YRKESHÖGSKOLAN NOVIA

100% Stator Earth Fault Protection for Multiple Synchronous Generators Operating in Parallel

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DEGREE THESIS

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Abstract

The thesis is a study and an investigation of 100% stator earth fault protection for generators in engine power plants with different configurations and multiple generators operating in parallel. The thesis also gives an overview of the necessary background knowledge about the engine power plants and their protection system, which is required to complete this study.

100% stator earth fault protection has become a frequent requirement from customers. This is important for protecting the expensive generators against all types of earth faults. Two principles for achieving 100% stator earth fault protection have been considered in this thesis, third harmonic-based and injection-based stator earth fault protection. The standard solutions available, as of making the thesis, recommended by the relay manufacturers have been showcased. More advanced and tailored solutions are also discussed in this thesis.

Improvements to the third harmonic-based stator earth fault protection have been investigated. In cooperation with protection relay manufacturers, measurement data necessary for the investigation has been gathered from different power plant installations.

The research has been made using literature regarding the topic, technical guidance documents from experts and mentor, discussions with protection relay manufacturers, and the gathered data from different power plants. Challenging situations for the third harmonic stator earth fault protection have been presented in the results. Based on the research the solution for 100% stator earth fault protection most reasonable for multiple generators operating in parallel on the same bus has been discussed.

Language: English
Key Words: 100% stator earth fault protection, Third harmonic stator earth fault protection, Low-frequency injection, 64S, 64TN, Engine power plant

EXAMENSARBETE

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Titel: 100% stator jordfelsskydd för flera synkrona generatorer som körs parallellt

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Abstrakt

Examensarbetet är en studie och en underökning av 100% stator jordfelsskydd för generatorer i motorkraftverk med olika konfigurationer och flera parallellt körande generatorer. Examensarbetet innehåller en överblick av nödvändig bakgrundsfakta om motorkraftverken och deras skyddssystem, vilket är väsentligt för att utföra denna studie.

100% stator jordfelsskydd har blivit ett vanligt förekommande krav från kunder. Det är viktigt för att skydda dyra generatorer mot alla typer av jordfel. Två principer för att uppnå 100% stator jordfelsskydd har beaktats i detta examensarbete, tredje övertonsbaserat och injektionsbaserat jordfelsskydd för statorn. Standardlösningar rekommenderade av relätillverkarna tillgängliga vid skapandet av detta examensarbete har presenterats. Mer avancerade och skräddarsydda lösningar har också diskuterats i examensarbetet.

Förbättringar för det tredje övertonsbaserade stator jordfelsskyddet har undersökts. I samarbete med skyddsrelätillverkare har mätningar och data, nödvändiga för undersökningen samlats in från olika kraftverksinstallationer.

Forskningen har utförts med hjälp av litteratur inom området, tekniska vägledningsdokument från experter och mentorn, diskussioner med skyddsrelätillverkare och den insamlade datan från olika kraftverk. Utmanande situationer för det tredje övertonsbaserade stator jordfelsskyddet har presenterats i resultaten. Baserat på forskningen har den lösningen för 100% stator jordfelsskydd rimligast för flera generatorer som körs parallellt på samma buss diskuterats.

Språk: engelska
Nyckelord: 100% stator jordfelsskydd, tredje övertonsbaserat stator jordfelsskydd, låg frekvens injektion, 64S, 64TN, motorkraftverk

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Nimike: 100% staattorin maasulkusuojaus useille rinnakkain toimiville synkronisille generaattoreille

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Tiivistelmä

Opinnäytetyö kattaa tutkimuksen ja selvityksen 100%:n staattorin maasulkusuojauksesta generaattoreille eri kokoonpanoissa ja useissa rinnakkain toimivissa generaattoreissa. Lisäksi opinnäytetyössä dokumentoidaan tämän tutkimuksen suorittamiseen tarvittavat taustatiedot moottorivoimaloista ja niiden suojajärjestelmistä.

100%:n staattorin maasulkusuojauksesta on tullut asiakkaiden toistuva vaatimus, mikä on tärkeää kalliiden generaattoreiden suojaamiseksi kaikenlaisilta maasuluilta. Tässä opinnäytetyössä on tarkasteltu kahta periaatetta 100%:n staattorin maasulkusuojauksen saavuttamiseksi, jotka ovat kolmas harmoninen ja injektiopohjainen staattorin maasulkusuojaus. Tämän opinnäytetyön luomiseen käytettävissä olevat standardiratkaisut, joita relevalmistajat suosittelevat, on esitetty. Tässä opinnäytetyössä käsitellään myös edistyneempiä ja räätälöityjä ratkaisuja.

Kolmannen harmonisen staattorin maasulkusuojauksen parannuksia on tutkittu. Eri monimoottorisista voimalaitosasennuksista on kerätty yhteistyössä suojarelevalmistajien kanssa tutkimukseen tarvittavat mittaustiedot.

Tutkimuksessa on käytetty kirjoja, tekniset ohjeet asiantuntijoilta ja mentorilta, aiheeseen liittyviä teknisiä artikkeleita, keskusteluja suojarelevalmistajien kanssa sekä eri voimalaitoksista kerättyä tietoa. Tuloksissa on esitetty tilanteita, joissa kolmannen harmonisen staattorin maasulkusuojaus on haastavaa. Tutkimuksen perusteella on käsitelty 100%:n staattorin maasulkusuojauksen ratkaisua, joka on järkevin useille rinnakkain toimiville generaattoreille samalla virtakiskolla..

Kieli: Englanti
Avainsanat: 100%:n staattorin maasulkusuojaus, Kolmannen harmonisen staattorin maasulkusuojaus, Matala taajuus injektio, 64S, 64TN, Moottorin voimalaitos

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1 Preface

Before getting into the thesis work, I would like to thank a few persons who have provided invaluable support during the making of this thesis. First and foremost, I want to thank all colleagues involved for their excellent cooperation during the thesis. I also want to thank my supervisors Joachim Böling at Novia and Srinivasa Raju Addala. Without your tips and ideas, the thesis would not have turned out as good as it is now. And lastly a special thank you to all suppliers that have been involved in the process and for all the valuable discussions we have had together.

2 Introduction

This thesis will investigate different methods for implementing 100% stator earth fault protection for generators in power plants. 100% stator earth fault protection is becoming a requirement from more and more customers in the power plant business. 100% stator earth fault protection means, as the name suggests, that the whole stator winding is protected from the generator terminal to the neutral point. It is however important to understand that even though the whole stator winding is protected, that is not the same thing as a 100% guarantee of no damage and need of repairs. The idea of 100% stator earth fault protection is that an earth fault will be detected no matter where along the winding it occurs. The task of the protection is then to minimize the damage. Several other protections are also used simultaneously to protect the generator from other common faults and abnormal operating conditions. 100% stator earth fault protection at power plants are implemented using protection relays.

In this thesis work solutions for 100% stator earth fault protection available today will be mapped and compared. The necessary background knowledge required for investigating this topic is also provided in the early parts of this thesis. Frequently occurring problems with the existing 100% stator earth fault protections will also be discussed. This thesis work will also cover the process of coordinating and gathering all necessary measurements from different power plants which the relay manufacturers would require to evaluate possible improvements to their existing 100% stator earth fault protections.

3 Background

The thesis work focus on power plants which generate electricity with generators driven by internal combustion engine technology. There are usually several engines and generators in these power plants. Different generator types are used, with the selection of generators based on various factors. Factors considered are, for example, engine type, grid codes specific requirements to the connected network, power plant size, and the type of operation.

The availability of electricity production is essential for the power plant operations. It is crucial to keep the generators in an operational state for as long as possible without posing any risks to personnel or damaging the equipment. One part of achieving this is to implement 100% stator earth fault protection. Problems related to the stator are frequently related to earth faults. The reasons for an earth fault to occur can however be many. An earth fault near or at the neutral point in a high-resistance grounded generator is rare and does not necessarily lead to any major immediate damage to the system. However, the earth fault has practically made the generator solidly grounded, which means earth fault currents are no longer limited by the grounding resistor and a second earth fault in the stator winding would be disastrous (Schneider Electric, 2020).

3.1 Working principle of generators

The working principle of the generator is based on Faraday’s law of electromagnetic induction. Faraday’s law is complemented with Lenz’s law which describes the direction of the induced current.

- Faraday’s law states that the value of electromotive force (emf) produced in a circuit or conductor is directly proportional to the rate of change of magnetic flux linking with it (Robertson, 2008a).

- Lenz’s law states that an induced electric current flows in a direction such that the current opposes the change that induced it (Robertson, 2008a).

This can be described with an example of a magnet moving past a coil of wire. The coil will be induced with voltage. It is however not mandatory for the magnet to move. The relative movement between the coil and the magnetic flux determines the voltage induced in the coil. It is therefore possible to move either the coil and keep the magnetic field static or keep the coil static and move the magnetic field. In generators, it is more practical to move the magnetic field and keep the coils static. (Robertson, 2008a).

For the generator to generate electrical output current, it needs two types of inputs. Mechanical input on the rotor shaft to turn the rotor, and electrical DC from the excitation system to magnetize the rotor winding. (Robertson, 2008b).

3.2 Active parts in generators

To protect the generator properly it is important to first understand the purpose of the generator components. The active parts in the generator are the crucial components for producing electricity. They are the stator, rotor, and excitation system. If any of these components fail, the generator can not produce electricity. A typical generator configuration with brushless excitation is shown in Figure 1.

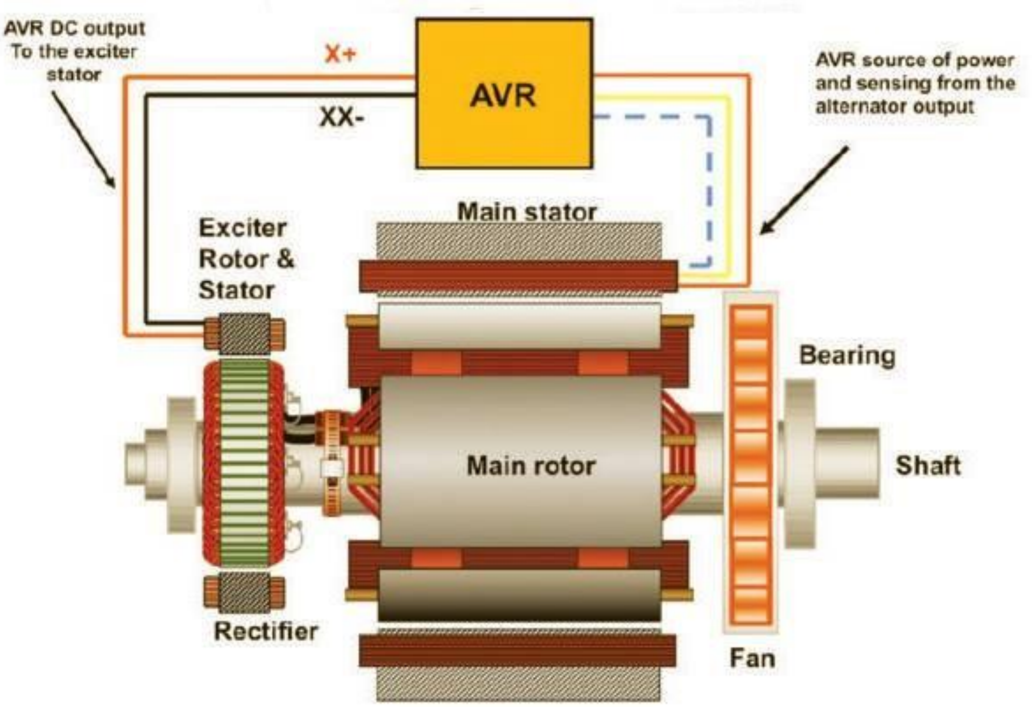


Figure 1. Typical generator with brushless excitation. (Sharma, 2022).

3.2.1 The stator

The stator consists of the stationary windings in a generator. It is insulated copper wire that is turned around a laminated iron core. The stator consists of three different windings, one for each phase. With the rotating magnetic field on the rotor, voltage is induced in the stationary stator windings due to the change in flux linkage according to Faraday's law. (Hewitson, Brown, & Balakrishnan, 2004).

The stator can be constructed with different winding pitches, normally 2/3 or 5/6. The winding pitch of the generator states how many slots each coil spans, divided by the number of slots per pole. A generator having 48 stator slots and 4 poles has 12 slots per pole. If each coil spans 10 slots, then the winding pitch is 10/12 same as 5/6. (ABB, 2019).

The stator needs to be monitored and protected against overcurrent, overvoltage, undervoltage, unbalanced currents, earth faults, abnormal frequency, and thermal overloading. In systems with more than one generator, protection from reverse power is also needed. The reverse power protection mainly protects the engine, it is however monitored at the generator and disconnects the generator when tripping. (Technical guidance document from experts and mentor, 2020).

Overcurrent results in heating of the insulation which in turn damages the insulation as well as the wires and will result in short circuits in long-term operations. (Technical guidance document from experts and mentor, 2020).

Generators are manufactured to operate according to the operational range described in the IEC60034-1 standard. A few percent of **overvoltage** is not catastrophic for the generator but it is not recommended to operate a generator continuously with overvoltage (Technical guidance document from experts and mentor, 2020). **Undervoltage** is not necessarily harmful to the generator. The equipment connected to the power system will however need more current to reach the same power if the voltage is lower. This may lead to overheating. (ABB Distribution Solutions, 2020).

Earth faults are a result of insulation failure between a phase and grounded parts. This leads to current leaking from the circuit and flowing to earth. Unattended interturn, interbranch, and phase-to-phase faults during the preventive maintenance and lack of adequate measures may develop into earth faults. (Chowdhury, Finney, Fischer, & Young, 2019).

Frequency is monitored because it is proportional to the speed of the generator. The speed does in turn correlate to the cooling of the generator. Underfrequency results in less cooling airflow due to slow rotating speed. Over-frequency results in increased mechanical forces on the rotor due to higher rotation speed, as a result of overspeed from the engine. (Technical guidance document from experts and mentor, 2021).

Thermal overload means that the generator is operating at a higher temperature than it is designed for. Measuring the thermal level can detect a temperature rise even when conventional overcurrent protection is not able to. Poor ventilation is one example. (ABB Distribution Solutions, 2020).

3.2.2 The rotor

The rotor consists of insulated copper wire turned around several poles. The rotor winding is supplied with DC to act as an electromagnet. This will result in electricity production when the rotor turns past the stator poles. (Robertson, 2008b).

Rotors can have different numbers of poles. The number of poles must be calculated to achieve the desired frequency. The frequency can be described with equation 1.

$$f = \frac{n \cdot p}{120} \qquad (1)$$

Where:
f is the frequency.
n is rpm.
p is the number of poles.

This equation indicates that for a given frequency, a lower rotor speed requires a greater number of poles. (Robertson, 2008b).

The rotor needs protection from earth faults, under excitation, and unbalanced currents in the stator (Technical guidance document from experts and mentor, 2020).

Earth faults in the rotor can cause parts of the rotor winding to be shorted out. This can lead to overcurrent in the conductors damaging the rotor. The magnetic field may also be misshaped resulting in vibrations in the generator. (Hewitson, Brown, & Balakrishnan, 2004).

Under excitation may lead to the generator losing synchronism. This can make the generator start behaving like an induction machine which leads to higher consumption of reactive power. High reactive power in the system causes instability in the network and stress on the prime mover. (ABB Distribution Solutions, 2020).

Unbalanced currents in the stator can occur when the loads are unbalanced or there are open conductors in the system. Unbalanced currents will result in double-frequency currents being induced in the rotor, which leads to overheating. (Technical guidance document from experts and mentor, 2020).

3.2.3 Excitation system

The task of the excitation system is to magnetize the field winding on the rotor. In theory, a DC is supplied to the rotor winding to generate a magnetic field. As the rotor turns the magnetic field follows. (Robertson, 2008b).

There are mainly two methods for supplying the rotor with DC.

- Static excitation systems, supply the DC with the use of carbon brushes and slip rings on the rotor axis.
- Brushless excitation systems, use an exciter and rectifier (Diode bridge for AC/DC conversion) mounted on the rotor axis to supply the DC through induction.

In most combustion engine power plants brushless excitation is currently used. The brushless excitation system requires far less maintenance than the static excitation system which requires regular replacement of the brushes.

The automatic voltage regulator (AVR) controls the output of the generator. This is done by adjusting the current that is fed to the rotor field winding. Whenever there is a change in load for the generator the AVR must rapidly adjust the field winding current to prevent over- or undervoltage in the system. The AVR has built-in features like a V/Hz limiter as well as an under- and over-excitation limiter. The AVR is also responsible for sharing reactive power with paralleled generators. (Technical guidance document from experts and mentor, 2021).

4 Protection

The task of the protection is to protect the equipment in the power plant as well as personnel. The protection is however not a guarantee that no maintenance or repair will be needed. Some protection principles are only able to detect and minimize damage after it has occurred.

When selecting protections for the equipment it is important to anticipate all potential failures and then choose suitable protective measures for each scenario. It is crucial to minimize the shutdown of the power plant sections to only those necessary in the event of a fault. Given the power plant's crucial role in numerous operations, the ability to sustain power generation, even with certain sections disconnected is highly desirable. Avoiding unnecessary tripping is equally important. (Hewitson, Brown, & Balakrishnan, 2004).

Protection relays are used to monitor the system and give instructions according to what fault has been detected based on the chosen settings. The protection relay is the brain of the protection system, but it needs instrument transformers to provide readable input data. (Hewitson, Brown, & Balakrishnan, 2004).

4.1 Measuring instruments

As mentioned in the previous chapter, for the protection relay to protect the system it needs readable measurements from the system provided by the instrument transformers. The measured currents may vary between a few amperes in smaller systems, and up to thousands of amperes in large power plants. The voltage level follows a similar principle. It can vary between a few hundred volts up to several kilovolts. Because of the very wide span of values that must be monitored, it is not sufficient to manufacture relays that can measure all values imaginable. Instead, current transformers and voltage transformers are used. They are referred to as instrument transformers. Their job is to transform the measured current and voltage levels respectively, to readable values for the protection relay. Additionally, the instrument transformers keep the relays insulated from the primary high voltage in the system. (Hewitson, Brown, & Balakrishnan, 2004).

4.1.1 Voltage Transformer

A voltage transformer (VT) consists of a primary and a secondary winding which are magnetically connected through mutual induction via an iron core. Voltage transformers have their primary winding connected in parallel to the source that needs to be measured. The circuit of the secondary winding is connected to the metering and protection equipment. The secondary circuit is designed for minimum current to be drawn from the source. It will still be induced with a voltage due to it being connected by the iron core. (Hewitson, Brown, & Balakrishnan, 2004).

The turn ratio between the primary and secondary winding decides the voltage level induced in the secondary open circuit winding, which the relay is then able to read. (Hewitson, Brown, & Balakrishnan, 2004). Voltage measuring of three-phase systems can mainly be done in two ways. For basic protection and measuring two VTs can be used in a "V-connection", as seen in Figure 2. Three individual voltage transformers are required in applications where phase-to-ground voltages are required. When U_0 needs to be measured three VTs must be used in a star connection on the primary side, see Figure 3. (Technical guidance document from experts and mentor, 2015).

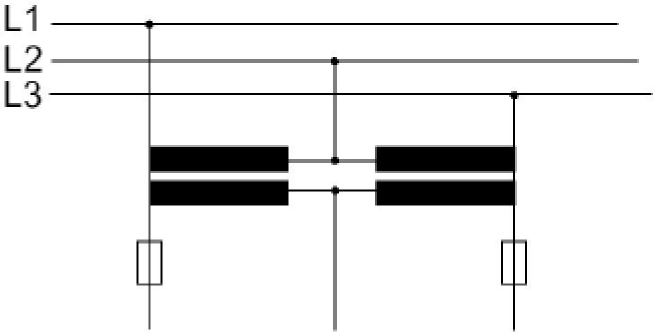


Figure 2. Voltage transformer V-connection. (Technical guidance document from experts and mentor, 2015).

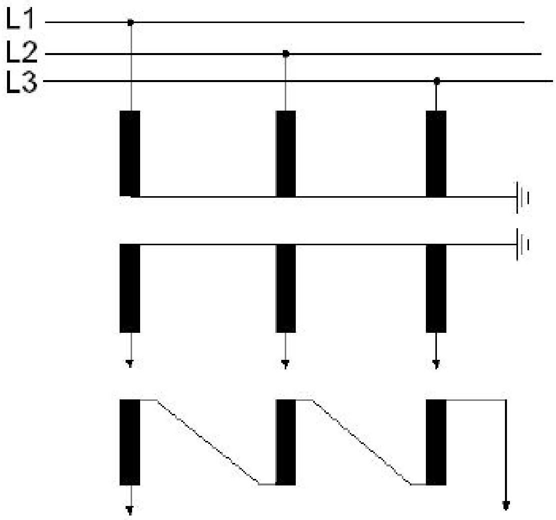


Figure 3. VT star connection for measuring U_0. (Technical guidance document from experts and mentor, 2015).

The voltage transformers for protection use must be capable of handling the primary voltage and frequency of the system. The voltage factor must also be considered. The voltage factor describes how well the VT can withstand overvoltage. It is a value between 1,2 and 1,9. Chosen depending on the earthing method and if they are intended for continuous or time-limited operations. The type of earth fault protection, tripping type or alarm type only, should also be considered. Voltage transformers for protection use have an accuracy class of 3P or 6P. The first digit in the accuracy class indicates the maximum percent error that is allowed for the voltage measurement. The percent error is not allowed to exceed the value in the accuracy class while measuring a voltage level ranging from 5% nominal voltage, up to nominal voltage times the voltage factor with a burden ranging from 25% to 100% rated burden. All this is tested with a power factor of 0,8. See Figure 4 for a typical VT rating. (International Electrotechnical Commission, 2003; Technical guidance document from experts and mentor, 2015).

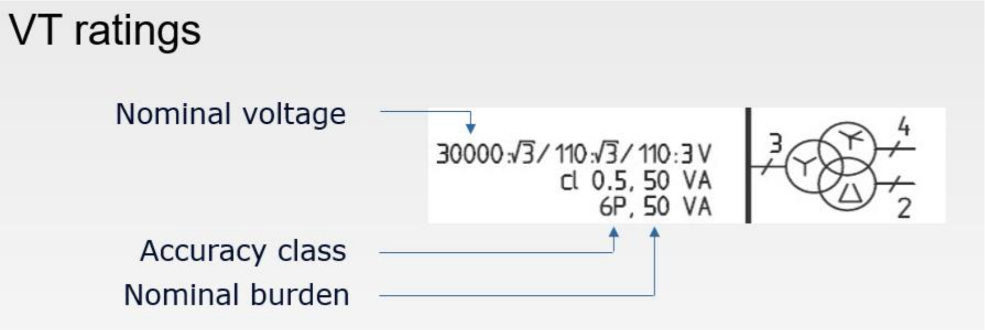


Figure 4. Typical VT rating. (Technical guidance document from experts and mentor, 2015).

4.1.2 Current Transformer

The CTs are mainly installed at the busbar or at the bushings, where the busbar itself acts as the primary and secondary winding over it. The fundamental working principle of the current transformer (CT) is however similar to the voltage transformer. They both consist of a primary winding and a secondary winding magnetically connected via an iron core. The main difference is that the secondary winding has a closed circuit to allow current to flow. The primary winding is connected in series with the main circuit. A current is then induced in the secondary winding with a magnitude according to the turn ratio between the windings. A readable current value is then provided to the protection relay. The current in the secondary winding of the current transformer must be within the range of supported values by the relay, 1A and 5A are standardized values. (Hewitson, Brown, & Balakrishnan, 2004; Technical guidance document from experts and mentor, 2015).

There are mainly two categories of current transformer cores: measuring cores and protection cores. Current transformers for protection use must be reliable in the range of possible values at the measuring point and not get saturated. If the primary current is too large the CT core will reach maximum flux density. This means that there is no more change in magnetic flux, which results in the voltage and current levels dropping in the secondary circuit. At this stage the CT core is saturated. For this reason, CTs are divided into different accuracy classes. This makes it possible to choose the right CT for the specific task. In CT classification the words load and burden are both used. The load refers to the rated current allowed in the primary circuit. Burden indicates the amount of resistance and impedance that may be connected to the secondary circuit without causing an error greater than what is allowed for that accuracy class. The rated burden is displayed in apparent power (VA) as standard. (Hargrave, Thompson, Heilman, & Schweitzer Engineering Laboratories, 2018; Technical guidance document from experts and mentor, 2015; GE Digital Energy, n.d.).

Current transformers for protection use have a rated burden, a rated overcurrent factor also called Accuracy limit factor (ALF), and an accuracy class, 5P and 10P being standard accuracy classes. A CT label can look as follows, 5P10, 20VA. The first digit(s) is the maximum allowed error in percent. The “P” stands for protection and indicates that the CT has a protection core. The second two digits are the accuracy limit factor. The last value is the rated burden. This translates to a 5% allowed error at 10 times the nominal current at the rated burden of 20 VA. See Figure 5 for a typical CT rating. (Bureau of Indian Standards, 2012; Technical guidance document from experts and mentor, 2015).

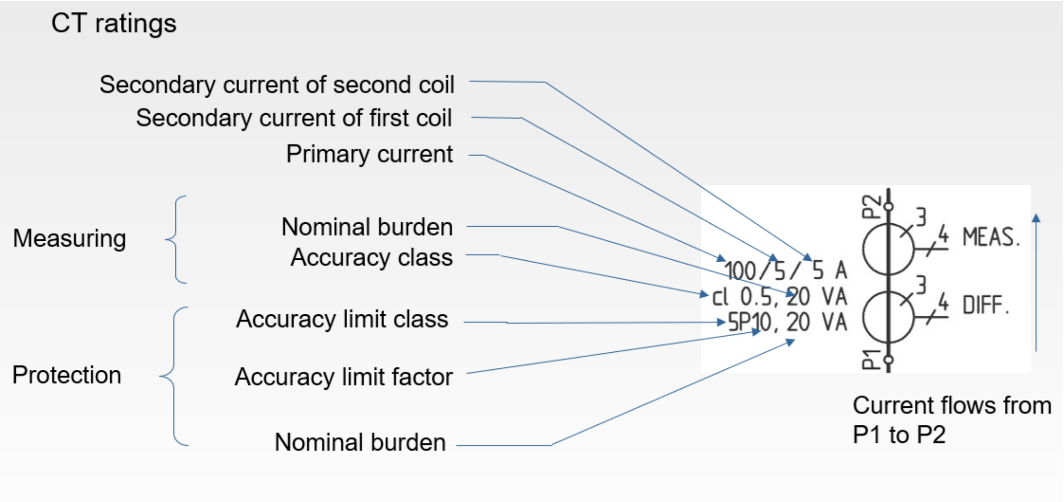


Figure 5. Typical CT rating. (Technical guidance document from experts and mentor, 2015).

4.2 Main protection

For the protection system to locate and disconnect faulty parts with maximum accuracy the power system is divided into smaller parts. Each protection relay has its designated part of the system which it must protect. Figure 6 shows how the main protection typically is divided into smaller sections. Every section should besides protection relays and instrument transformers ideally have means to disconnect and isolate faults internally, with circuit breakers and disconnectors as an example. This protection is referred to as main protection. The main protection is excellent for fast-operating times and selectivity properties. It is equally important for the protection to not be too sensitive as being fast and accurate. Or else it will result in unnecessary tripping. To achieve selectivity in the system some protections must not trip immediately as a fault is detected. These protections are equipped with a short time delay, overcurrent protection being one example. Overcurrent may be detected by several relays in the system simultaneously. To avoid all relays tripping at the same time, time-based discrimination is used making the relays trip in a specific order until the fault is cleared. Using this method, the whole power plant will not shut down at once. Parts of the system get disconnected until the fault is cleared. (Hewitson, Brown, & Balakrishnan, 2004; Technical guidance document from experts and mentor, 2016).

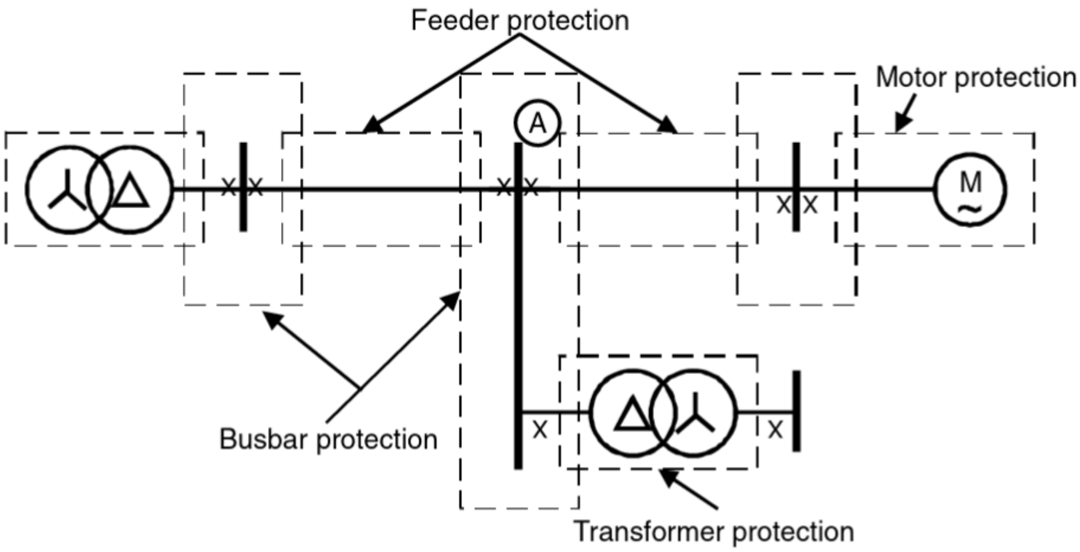


Figure 6. Typical main protection sections. (Hewitson, Brown, & Balakrishnan, 2004).

4.3 Backup protection

In such a situation where the main protection fails to disconnect the fault, it is important to have backup protections in place. There may be several reasons why the main protection fails. It can be anything from a mechanically stuck breaker to a software fault in the protection relay. If the backup protection gets triggered, that typically means the main protection either failed to disconnect the faulty section or failed to detect the fault. The backup protection is designed to disconnect the fault from the system at the next possible position. Since the next possible position might be outside the main protection’s operating area it would be only the backup protection that can disconnect the fault. It is always desired that the main protection takes care of the fault if possible. The backup protection is therefore time delayed to be operating after the main protection. (Hewitson, Brown, & Balakrishnan, 2004).

4.4 Earthing methods

Various earthing methods exist for generators in the power plant, each with its own set of advantages and disadvantages. The chosen earthing method plays a crucial role when designing the protection. In the following chapters, the most used earthing methods are presented.

4.4.1 Ungrounded

An ungrounded generator has a floating neutral. No intended connection is made to earth. The ungrounded generator has very limited earth fault currents, typically resulting in less damage due to earth faults. Immediate clearing of earth faults is not always necessary, this results in low downtime. The risk of electric shocks to humans is however the highest using this earthing method (Prasanna, 2023). It is challenging to pinpoint the location of faults with ungrounded generators, making it difficult to achieve selectivity. (Technical guidance document from experts and mentor, n.d. a).

4.4.2 Solidly grounded

A solidly grounded generator has minimal to no impedance between the neutral point and ground. The low-impedance path to earth redirects potential fault currents away from personnel and external equipment making this the safest system for humans (Prasanna, 2023). It is possible to achieve selectivity with protection relays. However, fault currents are not limited by any impedance, which may result in major damage to the generator. Multiple-point grounding may lead to circulating third harmonic currents. (Technical guidance document from experts and mentor, n.d. a).

4.4.3 High resistance grounded

High resistance grounded generators have a limited earth fault current, usually limited to 5–25 A by a resistor or transformer. High-resistance grounding is the most popular grounding method for medium voltage generators. It offers good voltage control, good equipment safety, and good protection characteristics. The main drawback is that the protective equipment must be able to withstand high temporary voltage surges. (Technical guidance document from experts and mentor, n.d. a).

4.4.4 Low resistance grounded

Low resistance grounded generators have a limited earth fault current, typically limited to 50–400 A by a resistor or transformer. It is possible to achieve selectivity with protection relays. The fault currents are lower than for the solidly grounded generator but higher than for high-resistance grounded generators, which may lead to greater damage for the generator. The neutral equipment is usually expensive in comparison to the high-resistance neutral equipment. Multiple-point grounding may lead to circulating third harmonic currents. (Technical guidance document from experts and mentor, n.d. a).

4.4.5 Low inductance grounded

Low inductance grounded generators have the earth fault current limited by an inductor coil to less than the phase-to-phase short circuit current. It is possible to achieve selectivity with protection relays. The fault currents are lower than for the solidly grounded generator but still greater than for high-resistance grounded generators. Neutral equipment is also expensive for this method. Multiple-point grounding may lead to circulating third harmonic currents. (Technical guidance document from experts and mentor, n.d. a).

4.5 Surge arresters

The task of the surge arrester is to protect equipment against temporary overvoltage surges. The surge arrester redirects and discharges the surge safely to earth without letting the voltage rise to a harmful level. The surge arrester is connected between phase and earth close to the equipment it is protecting. The operating parameters for surge arresters are not yet fully standardized, but commonly used parameters are: The voltage level at which it can operate continuously (U_c), a nominal voltage level at which it must be able to withstand for a short specified period (e.g. 10 to 1000 seconds) without leaking current, a residual voltage level which is the voltage between the terminals of the surge arrester at peak values, a factor T which describes the temporary overvoltage withstand strength of the surge arrester for different periods and lastly, the maximum amount of energy the surge arrester can redirect without the need for cooling breaks. (Technical guidance document from experts and mentor, 2015).

The system’s earthing method and the protection type (alarm or tripping) are crucial when choosing a surge arrester. The earth fault protection can be of the alarm type in an ungrounded system. In this case, the surge arrester must withstand voltages up to 10% above phase-to-phase voltage (U_m) for long periods U_c should be chosen based on equation 2. (Technical guidance document from experts and mentor, 2015).

$$U_c > 1{,}1 \cdot U_m \qquad (2)$$

If the earth fault protection is of tripping type, the maximum operating voltage may be lower, according to equation 3. (Technical guidance document from experts and mentor, 2015).

$$U_c > \frac{U_m}{T} \qquad (3)$$

4.6 Protection relays

Protection relays are intelligent devices that monitor the generators, transformers, and switchgear. The relay analyses measurements from the instrument transformers and decides when the circuit breakers should be opened. The operation of circuit breakers and disconnectors is controlled by the protection relay. The protection relay has hard-wired signals for opening and closing the circuit breakers and disconnectors. The relay will protect the equipment and personnel from abnormal and dangerous events. (Technical guidance document from experts and mentor, n.d. b).

4.7 Protection functions

The protection relays support standardized protection functions. The protection functions and communication protocols are standardized enabling relays from various manufacturers to operate simultaneously together in the same power station. (Schneider Electric, n.d.)

Each protection function has a standardized name for easy identification. There are however three different standards widely used internationally. IEC 61850, IEC 60617, and ANSI/IEEE standard C37.2. Each with their own names for the protection functions.

The standard generator protections that are commonly used are presented in the following chapters.

4.7.1 Generator differential protection

IEC 61850: MPDIF IEC 60617: Id>, Id>> ANSI: 87G

The generator differential protection measures the current entering and exiting the stator winding. If the current leaks anywhere creating a short circuit these currents will not match. The differential protection will not trip for external faults and is excellent for detecting internal faults in the generator. Interturn faults on the same phase are challenging to detect for differential protection unless they evolve into another fault. (ABB Distribution Solutions, 2020).

When there is a fault detected by the differential protection, the damage is typically already done and the generator will need repairing. The fault time is critical in limiting the damage. Since the differential protection only detects faults located between its measuring points, the tripping time can be as short as possible and still be selective. The function should however be secure enough to avoid false tripping. (Technical guidance document from experts and mentor, 2020).

4.7.2 Generator overcurrent protection

IEC 61850: PHPVOC IEC 60617: I>, I>> ANSI: 50/51

The overcurrent protection primarily protects the generator from overcurrent caused by external faults. Overcurrent protection is however still used as a backup for the differential protection for internal faults.

The low setting of the overcurrent protection can also be used as a rough backup protection for overloading. Overloads up to 110% are best covered by the thermal overload function since the temperature rise is still fast within this range. Overloading above 110% is primarily protected by the overcurrent protection. The overcurrent protection must be coordinated with the rest of the protection system with time delays to achieve selectivity as described in Chapter 4.2. The first stage of the function is set to pick up at 112% nominal current and configured for IEC normal inverse time operation with time dial $k = 0,2$. The second stage is set to pick up at 250% nominal current with a time delay of 0,6s. (Technical guidance document from experts and mentor, 2020).

4.7.3 Generator non-directional earth fault overcurrent protection

IEC 61850: EFLPTOC IEC 60617: Io>, I>> ANSI: 50N/51N

The non-directional earth fault overcurrent protection serves as a backup for the directional differential earth fault protection (67N/87N) in high-resistance grounded systems. The non-directional earth fault overcurrent function is configured to detect high earth fault current I_0. This function must be coordinated with other earth fault protections in the system to achieve selectivity. The first stage of the function is set to pick up at 2,0 A with a time delay of 1s. The second stage is set to pick up at 3,0 A with a time delay of 0,6s. (Technical guidance document from experts and mentor, 2020).

4.7.4 Generator directional differential earth fault protection

IEC 61850: DEFLPDEF IEC 60617: Ioϕ-> ANSI: 67N/87N

The directional differential earth-fault protection is the primary earth fault protection for the generator. The function monitors the earth fault currents on both sides of the generator, which makes the function only detect internal earth faults. Therefore, there is no need to coordinate with other earth-fault protections. The function is set to pick up at I_o > 2 A and U_o 10% with a time delay of 0,3s. (Technical guidance document from experts and mentor, 2020).

4.7.5 Generator thermal overload protection

IEC 61850: T2PTTR IEC 60617: T> ANSI: 49

The generator thermal overload protection calculates the temperature rise in the generator using the measured phase current rms value and thermal model according to IEC60255-149. The generator has a rated maximum continuous current. If this current is exceeded the generator heats up above recommended temperatures. Thermal overload protection does not only consider the magnitude of the current but also the duration of the overcurrent. Using the current rms value and the time duration the protection function calculates the temperature rise in the generator. The function trips if the temperature inside the generator exceeds what it is designed for. (Schneider Electric, 2020; Technical guidance document from experts and mentor, 2020).

The function's operation times are calculated using equations 4, 5 and 6.

Trip time: $$t = \tau \cdot \ln \frac{I^2 - I_p^2}{I^2 - a^2} \quad (4)$$

Alarm: $$a = k \cdot k_\theta \cdot I_{GN} \cdot \sqrt{alarm} \quad (5)$$

Trip: $$a = k \cdot k_\theta \cdot I_{GN} \quad (6)$$

Where:
t is operate time.
τ is thermal time constant (seconds).
ln is natural logarithm function.
I is measured RMS phase current.
I_p is pre-load current.
k is overload factor.
k_θ is ambient temperature factor.
I_{GN} is rated current of the generator.

The thermal time constant should be obtained from the generator manufacturer. The overload factor is usually 1,06. $alarm$ is set to the desirable alarm level (for example 60%=0,6). (Technical guidance document from experts and mentor, 2020).

4.7.6 Generator under excitation protection

IEC 61850: UEXPDIS IEC 60617: Q< ANSI: 40

If the generator loses excitation while connected in parallel with other generators, it will try to maintain its magnetic field by using power from the utility or other generators. Resulting in the generator consuming large amounts of capacitive power. The other generators in the system will have to generate more power to compensate for the faulty generator. The rotor will get induced with slip-frequency currents, which may lead to the rotor overheating.

The function is configured to pick up on reverse reactive power flow. The function is set to pick up at 0,9 – 0,95 leading power factor at full output, equal to -30% reactive power. The function is set with a time delay of 2s. (Technical guidance document from experts and mentor, 2020).

4.7.7 Generator reverse power protection

IEC 61850: DUPPDPR IEC 60617: P< ANSI: 32

The reverse power protection protects the engine driving the generator rather than the generator. If the engine loses its power the generator will start operating as an electric motor. Reverse power protection will detect a power flow in the wrong direction. The reverse power protection must disconnect the generator immediately when detecting reverse power to protect the engine. The function can typically be set to pick up at 4% reverse power and an angle setting of 0° where a reciprocating engine is used as the prime mover. After synchronization, the function is time delayed by 2 seconds to avoid false tripping. (Technical guidance document from experts and mentor, 2020).

4.7.8 Generator overvoltage protection

IEC 61850: PHPTOV IEC 60617: U>, U>> ANSI: 59

The overvoltage protection is configured to protect the generator from overvoltage. Overvoltage is usually a result of the AVR not operating correctly or a large sudden decrease in load. The overvoltage protection should be time-delayed giving the AVR a chance to regulate the voltage. The overvoltage protection has multiple stages. The first stage is set at 105% nominal voltage with a time delay of 30s. This stage is configured to send an alarm to notify personnel that the generator is operating above the limit of IEC60034-1 Zone A. The second stage is set to pick up at 113% nominal voltage with a time delay of 4s. The third stage can be set to pick up at 140% nominal voltage with a time delay of 2s. (Technical guidance document from experts and mentor, 2020).

4.7.9 Generator undervoltage protection

IEC 61850: PHPTUV IEC 60617: U<, U<< ANSI: 27

The undervoltage protection is configured to protect the generator from operating with undervoltage. Undervoltage is usually a result of the AVR not operating correctly or a large sudden increase in load. The undervoltage protection should be time-delayed, giving the AVR a chance to regulate the voltage. Two stages for undervoltage protection are usually used. The first stage is set at 95% nominal voltage with a time delay of 30s. This stage is configured to send an alarm signal to notify personnel that the generator is operating below the limit of IEC60034-1 Zone A. The second stage is set to pick up at 88% nominal voltage with a time delay of 20s. (Technical guidance document from experts and mentor, 2020).

4.7.10 Generator unbalance current protection

IEC 61850: NSPTOC IEC 60617: I2> ANSI: 46

The unbalanced current protection is designed to protect the generator from unbalanced currents. Unbalanced currents can be a result of unbalanced loads or open conductors for example. Unbalanced currents may lead to the rotor overheating (Technical guidance document from experts and mentor, 2020). The unbalanced current protection monitors negative sequence currents by measuring all three phase currents. The negative sequence currents arise when there is an asymmetry in the system. The generator’s capability to withstand negative sequence current is defined by the manufacturer. (Arcteq Relays Ltd., 2021).

4.7.11 Generator under- and over-frequency protection

IEC 61850: FRPFR IEC 60617: f<, f> ANSI: 81L/81H

The under- and over-frequency protection monitors the generator frequency. Under-frequency can be caused by loss of input power from the engine or a large rapid increase in load. Over-frequency is the result of a large rapid decrease in load or over-speed from the engine. Under-frequency will lead to less airflow for cooling of the generator. Over-frequency will lead to increased mechanical forces on the rotor due to faster rotation speed. The under- and over-frequency protection usually has several stages per function. (Technical guidance document from experts and mentor, 2020).

The first under-frequency protection stage is set to pick up at 98% nominal frequency with a time delay of 30s. This stage is configured to send an alarm to notify personnel that the generator is operating below the limit of IEC60034-1 Zone A. The second stage is set to pick up at 95% nominal frequency with a time delay of 4s and is configured to trip. (Technical guidance document from experts and mentor, 2020).

The first over-frequency protection stage is set to pick up at 102% nominal frequency with a time delay of 30s. This stage is configured to send an alarm to notify personnel that the generator is operating above the limit of IEC60034-1 Zone A. The second stage is set to pick up at 110% nominal frequency with a time delay of 4s and is configured to trip. (Technical guidance document from experts and mentor, 2020).

4.7.12 Generator residual overvoltage protection

IEC 61850: ROVPTOV IEC 60617: Uo>, Uo>> ANSI: 59N

The residual overvoltage protection serves as a backup for the non-directional earth-fault overcurrent protection (50N/51N). The function monitors the amount of zero sequence voltage in the generator circuit. The vector sum of the three phase-to-ground voltages divided by three makes up the residual voltage. In a healthy system, the residual voltage is very low. In the case of an earth fault, the residual voltage will rise above the limit set by the function. (Arcteq Relays Ltd., 2021).

The residual overvoltage protection can not determine the location of an earth fault therefore, it should be coordinated to be the last earth fault protection to trip. The first stage of the function is set to pick up at 10% nominal phase to ground voltage with a time delay of 2s. The second stage is set to pick up at 20% nominal phase to ground voltage with a time delay of 1,2s. (Technical guidance document from experts and mentor, 2020).

5 100% stator earth fault protection

The two most frequently used methods for achieving 100% stator earth fault protection are:

1. The third harmonic-based stator earth fault protection.
2. The low-frequency injection-based method.

Each with its advantages and disadvantages. Even though these functions often are referred to as 100% stator earth fault protection it must be noted that they should typically be combined and coordinated with other functions to provide the 100% stator earth fault protection (Hitachi Energy, 2023).

5.1 Third harmonic-based stator earth fault protection

IEC 61850: H3EFPSEF IEC 60617: dUo>/Uo3H ANSI: 64TN

The generator does not only produce three ideal sinus voltages. There are also several voltage harmonics produced, 1^{st}–50^{th} harmonic is usually measured. The third harmonic voltage is produced in each phase with the same angle. The third harmonic voltages do not cancel each other and can be measured both at the neutral point and terminal side of the generator. All odd multiples of the third harmonic, also called triplen harmonics, share similar characteristics in that they have the same angle in each phase. Harmonics other than the triplen harmonics generally cancel each other at the neutral point. Specifically, the third harmonic is used for detecting earth faults near the neutral point in generators. The third harmonic is chosen because it is generally the most significant harmonic at the generator's neutral point, and most importantly the characteristics of the third harmonic voltage during earth faults allow it to be used for detecting earth faults close to the neutral point. The third harmonic is 150 Hz in 50 Hz systems and 180 Hz in 60 Hz systems. (Schneider Electric, 2020; ABB, 2023). Figure 7 gives a visual representation of the third harmonic voltage in a three-phase system.

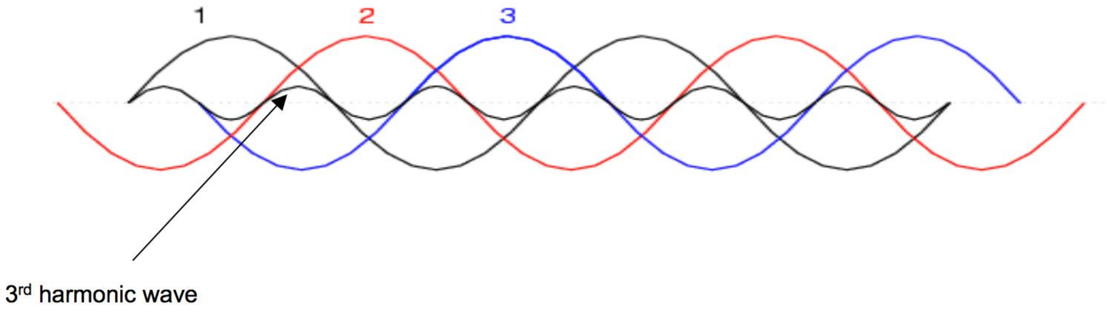


Figure 7. Visualization of the third harmonic wave in a three-phase system. (Controllix corporation, n.d.).

Below are a few illustrations of the third harmonic voltage during different scenarios measured both at the generator neutral point and terminal.

Case 1: Normal operation

Figure 8 provides a visual representation of the third harmonic voltage during healthy operation measured both at the neutral point and generator terminal. Vt is the third harmonic voltage at the generator terminal and Vn is the third harmonic voltage at the generator neutral point. Vt and Vn are very similar in magnitude under normal operation.

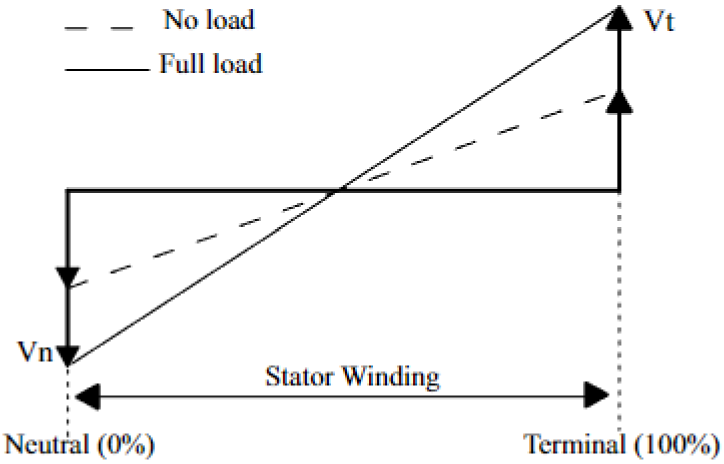


Figure 8. Third harmonic voltage during healthy operation. (Mondragón, Flórez, & Londoño, 2013).

Case 2: Earth fault at neutral point

If an earth fault occurs at the neutral point, the third harmonic voltage at the neutral point will drop to zero as described in Figure 9.

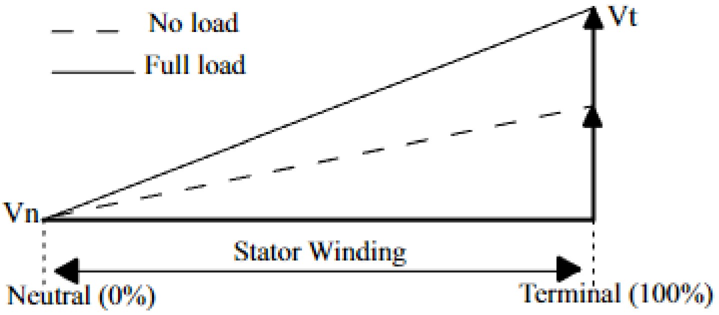


Figure 9. Third harmonic voltage during earth fault at the generator neutral point. (Mondragón, Flórez, & Londoño, 2013).

Case 3: Earth fault at generator terminal

If the earth fault occurs at the generator terminal, the third harmonic voltage will drop at the terminal end instead, as described in Figure 10. (Mondragón, Flórez, & Londoño, 2013).

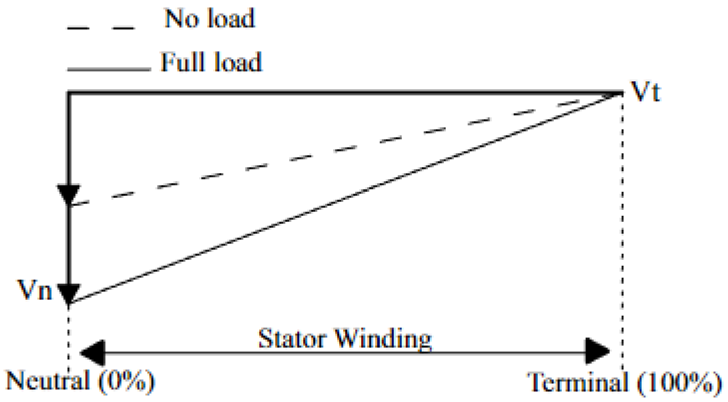


Figure 10. Third harmonic voltage during earth fault at generator terminal. (Mondragón, Flórez, & Londoño, 2013).

There are mainly two different protection principles using the third harmonic voltage (Salomon & Pairits, 2010).

- Third harmonic undervoltage (27TN) at neutral side. Detecting third harmonic undervoltage at the neutral point. See Figure 11 below.

- Third harmonic comparison (59THD) measured both at generator neutral and terminal side. Comparing the ratio of third harmonic voltage at the neutral point and terminal side. See Figure 12 below.

Theoretically third harmonic overvoltage can also be monitored at the generator terminal for detecting earth faults near the neutral point. When there is an earth fault at the generator neutral point the third harmonic voltage at the terminal increases. The voltage increase is however relatively small, which makes this principle less reliable than the two previous ones and is normally not used in practice. (Salomon & Pairits, 2010).

Figure 11 shows an example configuration of third harmonic undervoltage protection in combination with 59N for 100% stator earth fault protection for a high-impedance grounded generator:

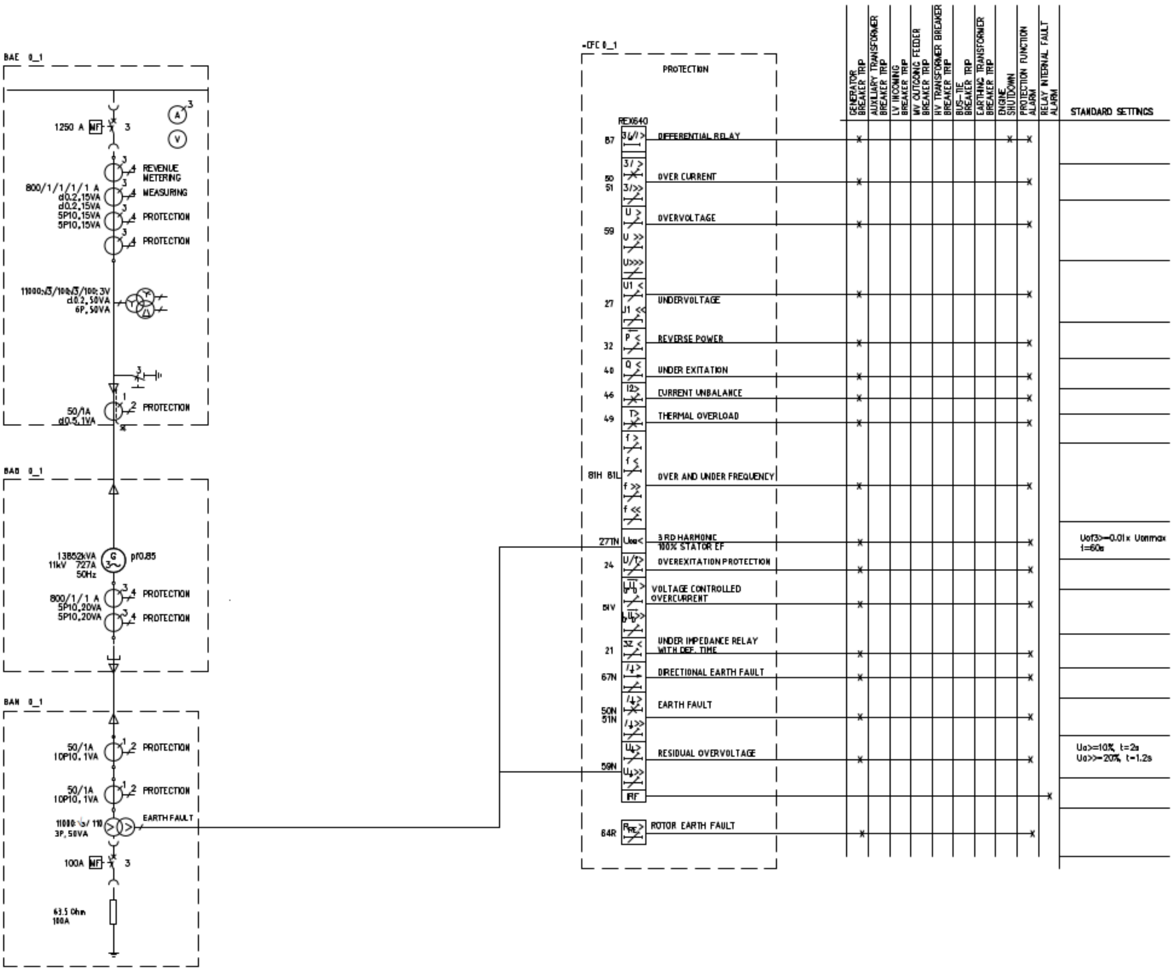


Figure 11. Example protection relay logic diagram for third harmonic undervoltage protection using REX640.

Figure 12 shows an example configuration of third harmonic comparison protection in combination with 59N for 100% stator earth fault protection for a high-impedance grounded generator:

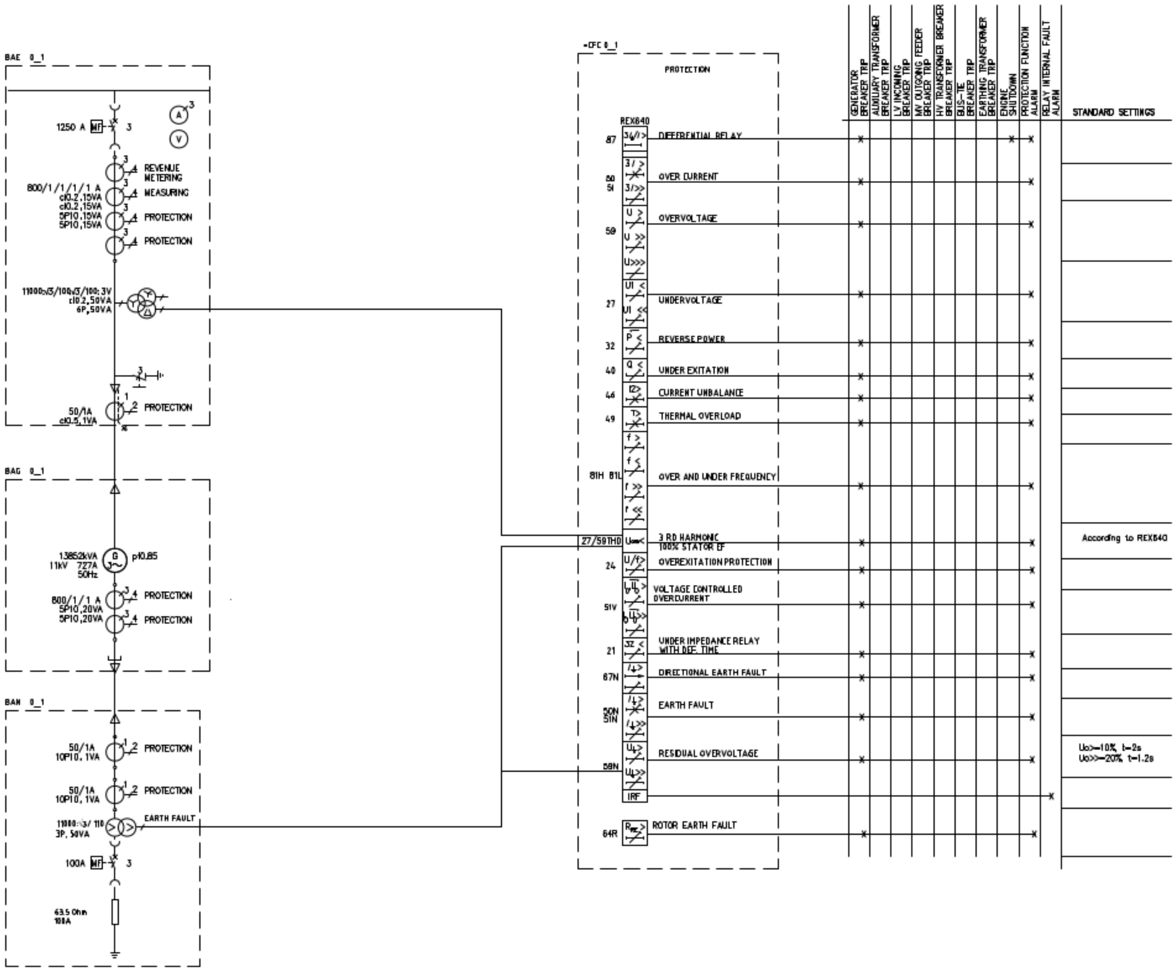


Figure 12. Example protection relay logic diagram for third harmonic comparison protection using REX640.

The third harmonic undervoltage protection scheme (27TN) simply measures the magnitude of the third harmonic voltage at the generator neutral point. If the third harmonic voltage at the neutral point drops below the setpoint, the function trips. This setpoint must be set below the minimum recorded level of third harmonic voltage during healthy operation with a margin for safety. (ABB, 2023).

The mathematical solutions for third harmonic differential protection (59THD) may differ from manufacturer to manufacturer. However, they all compare the measured third harmonic at the neutral point and the third harmonic measured at the generator terminal. The third harmonic differential protection is generally considered the most reliable and customizable principle based on the third harmonic. (Salomon & Pairits, 2010). The working principle of the third harmonic differential scheme in ABB’s REX640 is described below.

The third harmonic differential protection compares the measured third harmonic differential voltage with the third harmonic bias voltage. To acquire the third harmonic differential voltage the third harmonic must be measured both at the generator terminal and neutral point. If the third harmonic differential voltage increases above the third harmonic bias voltage the function trips after a set amount of time. (ABB, 2023). Equation 7 describes the working principle of the function:

$$\left|\overline{U}_{3H\_T} + \overline{U}_{3H\_N}\right| \geq Beta \cdot \left|\overline{U}_{3H\_N}\right| \qquad (7)$$

Where:

$\overline{U}_{3H\_N}$ is the neutral side third harmonic voltage phasor.

$\overline{U}_{3H\_T}$ is the terminal side third harmonic voltage phasor.

$Beta$ is a setting to achieve an adequate safety margin during healthy operation.

$\left|\overline{U}_{3H\_T} + \overline{U}_{3H\_N}\right|$ is the magnitude of the third harmonic differential voltage.

$Beta \cdot \left|\overline{U}_{3H\_N}\right|$ is the magnitude of the third harmonic bias voltage.

(ABB, 2023).

The amount of third harmonic voltage produced by the generator depends on the choice of winding pitch and the amount of active and reactive power in the system. For the third harmonic-based protection to work properly, the third harmonic voltage produced by the generator must be at least 1% of the nominal voltage during normal operation according to many relay manufacturer manuals. (Schneider Electric, 2020; ABB, 2023; Arcteq Relays Ltd., 2021).

The winding pitch of the generator alters the harmonic contents in the output voltage. Generators with 2/3 winding pitch eliminate the third harmonic component in the output voltage, making them suitable for solidly grounded systems where circulation of third harmonic currents would occur otherwise. However, generators intended for third harmonic-based 100% stator earth fault protection, must not eliminate the third harmonic voltage. Making 5/6 winding pitch a better choice for these applications. Even though approximated calculations of the third harmonic voltage magnitude can be done in advance, the third harmonic-based stator protection should always be expected to require some testing during commissioning to find adequate settings for the function. (ABB, 2019; Salomon & Pairits, 2010).

The greatest advantage of 100% stator earth fault protection based on the third harmonic is that there is usually no need for any additional hardware (Salomon & Pairits, 2010). At least one protection principle for 100% stator earth fault protection based on the third harmonic is supported in most standard generator protection relays. (Schneider Electric, 2020; ABB Distribution Solutions, 2020; Arcteq Relays Ltd., 2021).

Varying generator loading, significant variations in power factor, and other disturbances in the system will all alter the magnitude of the third harmonic voltage produced by the generator. Too large variations of the third harmonic voltage will make the third harmonic earth fault protection insecure and trip unnecessarily (Negahdari, 2018).

As mentioned, the third harmonic earth fault protection is said to require at least 1% third harmonic voltage. Third harmonic current is however not desired in electrical systems. The third harmonic current in electrical systems is known to cause several problems, such as increased power losses, high current in the neutral conductor, and strong electromagnetic fields to name a few. In transformers, it is also known to cause a temperature rise and shorten their lifetime (ABB Control Oy, 1999). Therefore, it is important to remember that while trying to achieve a sufficient level of third harmonic voltage for 100% stator earth fault protection. It is at the same time desired to have as low levels of third harmonic in the system as possible. High-resistance grounding of the generator will to an extent limit the third harmonic currents in the generator circuit (ABB, 2019) and is highly recommended when using this protection.

5.2 Third harmonic in generators with a shared step-up transformer

The third harmonic is restrained by the delta windings in the step-up transformer and auxiliary transformer. Most 100% stator earth fault protections based on the third harmonic are designed based on this fact. It is however common that multiple generators share the same step-up transformer as in Figure 13.

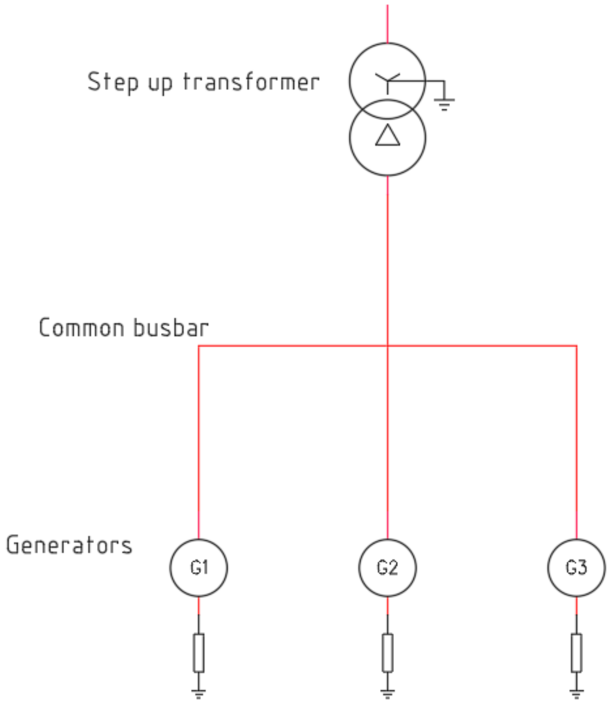


Figure 13. Simplified single line diagram of paralleled generators sharing step-up transformer.

These configurations can result in circulating third harmonic current if the paralleled generators produce different levels of third harmonic voltage. The state of the breakers will alter the network impedance i.e., how many generators are connected to the same bus simultaneously. The additional impedances are visualized in Figures 14 and 15. These factors will often make traditional third harmonic-based 100% stator earth fault protection malfunction. (Chowdhury, et al., 2019).

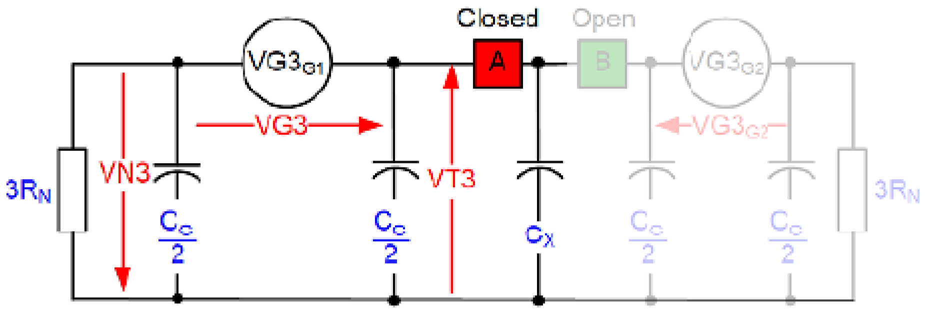


Figure 14. Circuit diagram of a single generator. (Chowdhury, et al., 2019).

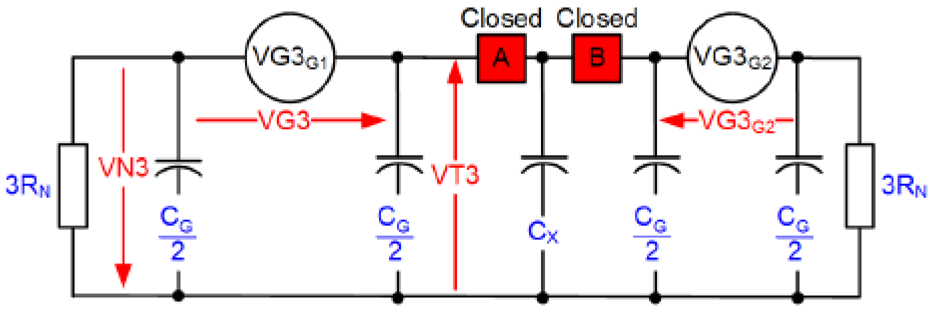


Figure 15. Circuit diagram of two paralleled generators. (Chowdhury, et al., 2019).

A solution for implementing third harmonic differential-based 100% stator earth fault protection for generators connected to a common bus is proposed in (Chowdhury, et al., 2019). In summary, when connecting multiple generators in parallel sharing the same step-up transformer, additional impedances are introduced to the system. This will lead to the third harmonic voltage on the terminal side to decrease and the third harmonic voltage at the neutral point to increase. These are also characteristics of an earth fault at the terminal side of the generator. Therefore, the principle given in (Chowdhury, et al., 2019) is designed to be immune to changes in impedance depending on breaker status and is detecting earth faults only near the generator neutral point. Secondly, circulating third harmonic currents will result in an increase of the third harmonic voltage on the terminal side and a decrease in the third harmonic voltage at the neutral point by the same amount. These are also characteristics of an earth fault at the neutral point. The proposed function has a few blocking signals. One important blocking signal worth mentioning is when a generator in the system is generating a high level of third harmonic voltage relative to the protected generator (third harmonic voltage produced by the generator times VG3MX). The VG3MX setting provides security for the function with varying amounts of generators connected to the bus. VG3MX must be calculated and set to different values depending on the number of generators connected to the bus. The complete description of the protection principle can be found in (Chowdhury, et al., 2019).

5.3 100% stator earth fault protection, injection-based

IEC 61850: STTIPHIZ IEC 60617: Rse< ANSI: 64S

The low-frequency injection stator protection (64S) injects a subharmonic frequency signal in the neutral circuit of the generator. This low-frequency signal will not interfere with the main frequency of the generator. This method is believed to provide 100% stator earth fault protection by itself or when paired together with residual overvoltage protection (59N), even when the generator is offline. Typically, an additional injection box that generates the injection signal, a bandpass filter, and a current transformer for measuring the injected signal are required to implement the low-frequency injection protection. (Turner, 2009). The protection relay must also support a function for 100% stator earth fault protection by low-frequency injection. Figure 16 visualizes an example low-frequency injection scheme setup for a high-resistance grounded generator.

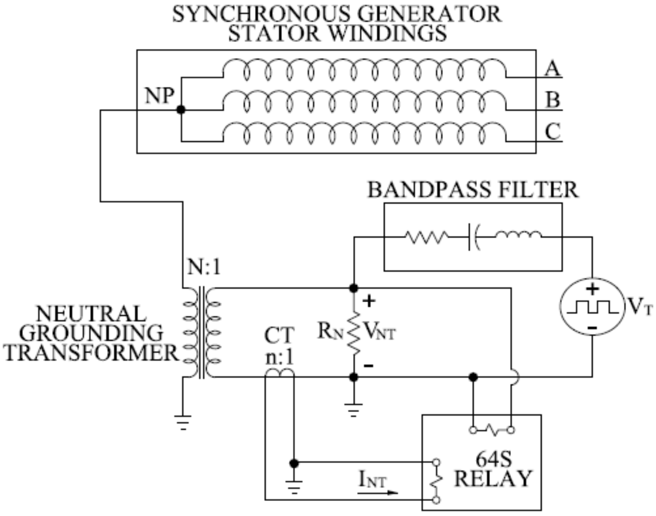


Figure 16. Example setup for 100% stator earth fault protection using low-frequency injection. (Safari-Shad, Negahdari, Toliyat, & Franklin, 2018).

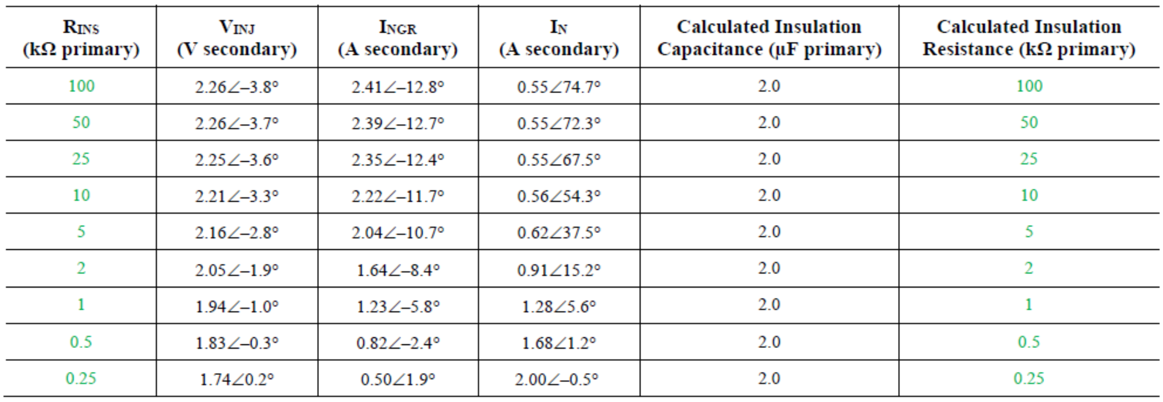
The injected voltage is measured at the injection point and the resulting current produced by the injection voltage is also measured. Based on these values the relay calculates the stator winding resistance to ground. The calculated resistance is then compared with the preset resistance to ground value for the alarm and trip levels. (ABB Substation Automation Products, 2016). For the low-frequency injection protection to work as intended it is important that the total capacitance to earth (C_{tot}) of the generator winding, bus equipment, and delta-connected windings of the unit transformer is accurately determined (Negahdari, 2018). The resistance of the injection signal source, the impedance of the bandpass filter, and the neutral grounding resistance may all change over time and due to temperature variations. C_{tot} may change due to variations in system voltages and deformations of the stator winding. These variations must be considered when implementing the low-frequency injection method. (Safari-Shad, Negahdari, Toliyat, & Franklin, 2018).

During an earth fault, the fundamental generator frequency current and voltage must be properly rejected at the relay measuring points or the relay will not operate correctly. If the fundamental frequency current is not properly rejected, then a high current may saturate the CT measuring the low-frequency injection signal current. Saturation can cause delayed operation or, worst case scenario, no operation at all. Saturation will also result in less than 100% stator protection from earth faults near the terminal side. Saturation typically occurs if the grounding resistor on the secondary side of the grounding transformer is less than 1 ohm. (Turner, 2009).

The low-frequency injection method is a valid option for generator applications lacking sufficient levels of third harmonic voltage for third harmonic-based 100% stator earth fault protection. However, a system with a very large capacitance and low grounding resistance may have a very small difference between the fault current and non-fault current making the protection insensitive (Turner, 2009). Since additional equipment typically is required to implement this function, it will generally be more expensive than third harmonic-based stator protection. If the power plant has multiple generators all requiring the 64S protection the cost difference will naturally be even more significant. This type of protection is mainly suitable for larger generators (Salomon & Pairits, 2010).

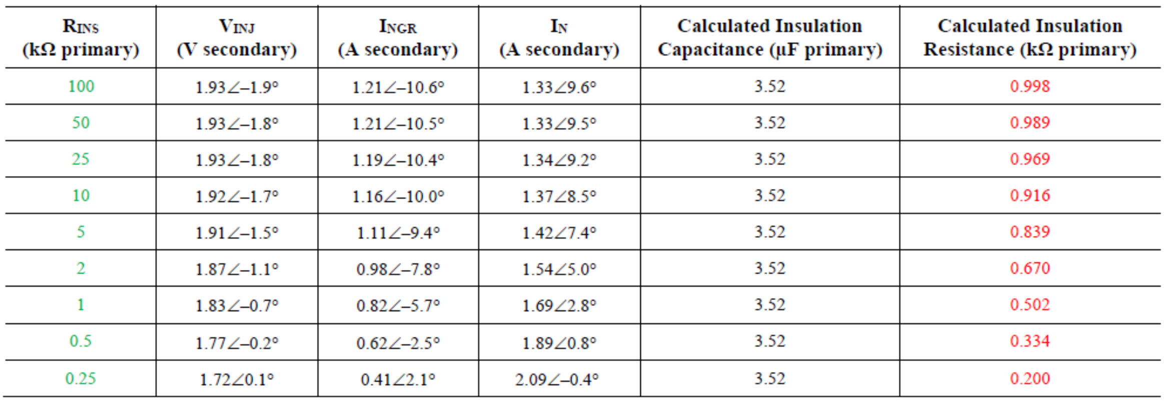
5.4 Low frequency injection in generators with shared step-up transformer

The injection signal used in 100% stator earth fault protection, STTIPHIZ (64S), to determine the generator impedance to earth, behaves similarly to the third harmonic in the sense that it is restrained by the delta winding in the step-up transformer and auxiliary transformer. Suppose this protection is implemented on a generator sharing the same step-up transformer with other generators on the same bus. Paralleled generators will show up as earth faults for the protected generator. This phenomenon is studied in (Chowdhury, et al., 2019) and illustrated in Figures 17 and 18.



RINS (kΩ primary)	VINJ (V secondary)	INGR (A secondary)	IN (A secondary)	Calculated Insulation Capacitance (µF primary)	Calculated Insulation Resistance (kΩ primary)
100	2.26∠–3.8°	2.41∠–12.8°	0.55∠74.7°	2.0	100
50	2.26∠–3.7°	2.39∠–12.7°	0.55∠72.3°	2.0	50
25	2.25∠–3.6°	2.35∠–12.4°	0.55∠67.5°	2.0	25
10	2.21∠–3.3°	2.22∠–11.7°	0.56∠54.3°	2.0	10
5	2.16∠–2.8°	2.04∠–10.7°	0.62∠37.5°	2.0	5
2	2.05∠–1.9°	1.64∠–8.4°	0.91∠15.2°	2.0	2
1	1.94∠–1.0°	1.23∠–5.8°	1.28∠5.6°	2.0	1
0.5	1.83∠–0.3°	0.82∠–2.4°	1.68∠1.2°	2.0	0.5
0.25	1.74∠0.2°	0.50∠1.9°	2.00∠–0.5°	2.0	0.25

Figure 17. Calculations of circuit parameters for a single generator with varying earth fault resistances. (Chowdhury, et al., 2019).



RINS (kΩ primary)	VINJ (V secondary)	INGR (A secondary)	IN (A secondary)	Calculated Insulation Capacitance (µF primary)	Calculated Insulation Resistance (kΩ primary)
100	1.93∠–1.9°	1.21∠–10.6°	1.33∠9.6°	3.52	0.998
50	1.93∠–1.8°	1.21∠–10.5°	1.33∠9.5°	3.52	0.989
25	1.93∠–1.8°	1.19∠–10.4°	1.34∠9.2°	3.52	0.969
10	1.92∠–1.7°	1.16∠–10.0°	1.37∠8.5°	3.52	0.916
5	1.91∠–1.5°	1.11∠–9.4°	1.42∠7.4°	3.52	0.839
2	1.87∠–1.1°	0.98∠–7.8°	1.54∠5.0°	3.52	0.670
1	1.83∠–0.7°	0.82∠–5.7°	1.69∠2.8°	3.52	0.502
0.5	1.77∠–0.2°	0.62∠–2.5°	1.89∠0.8°	3.52	0.334
0.25	1.72∠0.1°	0.41∠2.1°	2.09∠–0.4°	3.52	0.200

Figure 18. Calculations of circuit parameters for two paralleled generators with varying earth fault resistances. (Chowdhury, et al., 2019).

During the tests made by (Chowdhury, et al., 2019) with two generators operating in parallel the measured insulation resistance was never above 1kΩ which is a huge error. The measured resistance only gets moderately close to the actual value at very low insulation resistances.

By considering the current flowing through the paralleled generator ground, the measurement error of the insulation resistance can be greatly improved. A solution is proposed by (Chowdhury, et al., 2019) which includes wiring an additional CT in parallel allowing a differential current to be measured. This principle makes it possible to compensate for the current flowing through the paralleled generator ground. The proposed connection is illustrated in Figure 19. Note that this principle requires that all injection sources use different frequencies otherwise it is impossible to tell the signals apart. (Chowdhury, et al., 2019).

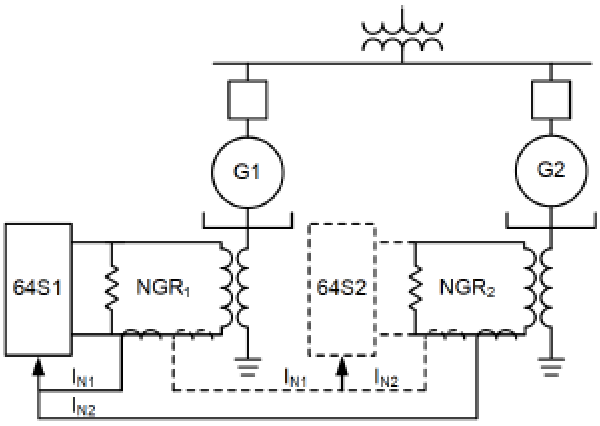
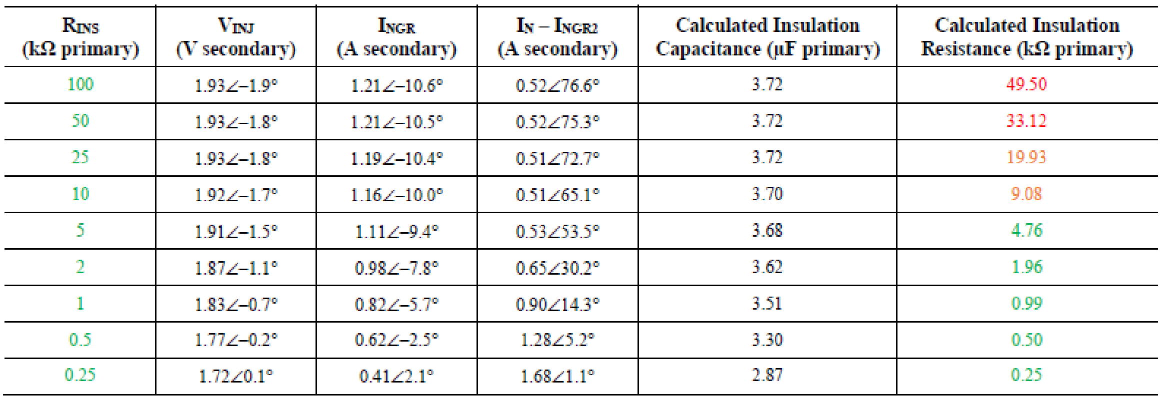


Figure 19. Proposed connection for 100% stator earth fault protection using low-frequency injection for two paralleled generators. (Chowdhury, et al., 2019).

Using this principle, far more accurate measurements of the insulation resistance were achieved in (Chowdhury, et al., 2019). The results are shown in Figure 20.



R_{INS} (kΩ primary)	V_{INJ} (V secondary)	I_{NGR} (A secondary)	$I_N - I_{NGR2}$ (A secondary)	Calculated Insulation Capacitance (µF primary)	Calculated Insulation Resistance (kΩ primary)
100	1.93∠–1.9°	1.21∠–10.6°	0.52∠76.6°	3.72	49.50
50	1.93∠–1.8°	1.21∠–10.5°	0.52∠75.3°	3.72	33.12
25	1.93∠–1.8°	1.19∠–10.4°	0.51∠72.7°	3.72	19.93
10	1.92∠–1.7°	1.16∠–10.0°	0.51∠65.1°	3.70	9.08
5	1.91∠–1.5°	1.11∠–9.4°	0.53∠53.5°	3.68	4.76
2	1.87∠–1.1°	0.98∠–7.8°	0.65∠30.2°	3.62	1.96
1	1.83∠–0.7°	0.82∠–5.7°	0.90∠14.3°	3.51	0.99
0.5	1.77∠–0.2°	0.62∠–2.5°	1.28∠5.2°	3.30	0.50
0.25	1.72∠0.1°	0.41∠2.1°	1.68∠1.1°	2.87	0.25

Figure 20. Calculations of circuit parameters for two paralleled generators with the proposed differential CT configuration. (Chowdhury, et al., 2019).

A complete and detailed description for implementing this principle can be found in (Chowdhury, et al., 2019).

5.5 Available solutions for 100% stator earth fault protection

The ideas of how to implement 100% stator earth fault protection vary between manufacturers. The amount of supported 100% stator earth fault protection principles also varies. Most generator protection relays do however support at least the third harmonic undervoltage protection (27TN). (ABB Distribution Solutions, 2020; Arcteq Relays Ltd., 2021; ABB Substation Automation Products, 2016; Schneider Electric, 2020).

In the following chapters solutions that are available from some selected manufacturers will be defined and compared. These chapters will only cover off-the-shelf solutions from the manufacturers.

5.5.1 Schneider P3G32

The Schneider P3G32 uses three different protection functions to cover 100% of the stator windings. The functions used are residual overvoltage protection (59N), earth fault overcurrent protection (50N/51N), and third harmonic undervoltage protection (64F3). The third harmonic undervoltage protection requires a VT between the generator's neutral point and earth.

The earth fault protection provided by 59N and 50N/51N covers about 95% of the stator windings, starting from the generator terminal. The 64F3 covers about 10–30% of the stator windings closest to the neutral point. When these functions are paired together, they overlap each other and protect 100% of the stator windings. The generator must produce a minimum of 1% third harmonic voltage relative to the generator's nominal voltage to implement this function. Additionally, for this function to operate selectively usually a unit transformer is required between the generator and the busbar. (Schneider Electric, 2020). Figure 21 describes the coverage of the functions used for 100% stator earth fault protection.

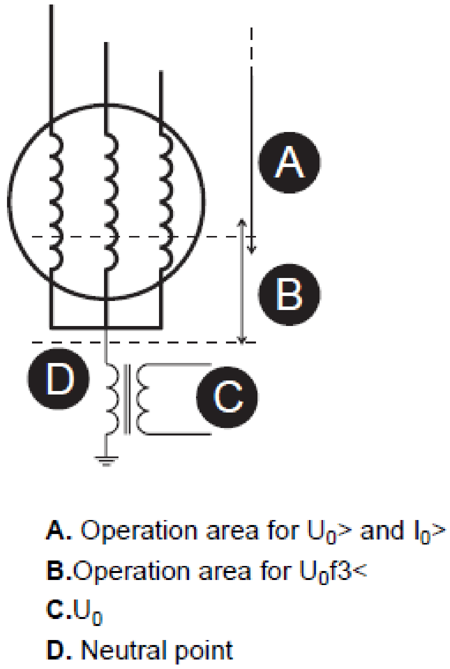


Figure 21. Coverage of the protections used by the P3G32 for 100% stator earth fault protection. (Schneider Electric, 2020)

5.5.2 ABB REX640

The ABB REX640 uses two protection functions to achieve 100% stator earth fault protection. Third harmonic-based stator earth fault protection H3EFPSEF (64TN) and residual overvoltage protection ROVPTOV (59N). The REX640 supports both the third harmonic undervoltage protection (27TN) and the third harmonic differential protection (59THD). The third harmonic differential protection requires phase-to-earth voltages at the terminal side to calculate combined the third harmonic or an open delta connection of the VT to directly measure the third harmonic at the generator terminal. The function can also be implemented with only one phase-to-earth voltage, in such cases, the combined third harmonic voltage magnitude is assumed to be equal to the third harmonic voltage in the measured phase. Measurement of the third harmonic at the neutral point requires a VT between the generator's neutral point and earth. When using the third harmonic differential protection the function should be blocked if the third harmonic at the generator terminal drops too low. The third harmonic undervoltage protection only uses the third harmonic voltage at the neutral point. (ABB, 2023). When using third harmonic undervoltage protection, the function should be blocked during start-up and shutdown of the generator (ABB Distribution Solutions, 2020).

The residual overvoltage protection (59N) can detect faults on 90–95% of the stator windings starting from the generator terminal. The third harmonic-based stator earth fault protection (64TN) detects earth faults on 15–20% of the stator windings starting from the neutral point. Together they provide 100% stator earth fault protection. The REX640 manufacturer recommends a minimum of 1% third harmonic voltage relative to the generator's nominal voltage for 100% stator earth fault protection. 0,5% is however the lowest settable value for REX640. The function is designed for applications with a step-up transformer between the generator and the busbar as shown in Figure 22 where the coverage of the functions is also displayed. (ABB, 2023).

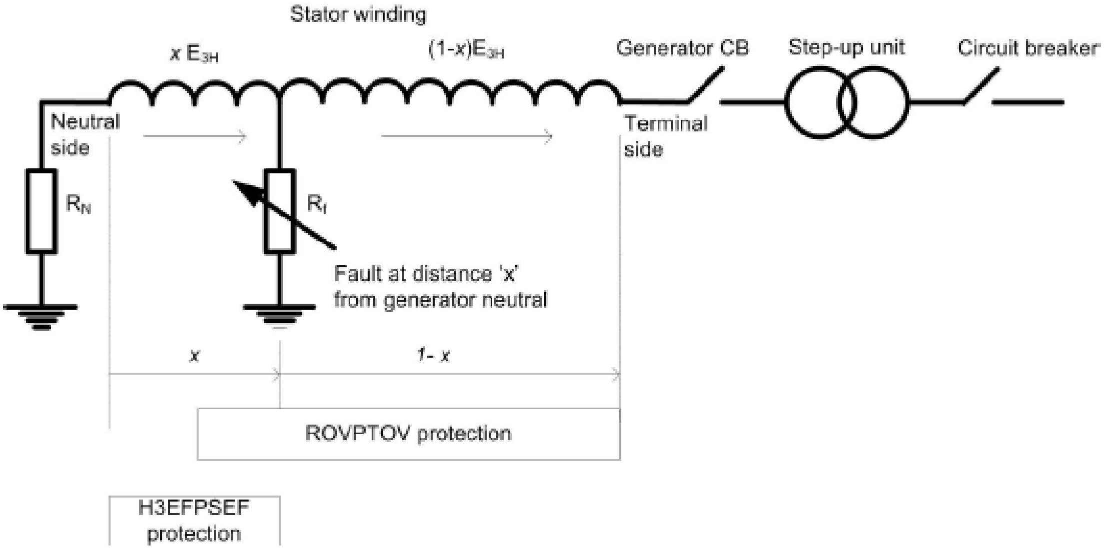


Figure 22. Coverage of the functions used by the REX640 for 100% stator earth fault protection. (ABB, 2023).

5.5.3 Arcteq AQ G257

The Arcteq AQ G257 uses two functions for 100% stator earth fault protection. Residual overvoltage protection (59N) and third harmonic undervoltage protection (27TN). The residual overvoltage protection covers up to 95% of the stator windings starting from the generator terminal and the third harmonic undervoltage protection protects the parts closest to the neutral point and overlaps into the range of the residual overvoltage protection. The third harmonic voltage produced by the generator must be at least 1% of the nominal voltage for the third harmonic undervoltage protection to work on Arcteq AQ G257. (Arcteq Relays Ltd., 2021). Figure 23 describes the coverage of the functions used to achieve 100% stator earth fault protection using this relay.

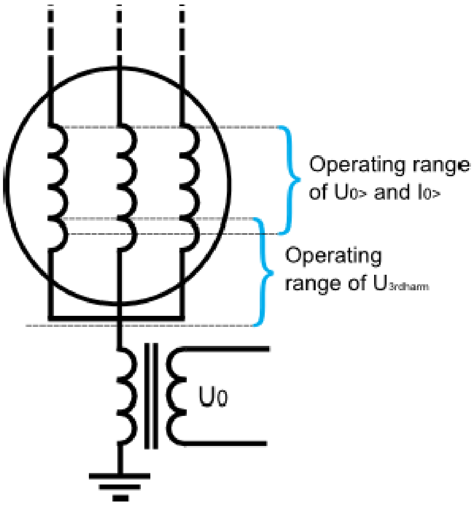


Figure 23. Coverage of the functions used by the AQ G257 for 100% stator earth fault protection. (Arcteq Relays Ltd., 2021).

5.5.4 Hitachi REG670

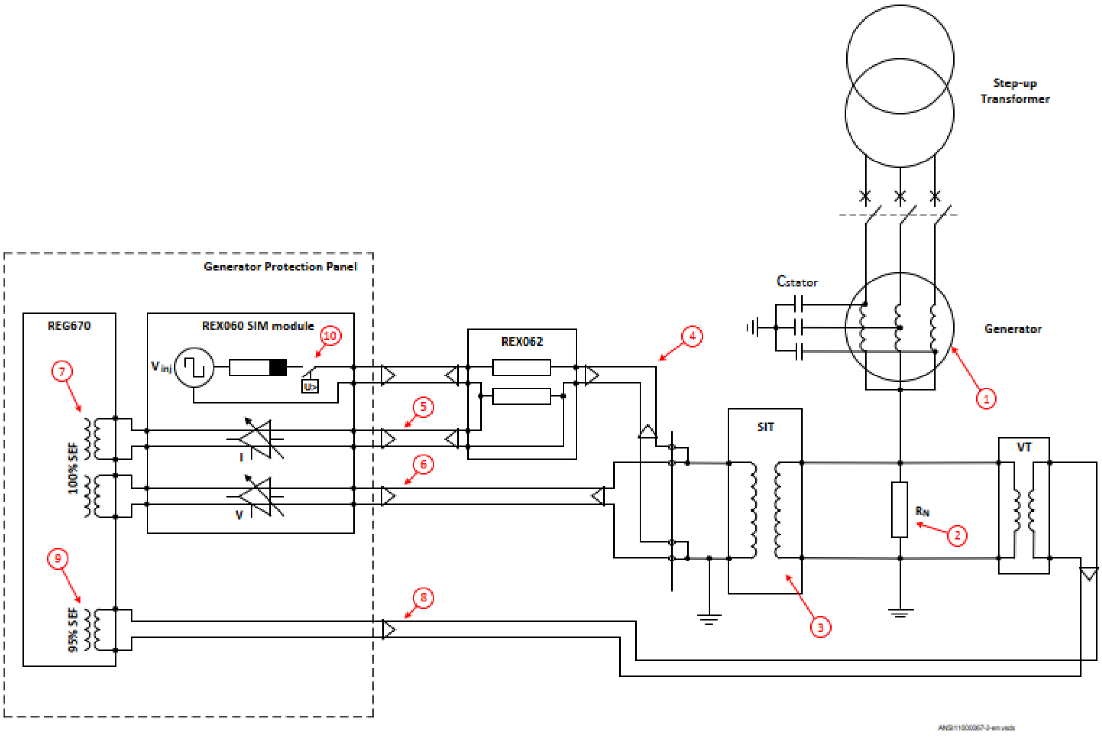
The Hitachi REG670 protection relay supports 100% stator earth fault protection based on the injection-based method, STTIPHIZ (64S) as well as third harmonic-based STEFPHIZ (59THD). For the implementation of STTIPHIZ (64S) using the REG670, the generator must be connected to the power system through a unit step-up transformer in a block connection. (Hitachi Energy, 2023). This relay is mainly suitable for larger generators (Discussion meeting 21.2.2024).

For the implementation of STTIPHIZ (64S) with REG670 the following additional hardware is needed:

- Injection device REX060
- Shunt resistor unit REX062
- Signal Injection Transformer (SIT)

A square wave current signal is generated by the injection device REX060. The square wave signal is injected into the stator windings through the REX062 shunt resistor and the SIT. (Hitachi Energy, 2023).

64S can detect earth faults in 100% of the stator windings at standstill. including the connected equipment, such as the high voltage windings of the excitation transformer as well as the bus ducts until the terminals of the generator circuit breaker. When the generator is online STTIPHIZ (64S) and residual overvoltage protection ROVPTOV (59N) should cooperate to provide 100% stator earth fault protection. 59N covers about 95% of the stator winding starting from the terminal side. 64S protects the neutral point of the generator and sections close to it resulting in the functions overlapping each other. Both functions must be configured in the same REG670. (Hitachi Energy, 2023). Figure 24 describes the connection of the STTIPHIZ (64S) function using the REG670 relay.



1 Generator unit consisting of a synchronous generator and a unit step-up transformer
2 Primary neutral grounding resistor
3 Signal injection transformer (SIT) that provides galvanic separation between primary circuit and injection equipment
4 Cable used to inject the square-wave current into the stator circuit
5 Connection for the measurement of the injected current. This signal is amplified in REX060 before it is given to REG670 for evaluation.
6 Cable for measurement of the injected voltage at the injection point. This signal is amplified in REX060 before it is given to REG670 for evaluation.
7 Two voltage inputs of REG670 which are used to measure injected current and voltage
8 Cable for 95% stator earth-fault protection using VT
9 Separate VT input of REG670 used for 95% stator earth-fault protection
10 Protection for over-voltage posed by the generator. The trip level depends on the set *UmaxEF* of REX060.

Figure 24. Connection of STTIPHIZ (64S) using REG670. (Hitachi Energy, 2023).

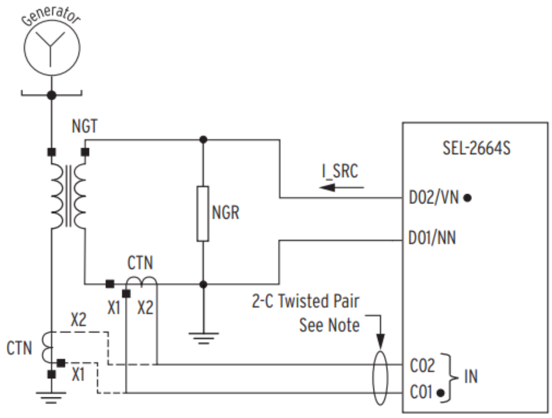
The Hitachi REG670 protection relay also supports 100% stator earth fault protection based on both the third harmonic undervoltage (27TN) at the neutral point and the third harmonic differential principle (59THD) (Hitachi Energy, 2023).

5.5.5 SEL-2664S

The SEL-2664S is a stator ground protection relay. The relay supports the IEC 61850 communication protocol and can be used as a standalone protection device or in combination with other SEL or third-party protection relays. The relay offers 100% stator earth fault protection by low-frequency injection (64S), rotor field ground protection (64F), residual overvoltage protection (59N), and neutral ground resistor monitoring. The SEL-2664S is said to be easily implemented into existing generator protection. SEL-2664S is designed for high-resistance grounded generator configurations. (Schweitzer Engineering Laboratories, Inc, n.d.).

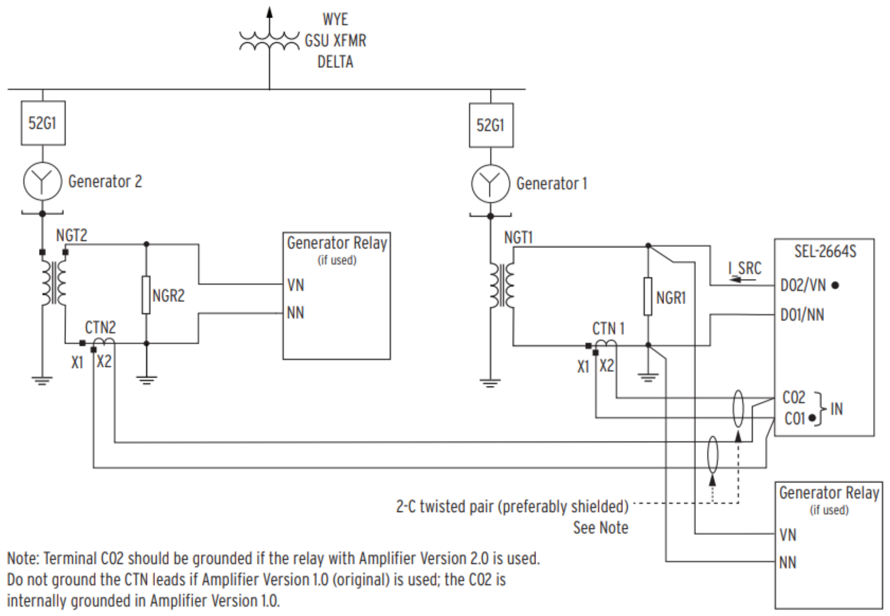
The SEL-2664S provides 100% stator earth fault protection (64S) by using a multi-sine signal injection at generator neutral. The 64S function should be used in combination with the 59N function to provide 100% stator earth fault protection. (Schweitzer Engineering Laboratories, Inc, 2022).

The SEL-2664S data sheet describes many possible connections of the relay. One possible connection for a single generator is described in Figure 25. Figure 26 describes one possible connection for two paralleled high-resistance grounded generators.



Note: Terminal C02 should be grounded if the relay with Amplifier Version 2.0 is used. Do not ground the CTN leads if Amplifier Version 1.0 (original) is used; the C02 is internally grounded in Amplifier Version 1.0.

Figure 25. Example connection of the SEL-2664S for a single generator. (Schweitzer Engineering Laboratories, Inc, 2022).



Note: Terminal C02 should be grounded if the relay with Amplifier Version 2.0 is used. Do not ground the CTN leads if Amplifier Version 1.0 (original) is used; the C02 is internally grounded in Amplifier Version 1.0.

Figure 26. Example connection of the SEL-2664S for paralleled generators. (Schweitzer Engineering Laboratories, Inc, 2022).

6 Testing procedure

The 100% stator earth fault protections based on the third harmonic voltage always require some testing during commissioning to find good settings for the function. During the making of this thesis, a relay expert was contacted and asked to describe their recommended testing procedure for setting the third harmonic-based 100% stator earth fault protection function.

- **How should the third harmonic-based 100% earth fault protection be tested at site, and what is a good procedure for finding sufficient setting values?**

> "At site, one can record/monitor the generator's healthy state third harmonic values at different loads. The Voltage N 3.H Lim setting (pickup setting) is then selected to be below the lowest recorded value by an amount which is higher than the protection function's stated operation accuracy, plus an additional safety margin which must be considered case by case. For setting of Beta and CB open factor parameters the REX640 Technical Manual gives instructions. With several generators running in parallel to a common bus, the story is then more complicated. Obviously, the minimum 1% of third harmonic voltage content under healthy condition must be satisfied.
>
> The simplest way of testing the function is to increase the voltage N 3.H Lim setting above the third harmonic healthy state content, obviously considering the loading situation and effect of Beta bias parameter." (Email conversation, 3.1.2024).

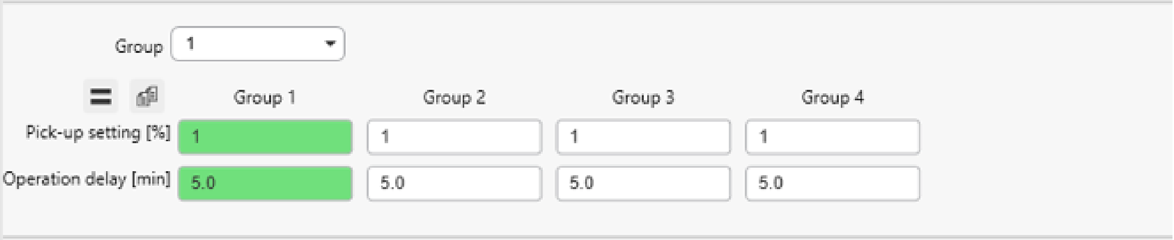
7 Suitable applications for implementation of 3rd harmonic-based stator earth fault protection

100% stator earth fault protection has been implemented in these types of power plants earlier due to specific requirements from customers and mandatory tender requirements. Ideally, third harmonic-based stator earth fault protection would be used for large-scale generators with big unit transformers, as mentioned in Chapter 5.2. It is not a straightforward procedure to implement this protection for generators sharing step-up transformers. It requires systematic testing and setting of the function to eliminate false tripping. Furthermore, the protection will generally have to be blocked during a few scenarios when the third harmonic voltage is very low. It is frequently occurring that modern generators occasionally produce too low levels of third harmonic voltage while several units share a step-up transformer. (Discussion meeting, 21.2.2024). The main improvements of the third harmonic stator earth fault protection that is focused on in this thesis, is to evaluate if the function could operate with a third harmonic voltage lower than 1% of the nominal voltage and be made more reliable while multiple generators share the same step-up transformer. Since the third harmonic is not desired in the system as described in Chapter 5.1, it is not a viable solution to redesign the generators to produce higher third harmonic voltage. Discussions about this topic have been held with two protection relay manufacturers. They both requested measured values of the third harmonic voltage in the form of disturbance recorder (DR) files downloaded from the protection relays at a power plant. The DR files should be downloaded from the relays while multiple generators are running and are connected to the same bus with varying load levels and power factors. The disturbance recorder should be triggered in all generator protection relays simultaneously.

8 Results

DR files were gathered from two different power plants during commissioning. Power plant 1 uses protection relays from relay manufacturer 1 and power plant 2 uses protection relays from relay manufacturer 2.

Relay 1 supports third harmonic undervoltage protection 27TN. The settable parameters are displayed in Figure 27. *Pick-up setting* is the settable pick-up value for the function. *Operation delay* is the time delay setting for the function.



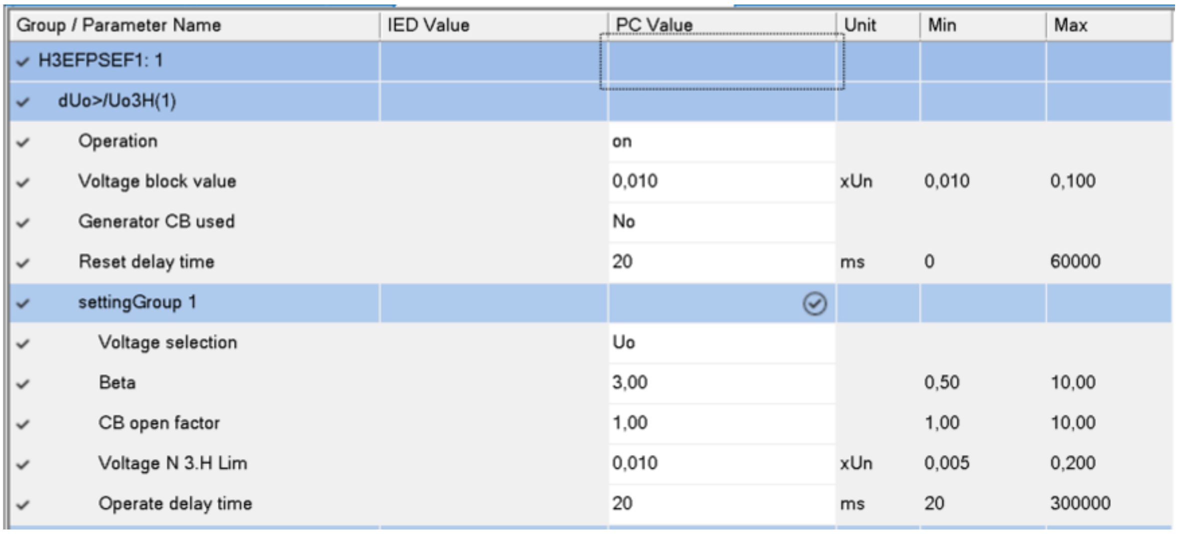
Group: 1

	Group 1	Group 2	Group 3	Group 4
Pick-up setting [%]	1	1	1	1
Operation delay [min]	5.0	5.0	5.0	5.0

Figure 27. Relay 1 settable parameters for third harmonic undervoltage protection.

In relay 2 both third harmonic undervoltage protection (27TN) and third harmonic differential protection (59THD) are available. The settable parameters are displayed in Figure 28. *Operation* is set to on/off to enable or disable third harmonic-based earth fault protection. *Voltage block value* is a low-level blocking for the 59THD function. *Generator CB used* specifies if there is a generator circuit breaker used. *Reset delay time* is the time delay for the function to reset.

The *Voltage selection* setting is chosen according to how the third harmonic voltage at the terminal side is measured when used as the 59THD function. The *Voltage selection* setting is set to “No voltage” to enable the 27TN function instead. *Beta* is used as a multiplier to the bias voltage as mentioned in chapter 5.1 when using the 59THD function. *CB open factor* is used as a multiplier to the bias voltage when the generator circuit breaker is open. *Voltage N 3.H Lim* is the pick-up setting for the 27TN function. *Operate delay time* is the time delay setting for the function.



Group / Parameter Name	IED Value	PC Value	Unit	Min	Max
✓ H3EFPSEF1: 1					
✓ dUo>/Uo3H(1)					
✓ Operation		on			
✓ Voltage block value		0,010	xUn	0,010	0,100
✓ Generator CB used		No			
✓ Reset delay time		20	ms	0	60000
✓ settingGroup 1		✓			
✓ Voltage selection		Uo			
✓ Beta		3,00		0,50	10,00
✓ CB open factor		1,00		1,00	10,00
✓ Voltage N 3.H Lim		0,010	xUn	0,005	0,200
✓ Operate delay time		20	ms	20	300000

Figure 28. Relay 2 settable parameters for third harmonic-based earth fault protection.

Power plant 2 has two busbars with three generators per busbar sharing the same step-up transformer. A simplified version of power plant 2 is visualized in Figure 29.

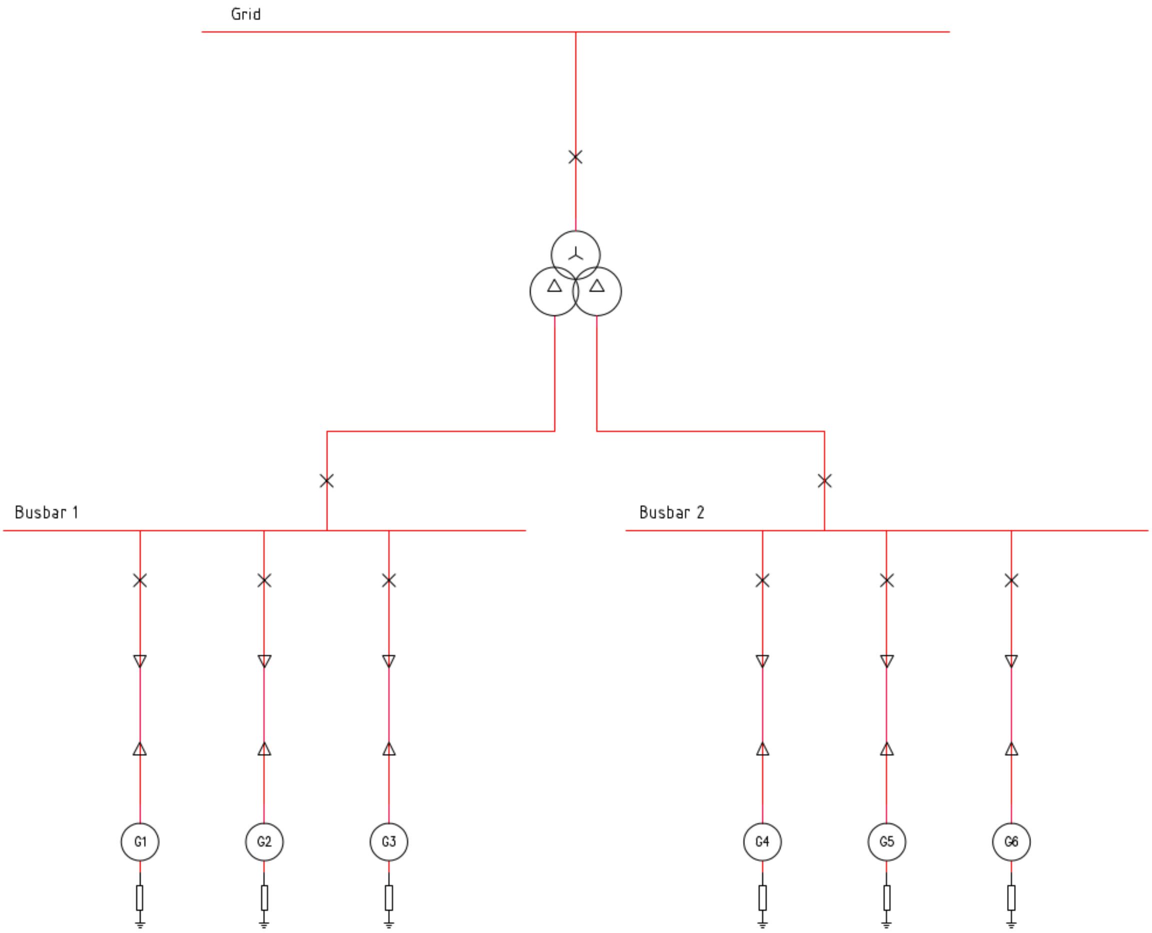


Figure 29. Simplified single line diagram of power plant 2.

Each generator has a nominal load of 18 MW. Below are different tests done at power plant 2 and their results described. During the test scenarios described below, third harmonic differential protection (59THD) was used with a time delay of 60 s. The 59THD trips if the differential voltage is larger than the bias voltage.

1. The 100% stator earth fault protection tripped immediately after synchronization with a Beta setting of 1,2. Beta was then changed to 2,5 and the protection worked as intended when one generator is connected to the bus. The difference between the Beta setting of 1,2 and 2,5 is visualized in Figure 30. All false trips were eliminated with one generator running when Beta was changed to 2,5 and this value was kept for the rest of the test cases.

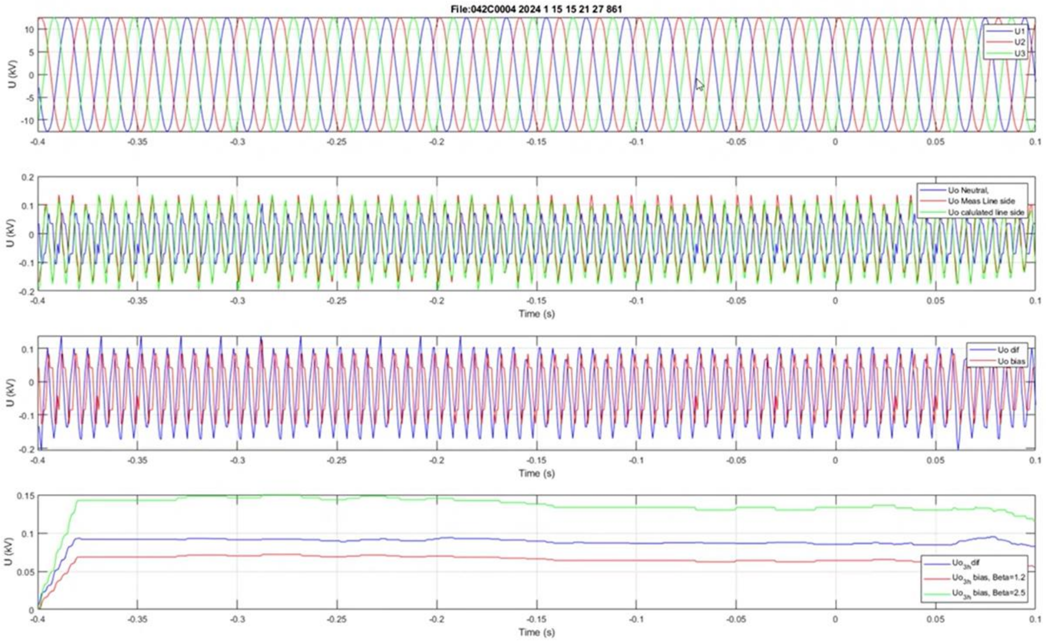


Figure 30. Testing of 100% stator earth fault protection with Beta 1,2 and Beta 2,5.

2. When generator 4 is operating at full load and generator 6 gets connected to the bus ramping up, the protection trips at about 4 MW of load on generator 6. The trip signal is cleared at about 10 MW.

3. When generators 4 and 5 are operating at full load and generator 6 is connected to the bus ramping up, the protection trips at about 4 MW of load on generator 6. The trip signal is cleared at about 12 MW.

4. When generator 4 is operating at full load, generator 5 is operating at 12 MW, and generator 6 is operating at 7 MW or below, the relay trips.

5. Generators 4 and 5 are operating at 75% load and generator 6 is operating at 7 MW. Power factors are as follows: generator 4 has PF 0,9, generator 5 has PF 0,8 and generator 6 has PF 1. The power factor for generators 4 and 5 is changed to PF 1. When the power factor is almost 1 for generators 4 and 5, generator 6's protection trips. Test case 5 is visualized with Beta settings 2,5 and 10 in Figure 31. 10 is the maximum available value of Beta.

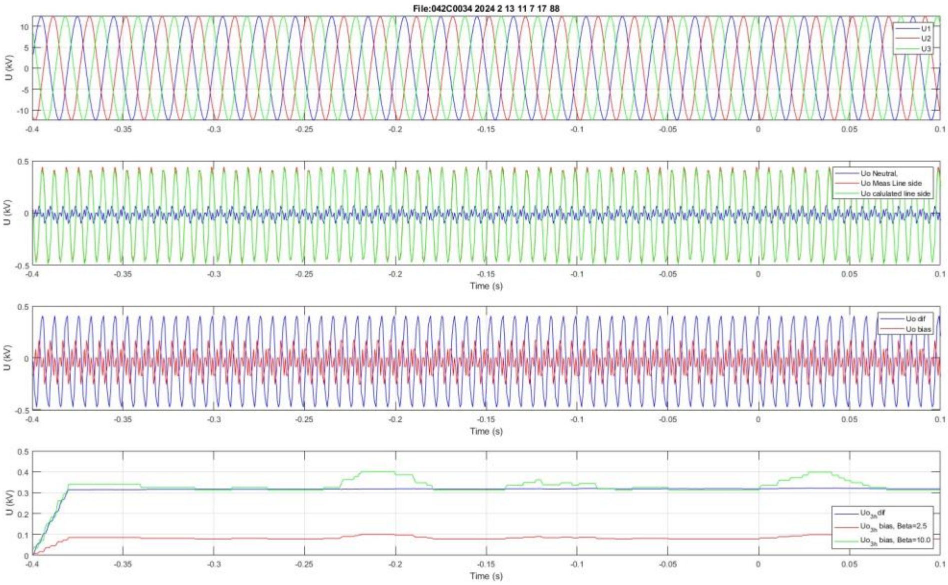


Figure 31. Test case 5 with Beta 2,5 and Beta 10.

6. All three generators operating with about 4 MW load and PF 1. No trip with Beta as 2,5.

7. All three generators operating with about 2,5 MW load and PF 1. There were risks of false tripping with Beta as 2,5.

These tests confirm that the magnitude of the third harmonic is dependent on the loading of the individual generators running in parallel to the common bus. The observation from these tests is also that the more generators connected to the bus, the higher the load per generator at which the protection gets cleared and vice versa. As shown in tests 2 and 3.

How the load is distributed between the generators seems however to be the key factor. As proven in test case 4, when generator 5 is operating at 12MW instead of full load. Generator 6's load can decrease down towards 7 MW before the protection trips. And in test case 6, where all generators were evenly loaded at only 4 MW there were no false trips.

During these tests, calculations were made by relay manufacturer 2 investigating the possibility of using third harmonic undervoltage protection (27TN) instead. The conclusion was that the 27TN function struggles in the same situations as the 59THD. The pick-up limit was also changed from 1% to 0,5% third harmonic voltage. However, situations with third harmonic voltage even under 0,5% were discovered.

Based on the test results Figure 32 was made by manufacturer 2 displaying the magnitude of the third harmonic voltage at the neutral and terminal side of the generator. The test case observed in Figure 32 corresponded to test case 2. Generators 4, 5, and 6 are all on the same bus. A similar phenomenon was also observed during test case 3. Generator 4 is operating at full load and generator 6 gets connected to the bus and starts ramping up. The measurements to the left are captured at generator 6 and the measurements for generator 4 are to the right.

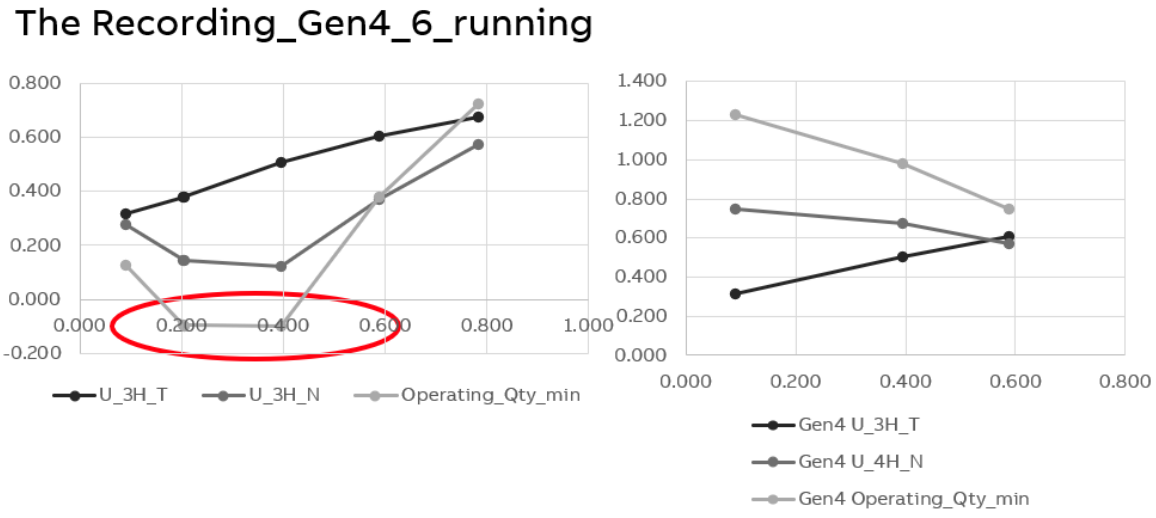


Figure 32. Third harmonic voltage variations at generator terminal and neutral point. (Discussion meeting 27.2.2024).

Figure 32 shows that the third harmonic voltage at generator 6's terminal is steadily increasing as the apparent load is increasing. The third harmonic voltage at the neutral side starts at a very similar magnitude as the third harmonic voltage at the terminal. The third harmonic voltage at the neutral side is however decreasing as the apparent load is increasing until about 40% load, where it starts increasing instead until it reaches a similar level to the third harmonic voltage at the terminal side. The third harmonic voltage at the neutral side is also decreasing on generator 4 which is operating with full load, however, not nearly as drastically. In these test cases with uneven load distribution, the cause of false tripping is the drop in the third harmonic voltage at the neutral side. "Operating_Qty_min" is used to monitor the behavior of the tripping signal. When Operating_Qty_min is negative the relay will send a tripping signal. Overall, the measurements at generator 4 which is operating at full load show steadier voltage levels.

A similar investigation has also been done at another power plant with 5 generators per busbar. The max load per generator is 14,7 MW. The result of that investigation shows that the protection picks up at lower loads, 1,95 MW – 7,5 MW, and must be blocked within this loading area to prevent false tripping. These results correspond to the findings in the earlier described tests.

All these influencing factors make it complex to find an appropriate setting for the protection to ensure the balance between the sensitivity of the protection settings and the reliability of the operations.

9 Conclusion

This thesis covers the topic of 100% stator earth fault protection for multiple generators operating in parallel in power plants. In principle, Generators in most cases have adequate earth fault protection which is covered by generator main protection to an extent of about 95% of the stator winding. However, by implementing the types of stator earth fault protection studied in this thesis, coverage to an extent of 100% is expected. 95% stator earth fault protection is generally considered to be sufficient earth fault protection and is provided as standard to all generators in power plants. 100% stator earth fault protection is implemented as an extra safety precaution based on special requests and requirements.

After studying different types of installations with single and multiple units and with various power plant configurations at varying operation conditions. It is observed that 100% stator earth fault protection is more suitable for power plants with one large generator compared to power plants with multiple smaller generators, regardless of the protection principle. This raises the question of what principle is most suitable for generators in power plants where many smaller generators are sharing step-up transformer.

Two main principles for 100% stator earth fault protection have been studied and both have their uses. The third harmonic-based stator earth fault protection, see Chapter 5.1, is a relatively suitable and reasonably cost-effective solution for the generators in the range of 10–25 MW.

As mentioned, most solutions for 100% stator earth fault protection based on the third harmonic are designed for one large generator with its own step-up transformer. It is however observed that the third harmonic-based 100% stator earth fault protection for multiple generators operating in parallel works satisfactorily while the load is evenly distributed between the generators and not effective with unevenly distributed loads or at very low loads. It was challenging to make a good choice of protection settings, especially when the generators were operating at lower or unevenly distributed loads. After carrying out different assessments to make a balance of the protection settings between the reliability of the operation and protection of the equipment, especially in those cases where the protection triggers at lower and uneven loads, it may be justified to block this protection for the generators that are operating with low loads relative to other generators on the bus. The recommendation would be to use the PEMMXU load measuring block in PCM600. The load measurements from each relay would be compared using GOOSE (Generic Object Oriented Substation Event) communication protocol, and a blocking signal is sent to the generators with low load relative to the highest loaded generator on the bus. This must be agreed upon with the customer and operations. It is also possible to provide the analog load signals between the relays, however, there is a limitation about the number of analog signals that can be wired to a relay. Considering this, GOOSE communication is more feasible.

With this concept, the third harmonic stator earth fault protection needs to be blocked at low load operations and for uneven load operations by using the PEMMXU block function as described in the previous paragraph. However, as and when the machine is put into a reasonably loaded condition with the loads evenly distributed between the units, the existence of stator earth faults can be detected also near the neutral point. It would be recommended to operate the generators above about 20% load with the load evenly distributed frequently instead of operating them at low and uneven load operations for long durations. Thanks to modern technology and the flexibility of the operations with multiple gensets, it is not required to run at low loads as the standby gensets can start and come to full load in a few minutes. Whenever the third harmonic stator earth fault protection gives an alarm the operators at site can perform an insulation test on the unit. Since an earth fault at the neutral point is not immediately dangerous, this solution is not bad but would still benefit from improvements to be unblocked as often as possible. If the protection will have to be blocked during some occasions it is very important to have uniform insulation of the stator windings. This will further minimize the risk of earth faults near the neutral point. An important note is that even during situations when the 100% stator earth fault protection is blocked, the traditional earth fault protection operates as usual and protects up to 95% of the stator winding. It is only the protection for the last 5–10% of the stator winding that is disabled during the blocking of the third harmonic earth fault protection.

The injection-based principle, see Chapter 5.3, is a decent alternative to the third harmonic-based stator earth fault protection if the generator is not producing sufficient levels of third harmonic voltage or if it is completely unacceptable for the 100% stator earth fault protection to be blocked even occasionally. The injection-based principle is also able to monitor the stator insulation while the generator is offline. To be remembered is that the injection principle by many manufacturers also is intended for one large generator with its own step-up transformer. In chapter 5.5.5 a solution is showcased for multiple generators running in parallel to a shared step-up transformer. The mentioned solution requires that every generator has its own SEL-2664S relay injecting a signal with a unique frequency. In applications with many smaller generators, this solution naturally comes with an unreasonable cost and is therefore generally more suitable for power plants with few or one large generator.

10 Discussion

During the making of this thesis, it was noticed that the 100% stator earth fault protection is challenging to implement on multiple generators sharing step-up transformers. The relay manufacturers do however offer well-working solutions for generators with a unit transformer. The stator earth fault protection based on the third harmonic has been the main focus of this thesis since it is the most reasonable solution for this size of generators between 10–25 MW.

Generator designs have been developed over the years to produce as low levels of harmonics as possible including the third harmonic. This is a good direction for generator development since harmonics are unwanted in the system and regulated by grid codes. The problem today is however that the third harmonic voltage produced by the generators is generally too low for third harmonic-based 100% stator earth fault protection when multiple generators share a step-up transformer. This is the motivation why the third harmonic stator earth fault protections would require an overhaul and investigation of possible improvements to be suitable for modern generator applications and power grids.

In chapter 8 the results of the third harmonic measurements at different power plants were presented. The test cases at power plant 2 were done only on busbar 2 with generators 4, 5, and 6 running, see Figure 29. The timeframe did not allow for more tests this time. Test cases with generators running on two busbars simultaneously could still be of relevance for this investigation in the future. During the thesis work, alternative methods of gathering the necessary measurements were also evaluated. Simulations of the third harmonic voltage for paralleled generators were considered. However, a conclusion was made that creating a simulation accurate enough would require a lot of work and was not reasonable as a part of this thesis. DR files were also gathered from the generator protection relay at a generator testing facility. The generators at the testing facility are ungrounded, as described in Chapter 4.4.1, and are loaded by inverters. It is a viable and necessary solution at the testing facility since the generators are swapped out very frequently. The third harmonic voltage in these measurements was however almost non-existent. This emphasizes the importance of gathering the data from configurations similar to those the development is intended for.

After all the information in this thesis has been considered, my own opinion is that the third harmonic-based stator earth fault protection, blocked as described in chapter 9, together with uniform stator insulation is a reasonable workaround solution to implement 100% stator earth fault protection. It is unlikely for an earth fault to occur in the last 5% of the stator winding in the first place. Additionally, a second earth fault closer to the terminal would have to occur before the third harmonic-based stator earth fault protection gets unblocked, for it to result in any significant damage to the generator. Making it a very unlikely scenario. For many applications, it is difficult to justify the significant additional cost of the injection-based principle for the minor extra protection it offers.

The investigation covered in this thesis will continue in cooperation with the relay manufacturers to further develop the performance of 100% stator earth fault protection for these types of power plants in the future. A suggestion for the direction of future development would be to investigate the possibility of making the third harmonic-based stator earth fault protection more secure during the challenging scenarios, described in chapter 8, rather than blocking it. For example, by implementing a dynamic Beta value that the relay would automatically increase during the challenging scenarios, which should result in better-performing protection.

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