} is calculated according to the guidelines in IEEE standards Std C62.92.2-2017, C37.102-1006 and C37.101-2006 about the design of the generator neutral grounding equipment equal to all contributing capacitances to ground (distributed capacitances of generator stator windings, installed surge capacitors, distributed capacitances of the step-up transformer low-voltage windings, auxiliary transformers high-voltage windings and insulated phase bus ducts, capacitances of eventual other installed devices) that are combined and modeled as a single capacitor connected between the generator neutral point and ground.

The evaluation considers the Z_{tot} when generator breaker is both open and closed. The Z_{tot} is smaller when the generator breaker is closed as the C_{tot} is higher. If Z_{tot} does not meet a minimum threshold, then there is a risk that the injected signal cannot be detected and the conventional design of injecting into the NGT cannot be used.

Data obtained from field trials have shown when the NGR is less than 1Ω connected across the secondary terminal of the NGT, the voltage measured is limited which reduces the protection sensitivity and further limits the range of different system parameters that can effectively be protected.

The absolute value of the total impedance-to-ground at the generator neutral is the basic parameter to run the preliminary check for a new installation and verify if it is inside the range of application of the advanced injection-based solution.

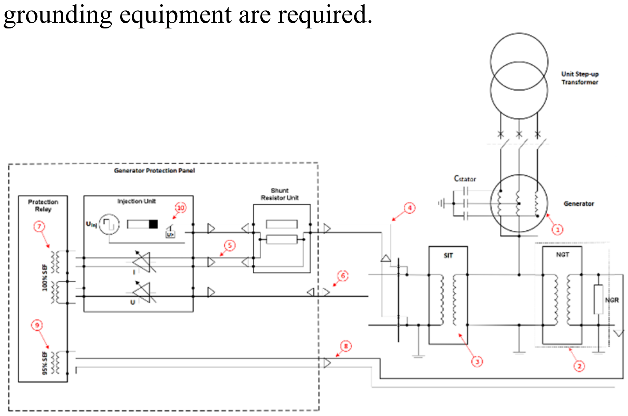
The simplified model in Fig. 2 has limitations as it does not allow the definition of parameter settings in the relay used to detect a ground fault and changes to the performance of the protection function that can occur during various operating conditions. For this reason, the advanced injection-based solution requires installation and calibration procedures to define these parameter settings which are defined during the commissioning stage and based on the analysis of site measurements. These analyses are performed by the vendor using data provided by Manitoba Hydro.

The evaluation concluded that because the generators at Long Spruce have a C_{tot} of 4.017µF with the generator circuit breaker closed and a NGR size of 0.3Ω, the selected vendor's device could provide coverage of the blind zone with sufficient overlap of the protection functions if additional hardware is used to improve the Useful Signal in the signal injection method. The Useful Signal is a parameter defined by the vendor that gives an indication about the strength of the injection signal.

VI. Advanced Injection-Based Solution Design And Implementation At Long Spruce

The selected vendor's solution is an advanced injection-based stator ground fault protection that injects a signal with a recommended frequency of 103 Hz, higher than the power system nominal frequency of 60 Hz. The recommended injection frequency is chosen to avoid interference from normally expected sources but is also settable and can be tuned to a proper customized value if interferences with other signals are detected during commissioning.

The advanced injection-based system (referred to as the 100% stator ground fault protection function) as shown in Fig. 3, includes a separate injection device, a shunt resistor unit, and a signal injection transformer (SIT). The injection device generates a square wave current signal which is injected into the stator windings through the shunt resistor unit and the SIT. The injected current signal is measured through a shunt that is inside the shunt resistor unit. The high voltage terminals of the signal injection transformer are connected between the generator neutral and ground. Neither changes nor rearrangements of the generator neutral grounding equipment are required.



1. Synchronous generator and a generator step-up (GSU) transformer.
2. Neutral grounding transformer (NGT).
3. Signal injection transformer (SIT).
4. Shielded cable for the square-wave current injection signal.
5. Connection for the measurement of the injected current.
6. Shielded twisted pair cable for measurement of the voltage at the injection point.
7. Two voltage analog channels of the multi-function protection relay used to measure the injected current and voltage.
8. Cable for 95% stator earth-fault protection.
9. Voltage analog channel of the multi-function protection relay for the 95% stator earth-fault protection.
10. Overvoltage protection of the injection circuit of the injection unit. The trip level depends on the settable parameter *UmaxEF* of the injection unit.

Fig. 3: Simplified Connection Drawing of the 100% Stator Ground Fault Devices

The injected voltage signal is measured at the low voltage terminals of the SIT. These two measurement signals are amplified by the injection unit and fed into two voltage analog channels of the multi-function protection relay as shown in Fig. 3. The 100% stator ground fault protection function does not require a dedicated measuring CT device; thus, does not have any CT saturation issues that could occur on the secondary of the NGT during a ground fault.

When the synchronous generator is at standstill, the 100% stator ground fault protection function can detect ground faults at the generator neutral, along the stator windings and at the generator terminals, including the connected equipment, like the high voltage windings of the excitation transformer and the bus ducts up to the terminals of the generator circuit breaker.

When the synchronous generator is not at standstill, the 100% stator ground fault protection function and the conventional 95% stator ground fault protection cooperate to protect 100% of the machine stator windings with an overlap zone between the protection functions.

The reach of the stator winding from the neutral point of the 100% stator ground fault protection function is related to the setting of the internal overvoltage protection of the injection unit (item 10 of Fig. 3). This overvoltage protection opens the injection circuit if the measured voltage exceeds the maximum operating range of 10% of the maximum steady voltage at the low voltage side of the SIT. This voltage is defined by a settable parameter *UmaxEF* of the injection unit. This feature ensures that:

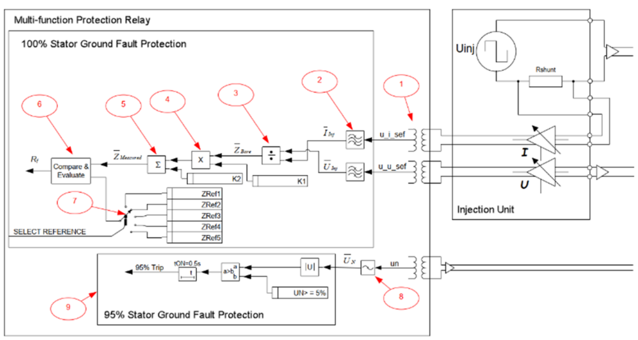
- The injection circuit does not interfere with the generator grounding equipment during ground faults outside the reach of the 100% stator ground fault protection.
- The injection circuit is not damaged by voltages higher than its maximum operating range (for example, in case of a direct phase-to-ground fault at generator terminals, the generator neutral steady fault voltage is theoretically equal to the rated phase-to-ground voltage of the generator; this fault is detected and cleared by the 95% stator ground fault protection).

A SIT is a dedicated injecting transformer connected in parallel with the NGT which is the additional hardware recommended by the vendor as the signal injection interface. The main advantage of injecting into an SIT as compared to an NGT is that it allows a more effective signal injection and eliminates the influence of small NGR values connected in the secondary circuit that limits voltage measurements. The SIT allows the injection of a Useful Signal into the generator neutral that is 5 to 10 times higher than without the installation of the SIT.

Since the SIT is connected between the generator neutral and ground, the same as the NGT, IEEE standard C62.92.2-2017 is followed to select the primary voltage rating and define its range of application. The SIT can be used with generators with rated voltage not higher than 22kV.

The rated primary voltage rating of the SIT installed at Long Spruce is 14.4kV primary and a secondary voltage rating of 240V (to match the secondary voltage rating of the NGT at Long Spruce).

A 100Ω resistor is connected on the secondary terminal for ferro-resonance suppression. It acts as a very large resistance when reflected to the HV side of the SIT producing no adverse impact to generator high-resistance grounding. In addition, it allows the use of an independent channel for the injection equipment and 100% stator ground fault protection.



1. Voltage analog channels of the multi-function protection relay.
2. Advanced numerical filters of the 100% stator ground fault protection function.
3. Calculation of the bare impedance Z_{bare}.
4. Calculation of Z_{bare} adjusted by k1 factor.
5. Calculation of the measured impedance $Z_{measured}$.
6. Evaluation of the resistance to ground R_f from $Z_{measured}$ and the active reference impedance Z_{Ref} and comparison to the settings R_{Alarm} and R_{Trip}.
7. Selection of the active reference impedance Z_{Rfef}\ (a reference impedance selection logic is configured in the application logic of the multi-function protection relay and connected to one input of the protection function to select the active reference impedance according to the operating condition of the generator).
8. Normal Fourier filters.
9. 95% stator ground fault protection that uses the normal Fourier filters to extract the fundamental frequency voltage at the generator neutral point.

Fig. 4: Simplified Logic Diagram of the Protection Functions

The principle of operation of the 100% injection-based stator ground protection function and 95% stator ground protection function is summarized in Fig. 4. A dedicated software function shown in items 2 through 7 in Fig. 4 run an advanced numerical filtering algorithm that extract the injected voltage phasor U_{Inj} and the injected current phasor I_{Inj} at the set injection frequency from the signals in item 1. These phasors and the complex factors k1 and k2 (k1 and k2 are defined during the commissioning of the function by a calibration procedure) are used to calculate a complex measured impedance $Z_{measured}$. The stator windings resistance to ground R_f is evaluated from the measured impedance $Z_{measured}$ and the active reference impedance Z_{ref}.

$$\frac{1}{R_f} = \left| Re\left(\frac{1}{Z_{measured}} - \frac{1}{Z_{ref}}\right) \right| \quad (\Omega)$$

The calculated resistance R_f is then compared to the set alarm and trip levels (R_{Alarm} and R_{Trip}) of the protection function; the outputs START, TRIP and ALARM of the function are updated according to this comparison and the delay characteristics.

Items 8 and 9 describe how the relay operates for the 95% stator ground protection function (59G).

VII. The Advanced Injection-Based Solution Calibration And Commissioning Process

The commissioning of the 100% stator ground fault protection needs a preliminary analysis of the generator operating conditions. This analysis defines the number of reference impedances and the strategy to select the active reference impedance corresponding to each operating condition. An appropriate reference impedance selection logic is therefore defined in the relay. If this activity is performed before the commissioning, the relay can properly select the active reference impedance during the commissioning.

The voltage at generator neutral and the equivalent impedance that is measured between the generator neutral and ground, can have different values in different generator operating conditions. Under healthy conditions, the main contribution to the voltage at generator neutral is given by the third harmonic voltage.

The equivalent impedance measured between the generator neutral and ground is affected by:

- The total equivalent capacitance to ground of generator stator windings and equipment connected to the generator terminals. When the generator circuit breaker is closed, devices between the circuit breaker and the step-up transformer are connected to the generator terminals, and their capacitances to ground affect the total capacitance to ground.
- The non-linear behavior of magnetic cores.
- The temperature of the neutral grounding resistor.
- The changes of the electrical behavior of components in the measurement loop that are related to electromechanical forces.

The commissioning of the 100% stator ground fault protection includes offline activities and online activities. Offline activities are:

- Installation procedure.
- Calibration procedure.
- Definition of additional reference impedances if they are needed.
- Applying test resistances tests to simulate ground faults to verify the behavior of the function.
- Analysis of results of the offline activities to confirm the defined parameter settings.

Online activities are:

- Monitoring the complete sequence of generator operating conditions to collect data through the logging feature of the injection commissioning software tool (ICT) and disturbance recordings that are manually triggered.
- Preliminary values of the additional reference impedances that are defined by the commissioning software tool for each online operating condition of the generator.

Data collected during online activities is analyzed to achieve the following targets:

- Verification that there is no signal interference with the injected signal. The analysis of frequency spectra in the disturbance recordings is performed for this purpose.
- Assessment of the preliminary values of the reference impedances that are defined during the online monitoring. These values can be either confirmed or improved by the definition of new values. The assessment is performed by the analysis of the data in the logfiles that are captured by the logger of the ICT.
- Identification of transients at the change of generator operating conditions. These transients can require a temporary block of the function. The analysis is done on the data in the captured logfiles.
- Identification of eventual mismatches between the active reference impedance and the needed one at the change of generator operating conditions. These mismatches can require a temporary block of the function. The analysis is done on the data in the captured logfiles.
- Identification of eventual operating conditions (e.g., static starter operation during start-up) that require a temporary block of the function. The analysis is done on the data in the captured logfiles.

- The definition of alarm and trip settings of the 100% stator ground fault protection function. The value of these settings is based on site measurements during the monitoring and are fine tuned for the generator and the site conditions. The analysis is done on data that are calculated from the ones in the captured logfiles.

Upon completion of the analysis, the settings of the 100% stator ground fault protection function are updated, and an eventual ancillary logic is added to the relay configuration to perform the eventual temporary blocks of the function.

In case of a power plant with several twin generators, the ancillary logics that are defined for the first generator can typically be used also for the other twin generators.

VIII. Commissioning The Advanced Injection-Based Solution At Long spruce

Commissioning the 100% stator ground fault protection function are the final tests to be performed before the unit can be put into service as the system configuration must meet the following operating conditions:

- Generator is normal offline condition.
- Generator Circuit Breaker is open.
- Excitation Breaker is open.
- All grounding chains are removed, and all earthing switches are open.
- No additional impedances are connected in parallel to the stator circuit.
- All wirings are finalized, and they are the definitive ones.
- All primary and secondary devices are connected and switched on.

The injection unit is switched on at least a half hour prior to starting the calibration to ensure thermal stability of the devices in the injection chain. Disturbance recordings are triggered offline before and after the injection unit is turned on and voltage measurements of the SIT and injecting device are recorded to ensure no wiring or equipment issues.

Once complete, the installation procedure may begin consisting of several checks on both the status of the function and levels of the injected current and voltage. The check of signal levels requires the parameter setting of the *UMaxEF* and is determined in this procedure.

UmaxEF has four setting options: 120, 160, 200 or 240V. The option that is chosen is the next highest setting once Umax is determined which is the max steady voltage on the low voltage side of the SIT.

$$Umax = \frac{U_{\text{g,ph-ph}}}{\sqrt{3} * k_{\text{SIT}}} \text{ (V sec)}$$

For Long Spruce, the following values were used:
$U_{g,ph\text{-}ph}$ = 13.8kV
k_{SIT} = 14.4/0.24kV = 60 (ratio of SIT)

With Umax equal to 133V, a *UmaxEF* setting of 160V is selected.

The calibration procedure is the second activity that is performed by ICT where the calibration of the parameters k1, k2 and the reference impedance are presented. This involves using the ICT to perform measurements in the following configurations to define the above parameters:

- Generator is in an offline configuration with all grounding removed.
- A 500Ω calibration resistance is connected between the generator neutral and ground in the grounding cubicle.
- A dead short is connected between the generator neutral and ground in the grounding cubicle.

Once the continuous measurements in the ICT are complete for each measuring step, the calibration process will then go through a three-check process that are performed on the calculated parameters. This ensures that no errors were made during the calibration process and that the Useful Signal is above the minimum requirement. A failure of not meeting the minimum requirements for the injected voltage and current signals indicates that the function is not able to detect direct faults to earth and further design changes may be required.

After the checks have passed, the monitoring part of the calibration can take place. This is done by applying the known fault resistance and comparing them with the actual function measurement. Disturbance recordings are triggered and analyzed for each fault resistance applied. The error of each fault resistance is calculated to ensure that it is less than 10% which is taken from a dead short up to 10kΩ. The fault resistances applied are typically in steps of a 100Ω from a dead short to a 1kΩ and then in steps of a 1kΩ from a 2kΩ to 10kΩ. This will conclude the offline portion of the testing.

For the online portion commissioning procedure, the generator can be in several operating conditions and the measured stator winding to ground impedance ($Z_{measured}$) can vary between these conditions. Typical operating conditions are:

- Generator at stand still with excitation breaker open and unit breaker open.
- Generator at stand still with excitation breaker closed and unit breaker open.
- Generator start up, not synchronized to the network.
- Generator synchronized and unloaded.
- Generator synchronized and loaded.
- Shutdown.

Logic is implemented in the Long Spruce setting to select different reference impedances in the following operating conditions:

- The first reference impedance (RefZ1) is active when the generator is at standstill with the excitation and unit breaker open. It is expected that RefZ1 is active only after a trip of the generator.
- The second reference impedance (RefZ2) is active during start-up and shutdown when the RMS neutral voltage is higher than 40V, the excitation breaker is closed, and the generator circuit breaker is open.
- The third reference impedance (RefZ3) is active when the generator is synchronized and loaded when the generator is excited, and the generator circuit breaker is closed.
- The fourth reference impedance (RefZ4) is active during start-up and shutdown when the RMS neutral voltage is lower than 40V, the excitation breaker is closed, and the generator circuit breaker is open.

The fourth reference impedance was added to Long Spruce during the commissioning stage as it was discovered the excitation breaker is not opened during a normal shutdown and this configuration more accurately represents the offline operating condition. The 40V threshold used to change between RefZ2 and RefZ4 was determined by field measurements.

ICT log files are started before the unit is synchronized to the system and the online commissioning procedure begins. Disturbance records are triggered with the unit running up with the excitation on and off and when the generator synchronized to the system with the circuit breaker closed. The unit is then run at 75% of full load for an hour. This ensures the unit is at its normal operating temperature before any further disturbance records are taken.

Disturbance records are then taken at increments of -10% (which is every -10MW at Long Spruce) starting at full load and going to no load, as the unit is shut down with circuit breaker and then again one hour after shutdown. Disturbance records are also taken with the injection signal on and off at full load to look at the impact the injection signal has.

The purpose of capturing all the disturbance records and ICT log files is to analyze the following:

- Ensure there are no signals that are interfering with the injected signals.
- Check/define the reference impedances.
- Check the behavior at switches between reference impedance.

- Compare logfiles at standstill before the complete sequence and after the complete sequence.
- Suggest settings for Rtrip, Ralarm and tAlarm.

The analysis of the spectra of the injected signals is shown in Fig. 5 with the generator synchronized at full load with the injection signal on and in Fig. 6 with the injection signal off. The red signal is the injected voltage, and the green signal is the injected current. No interfering signals are present around the 103 Hz injection signal and therefore this injection frequency can be used.

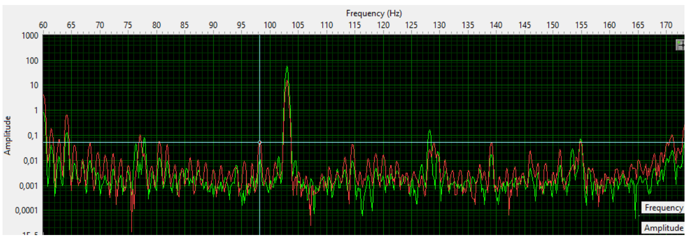


Fig. 5: Frequency Spectra with Injected Signal On

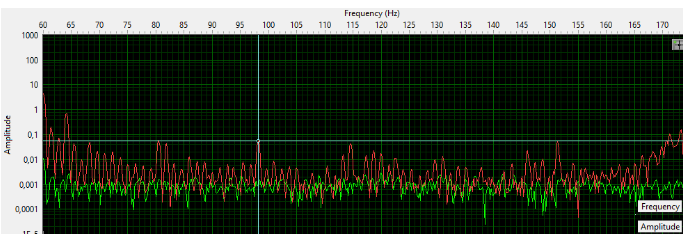


Fig. 6: Frequency Spectra with Injected Signal Off

The reference impedances are also reviewed to ensure they are at their optimal values. One or more candidate values can be calculated for each reference impedance considering the real and imaginary parts of the measured impedances that are recorded in the logfiles. They are the average values of the measurements when the corresponding reference impedance is active. The log files can be exported in a CSV format and are plotted for the analysis.

The selection of the value of each reference impedance is based on the comparison of the performance that is achievable when the resistance to ground is evaluated from the defined reference impedance (that is the value that was defined during the online monitoring) and the candidate values of the reference impedance.

When changing between the reference impedances, a short blocking time of the advanced injection-based stator ground function was added due to transient measurements caused by the transition between two operating conditions. Disturbance records and log files are captured and analyzed to determine how long blocking delay is required. Fig. 7 and Fig. 8 show the real and imaginary parts of the measured impedance (blue) and of the active reference impedance (green). The active reference impedance depends on the operating condition of the generator. The figures show that the measured impedance has a different value in different operating conditions; therefore, different reference impedances are needed to correctly calculate the resistance to ground.

The samples of the real and imaginary parts of the measured impedance before 1800 seconds are related to the standstill and start-up as there are transitions from the first reference impedance (RefZ1) at standstill, to the fourth reference impedance (RefZ4), when the excitation breaker is closed, to the second reference impedance (RefZ2), when the unit is starting up. Between 1800 seconds and 8400 seconds, the generator is online and connected to the system as indicated from the third reference impedance (RefZ3), and after 8400 seconds, the samples correlate to the generator being shut down in the fourth reference impedance (RefZ4).

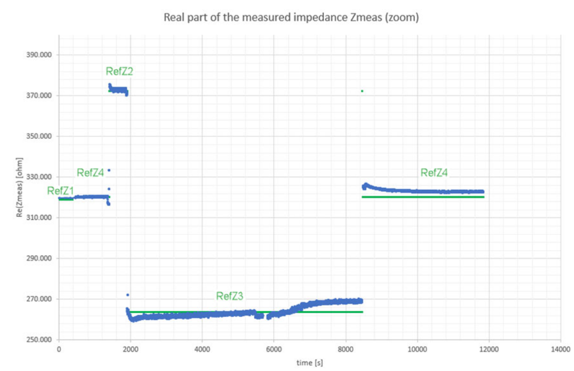


Fig. 7: Real part of the measured impedance

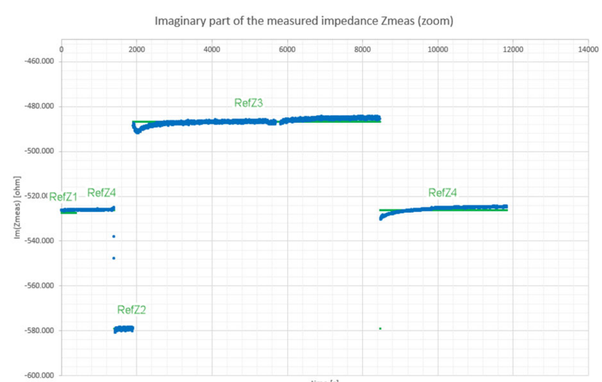
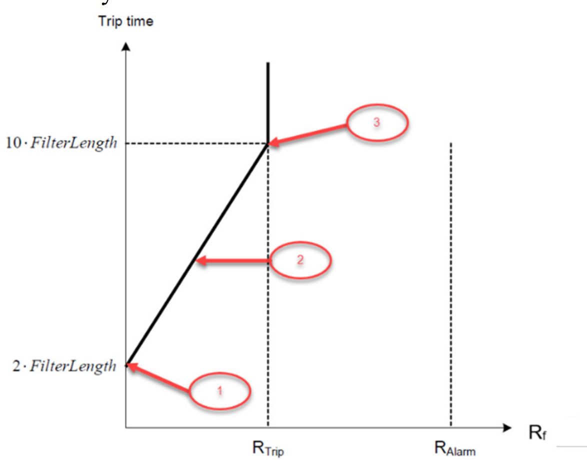


Fig. 8 Imaginary part of the measured impedance

The *FilterLength* parameter is an important setting determined in the analysis from the online data. The filtering calculation does not use a normal Digital Fourier Filter, rather a special filtering algorithm that has the capability to extract accurately a signal with a selected frequency outputting it as the phasor with the highest magnitude within a certain “pass frequency band” around the set injection frequency. Two filter length values can be selected in the function: 1 second or 2 seconds.

If the highest value of the filter length is selected, the filter capability to separate the desired signal from the other disturbing signals is improved. Fig. 5 shows a voltage signal that has a frequency 98 Hz. If the filter length is set to 2 seconds, the pass frequency band around 103 Hz is ±1.8 Hz and the potentially disturbing signal at 98 Hz is filtered out.

The alarm pickup setting for the advanced injection-based stator ground function is to be set lower than 20% of the *FaultNoise Limit* from the minimum R_f values that are calculated from each of the four defined reference impedances. It was determined the minimum *FaultNoise Limit* was 30kΩ corresponding to a maximum setting of 6kΩ for the alarm pickup. An alarm pickup setting of 5kΩ was used. The definite time delay of the alarm is determined to be greater than 10**FilterLength* plus the time of the reference mismatch that can occur when switching between reference points. The alarm was set to a 30 second definite time delay.



1. Trip Time is 2 x 2 = 4 seconds plus a tolerance equal to 1 *FilterLength*.
2. Trip Time is (0.016 x R_f + 4) plus a tolerance equal to 1 *FilterLength*.
3. Trip Time is 2 x 10 = 20 seconds plus a tolerance equal to 1 *FilterLength*.

Fig. 9: Trip time characteristic as a function of fault resistance for Long Spruce

The trip setting is based on all the following:

- Below the mismatch of reference impedance at the reference switch.
- Typically set between 500Ω and 1kΩ.
- Coordination with the alarm setting, the trip setting is to be at maximum 50% below of the alarm setting.
- Below 20% of the Fault Noise Limit.
- Coordination with the neutral ground resistor.

A trip pickup of 1kΩ was selected and the time delay is based on the chart in Fig. 9.

Once all the data has been reviewed and the parameters have been checked and calculated to confirm final settings, they are then applied to the relay and the generator unit is returned to service.

IX. Conclusion

Manitoba Hydro and the vendor went through an extensive and thorough process of evaluating and commissioning an advanced injection-based stator ground protection scheme at Long Spruce to provide 100% coverage of the stator winding. With the challenge of a large total capacitance to ground and a small NGR value, implementing an injection-based protection design with strong signal strength at a frequency above 60 Hz with advanced filtering techniques to properly detect stator ground faults was accomplished. This process has proven to be valuable in gaining confidence on the reliable and correct operation of the overall protection scheme in different operating conditions and ensuring no disturbing signals interfere with the measuring of the injecting signal.

X. Acknowledgments

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XI. References

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XII. Biographies

Kristopher Manchur is a Senior Protection Engineer in the Protection and Control Performance Section at Manitoba Hydro, where he has been employed since 2006. He has 15 years of experience in the application of protective relaying on transmission, generation, and distribution systems, specializing in generation, synchronous condenser, and filter bank protection. Kris received a Bachelor of Science degree in Electrical Engineering from the University of Manitoba and is a registered Professional Engineer in the province of Manitoba.

Gilberto Maioli is a Senior Applications Specialist at Hitachi Energy (formerly ABB) Grid Automation Products in Västerås, Sweden. He received his MS degree in Electrical Engineering with full marks from the University "La Sapienza" of Rome (Italy) in 1994. Since 1995 he has been working in the area of power system protection and control within ABB, joining initially the R&D department and then covering several roles in the Engineering department of ABB Power System Division (formerly ABB Muratori), reaching the position of Senior Project Leader.
In 2010 he moved to Sweden, joining the Technical Application Department of ABB GA Products, specializing in synchronous machine protection. He is a Cigré and AEIT member.