Injection based 100% stator earth fault protection in REG670

1 Introduction

Earth faults in the stator winding are the most common faults in a synchronous generator [1, 2]. Such faults may cause severe damage and long outage time, therefore measures are taken to detect such faults and to limit the consequences, should they appear. The neutral point grounding method is an important example in the latter category; an appropriate impedance to ground will limit circulating currents from a single phase to ground fault. However, if more than one ground fault appear, strong currents will circulate and as a consequence the stator iron will be severely damaged. Thus it can be concluded that high impedance grounding only prevent machine damage for the first ground fault. For any consecutive ground fault machine iron will be compromised. Therefore for large machine it is of outmost importance to detect the first ground fault even if it is located at the star point of the machine!

To detect stator ground faults, the basic method is to measure the voltage or current at the neutral point. If the fault occurs in a sufficiently stressed region, an increased neutral point voltage and current will appear. Therefore, these methods cannot find an earth fault close to the neutral point. They are thus referred to as “95% ground fault protection” as they typically cover 95% of the stator winding, dependent on the settings. Further, they can only be active when the machine is excited.

Even though a ground fault close to the neutral point may not cause any direct harm, it is a serious threat if a second ground fault appears and their detection is therefore important. A possibility to detect faults in the entire winding is to compare the amplitude of the 3rd harmonic at the terminals to the neutral point [1]. If no ground fault is present, the 3rd harmonic amplitude at terminals and neutral point should be equal in amplitude but opposite in sign. Deviations from this condition are an indication of a ground fault. As this method is dependent on the voltage generated by the machine, it can only be active when machine is excited.

It is often considered valuable to be aware of ground faults before energizing the machine; therefore other methods must be found. Obviously, such methods must provide their own test signal and can therefore be active at all times, even at standstill. To inject a test signal into the machine, some provisions in the primary circuit are usually required. Therefore, these injection-based methods tend to be rather costly and are usually only considered for the biggest machines. Some examples of such methods can be found in [1, 2] while [3] gives a very condensed history of stator ground fault protection...
with many illustrations on various variants. In this document, an injection-based method that does not need any modification of the primary stator circuit and therefore may find use in a wider range of generators will be described.

The focus of this document will be on the measurement principles of the injection based 100% stator earth fault protection in REG670. In contrast to many of the presently used methods, this method gives an estimate of the present stator impedance to ground in Ohms and consequently determines the existence of a ground fault in the stator winding.

2 Properties of previous injection-based methods

All previously existing stator ground fault detection methods [3] are dependent on the grounding scheme of the generator. Quite a number of grounding scheme variants is used, as shown in Figure 1.

All previous injection schemes use a low frequency signal with fixed frequency (e.g. in range from 10Hz up to 25Hz) as an injection signal [3]. Such a frequency is used in order to easily suppress interfering signals with power system frequency and/or its harmonics (e.g. 3rd harmonic commonly present in the machine star point). Under healthy conditions, the amplitude of the voltage signal with the nominal frequency at the neutral point is very low. The neutral point voltage is mostly dominated by the third harmonic which can be up to several percent of the machine nominal voltage.

A standard Digital Fourier Filter will suppress exact harmonics of the frequency being extracted, however all other frequencies will influence the measured signal. Thus by choosing an injection frequency as sub-harmonic to the power system rated frequency (e.g. 12.5Hz in 50Hz system), the signals having power system frequency and/or its harmonics (e.g. 3rd) will be completely suppressed by this filter. If the power frequency deviates from the nominal one, this suppression will however be less effective and there is a
risk for unwanted operation. This may happen when the machine is not synchronized. Therefore, many present solutions incorporate an additional low-pass filter (hardware) to further suppress the power frequency and its harmonics which increase complexity and cost of the installation. A second motivation for a low injection frequency is to reduce the relative portion of the capacitive current so that a resistive current from a ground fault is easier to detect. Under normal conditions, there is mainly a capacitive current to ground from the stator. The capacitive current limits the fault detection sensitivity for those systems that only measure the current magnitude and not the current phasor. This is particularly important in large machines, typically large hydro generators, which may have several µF in capacitance to ground. By reading only the current magnitude, it is difficult to detect resistive faults that are a few times larger than the capacitive impedance.

Most previous injection-based systems recommend injection through a dedicated neutral grounding transformer (NGT), as shown in Figure 2b, or directly in the primary circuit, as shown in Figure 2a. Almost all of them required special arrangements or splitting for the neutral grounding resistor (NGR).

![Typical connections for previous injection scheme](image)

Figure 2: Typical connections for previous injection scheme

The main reason is that low frequency signal has a problem to propagate through a transformer due to its internal reactance. Most transformers used in the power system are designed for 50Hz or 60Hz and perform poorly at lower frequencies. Note that for low frequencies, the transformer magnetizing current is also increased comparing to 50Hz value. As this magnetizing current is also a part of the total injected current and consequently measured by the relay it will also influence the maximum achievable relay sensitivity. To illustrate this, consider Figure 3, which shows the no-load input admittance, (one can understand this as magnetizing current in relation to the applied voltage), for a small distribution transformer of a similar type as could be used as a neutral grounding transformer. For low frequencies, the no-load current is increasing dramatically. As the no-load current is measured together with the injected current, this will give an error in the fault resistance estimation if it is not properly handled. Note that the no-load admittance shown in Figure 3 is valid for one specific transformer only. Other transformers may have steeper or flatter slope, depending on their construction. It thus seems that, to
use low-frequency injection through a transformer can be problematic and sensitivity on actual site definitely depends on the properties of the used grounding transformer!

Due to above described problems, it is common to recommend trip settings of such injection protections around 1 kΩ and alarm settings of 5 kΩ by the relay manufacturers.

![Figure 3: No-load input admittance as a function of frequency for a 20 kVA 5 kV/220 V distribution transformer. Three different voltage levels are applied on the low-voltage side, ranging from 3 V (red) to 18 V (green). Note the strong increase of admittance at low frequencies and low voltage levels.](image)

3 Properties of injection principle used in REG670

The basic philosophy behind this injection-based method is to use primary equipment already present in the installation as much as possible. Especially avoiding custom made high-voltage components which would be costly to apply was a main development goal. Additionally it shall be possible to inject across the whole NGR without any need for splitting. Finally, for stator injection it shall be possible to inject both via the grounding transformer or voltage transformer, as shown in Figure 4.

![Figure 4: Typical injection point with REX060 injection unit](image)

a) Injection via VT  

b) Injection via NGT
To enable the use of a voltage or a grounding transformer for injection, it is important to keep their internal reactance in mind. As already stated transformers used in the power system are designed for 50Hz or 60Hz signals and perform poorly at lower frequencies. Thus, it would be attractive to use an injection frequency close to, but slightly higher than the power system nominal frequency. Such a solution would have benefits hardware-wise, but it becomes more difficult to use the Digital Fourier Filter typically used in numerical protection relays today, as such a filter will have problems to reject the nominal power system frequency and its harmonics. Thus, another filtering method must be deployed. Using long filtering windows (e.g. 1s) and modern numerical filtering techniques such as interpolated Fast Fourier Transformation (FFT) it is possible to achieve suppression for all signals with frequency outside a ±5Hz range around the injected frequency. In addition to the complex amplitude of the injected signal also an accurate estimate of the frequency of the injected signal is obtained in such filtering process. This additional information can be used to supervise the injection protection and prevent possible problems during machine start-up and shut-down. With such interpolated FFT methods, it is also possible to select any frequency to be extracted and therefore the injected frequency can be made settable. There is a relatively large freedom to select the injection frequency but frequencies within range to known disturbances and their harmonics should be avoided (e.g. 16.67Hz used for railway supply in Sweden). Typically, an 87Hz injection signal is used in a 50Hz power system [4].

The principal connection diagram of this injection method for the stator is shown in Figure 5. An oscillator generates a voltage signal which is fed to a transformer connected to the machine star point. Voltage and current signals into this transformer are measured and the corresponding phasors at the injection frequency are extracted by help of the above mentioned filter. Note that the voltage must be measured at the injection point in order to minimize the effect of the cable length on the injection equipment. Now the ratio of the injected voltage and current phasors give a complex impedance, which in the following text will be called the bare impedance (i.e. \( Z_b = \frac{U_{inj}}{I_{inj}} \)), which is also shown in Figure 5.

![Figure 5: Principle connection for REG670 stator injection](image_url)
3.1 Stator impedance measurement principle in REG670

In order to provide stator earth fault protection the ratio of the measured voltage and current (i.e. the bare impedance) must be converted by the REG670 to the actual impedance of the stator winding to ground. To do that one need to provide corrections for:

1) All amplifications in the measured chain (i.e. ratio of the neutral transformer, but as well for ratios of all internal transformers in REX060 and REG670 as well as selected amplifier gains for voltage and current in injection unit REX060). Note that the current is also measured as a voltage across the shunt. Thus even this current-to-voltage conversion factor must be accounted for.

2) All series impedances between the voltage measurement point and the stator primary circuit. In actual installation the largest part of it would be the series impedance of the neutral grounding transformer or of the voltage transformer which is used to inject the signal into the stator winding. Typically this value is not known at all.

It can be shown that it is possible to compensate for all of the above influences by using the following complex transformation in order to obtain the wanted stator impedance to ground (i.e the measured impedance) $Z_m$ from the bare impedance $Z_b$:

$$Z_m = k_1Z_b + k_2$$

In the above equation the complex factor $k_1$ (i.e. unit-less gain) will compensate for all amplifications in the injection protection installation (see point 1 in the above list). At the same time the complex additive $k_2$ (i.e. impedance in ohms) will compensate for all series impedances in the installation (see points 2 in the above list).

Note that the injection voltage is measured at the injection point. This is done in order to minimize the influence of the actual cable length onto the whole measurement chain. This must be done because the impedance seen at the injection point by the injection equipment is always very small (typically in order of couple of Ohm or even smaller)! This is easiest to understand by looking into Figure 4b. Here the impedance seen by the injection equipment is always less than the value of the neutral grounding resistor (NGR). Typical values for the NGR are below one ohm! Note that the fault resistance will be seen as a parallel connection to this already quite low impedance. Thus a very accurate correction is needed in order to obtain a sensitive stator earth fault protection!

Practically is impossible to calculate by hand the values for the $k_1$ and $k_2$ factors with required precision for a specific installation in advance. There are too many constituents in the whole injection measurement chain which can influence these values. At the same time for some of these constituents all properties are not readily available. At the same time but simplifications in this calculation are allowed due to protection sensitivity requirements. Therefore $k_1$ and $k_2$ values shall be only obtained on site during commissioning of the whole injection system. See next chapter for more information about that.

Finally let us define a reference impedance, $Z_{ref}$, which represents the measured impedance of the healthy stator winding to ground without any fault present. If this value is known it is possible to estimate the ground fault resistance, $R_f$, which can occur in parallel to the reference impedance. The parallel connection formula is used but only the real part of it is taken into account as follows:

$$\frac{1}{R_f} = \text{Real} \left[ \frac{1}{Z_m} - \frac{1}{Z_{ref}} \right]$$
Note that by taking only the real part of the above equation, influence of possible changes in capacitance due to applied excitation to the rotor or existence of the generator breaker is eliminated.

Note as well that the measured impedance is always given as a series impedance (i.e. $R_m + jX_m$) in REG670. For a human being it may be easier to convert it into equivalent parallel circuit consisting of a resistance and reactance (i.e. capacitance to ground). This can be easily done by using the following two equations:

$$R_{m,\text{parallel}} = \frac{1}{\text{Re}[1/Z_m]}$$

$$C_{m,\text{parallel}} = \frac{\text{Im}[1/Z_m]}{2\pi f_{\text{inj}}}$$

where $f_{\text{inj}}$ is the injection frequency. Note that the above conversion is not performed by the REG670. If required such calculations shall be performed by hand.

### 3.2 Commissioning procedure

It was noted above that the parameters of the transformation from the bare impedance to the measured impedance cannot easily be determined beforehand. Moreover, for a sensitive detection of ground faults, a precise value of the reference impedance $Z_{\text{ref}}$, and $k_1$ & $k_2$ factors are absolutely needed. The determination of these parameters thus calls for measurements on site during commissioning and the most exact and practical method is indeed to use the full injection system itself to perform these measurements.

For these reasons, an Injection Commissioning Tool (ICT) was conceived, which is a computer tool that communicates with the REG670, reading measurement values and setting parameters. The human interface guides the commissioning engineer through the required calibration measurements and calculates the resulting parameters which then may be downloaded into the REG670.

To determine $k_1$, $k_2$ and $Z_{\text{ref}}$ the following three measurement are required during commissioning at machine standstill:

1. The healthy generator impedance to ground (i.e. without any fault resistance). This measurement should give us $Z_{\text{ref}}$ as measured impedance.
2. The generator with a known fault resistance, $R_f$ to ground. This measurement should give us value of $Z_{\text{ref}}$ in parallel with known $R_f$ as measured impedance.
3. The generator with a solid ground fault ($R_f=0$). This measurement should give us zero value for measured impedance.

Thus the following three equation can be written during calibration procedure:

$$k_1Z_{\text{b1}} + k_2 = Z_{\text{ref}}$$
Note that the bare impedance under these three calibration tests (i.e. $Z_{b1}$, $Z_{b2}$ and $Z_{b3}$ in the above three equations) are determined in the ICT by actually using the measured quantities directly from the 100% stator earth fault protection function in REG670. Once these three bare impedances are known, three equations with three unknown are obtained. From them $k_1$, $k_2$ and $Z_{ref}$ can be solved for. These values are unique to every installation.

In addition to this important functionality, ICT performs a number of other useful tasks. It monitors the measurement results under every test in order to check for existing noise in the installation. Further there are a number of checks performed during the calibration process before the three equations are solved, which are intended to certify that the present installation will have a proper performance. For example, if the calibration is performed while the safety grounding of the stator winding is accidentally applied, this erroneous condition will be detected by the ICT Tool and the corresponding $k_1$, $k_2$ and $Z_{ref}$ values will be rejected. Finally, ICT can also be used to derive additional reference impedances if needed for a specific installation.

### 3.3 Checking the $k_1$, $k_2$ and $Z_{ref}$ values obtained from ICT Tool

Once the calibration is finished and these three calculated values from ICT are stored in the REG670 they can be verified by using the following simple procedure. A number of known resistances can be introduced (i.e. applied) in the machine star point or even in one phase on the HV side of the synchronous machine. For every of these applied resistances the measured $R_f$ value from the 100% stator earth fault function shall be recorded. After that a graf $R_f=f$(Applied Resistance) can be created, for an example see Figure 6. Ideally it shall be a straight line with 45° slope.

Note that for a large applied resistance value it may take some time to display the final $R_f$ value in REG670 built-in HMI or ICT Tool. The reason behind this is that the values shown in these two places are the averaged measurement values over certain time period. This is done in order to provide stable measurement to the “outside world”. Internally within the protection function itself more or less instantaneous measurements are used in order to get quick reaction of REG670.

Example from two actual installation on two different machines are given in Figure 6. These machines had the following ratings.

1. The rotor injection on a 75 MVA, 11 kV, turbo generator,
2. The stator injection for the same turbo generator injecting through a terminal open-delta voltage transformer
3. The stator injection of a 315 MVA, 11 kV, hydro generator/motor injecting through a neutral grounding transformer

Note that Figure 6 includes the rotor injection for the first machine as well. This is shown here in order to demonstrate that the same approach can be used even for rotor injection in REG670.
Figure 6: Comparison of measured ground fault resistance to the introduced (applied) resistance to ground for three different injection systems. The turbo machine rotor is shown in orange and the stator in blue while the red dots show the result for the hydro machine stator. The green line indicates the ideal result.

4 Conclusion

In this document the measurement principles of the 100% stator earth fault protection function (STTIPHIZ) in REG670 are explained [4]. By using this function together with standard 95% stator earth fault protection complete coverage of the machine stator winding under all operating conditions is obtained.

5 References