Synchronization of Generators to Grid in a Flexible Testing Environment

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BACHELOR'S THESIS

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Abstract

This Bachelor's thesis is about synchronization of generators and is made for Wärtsilä Finland Oy at the Engine Laboratory in Vaasa. The purpose of the thesis was to gain better knowledge about synchronization and to investigate which factors have impact on it. Furthermore, the goal was also to plan a solution for synchronizing generating sets in a flexible testing environment.

The theory for this thesis contains conditions that must be met for a synchronization. To get a better overview of the synchronization, components in the distribution from generating set to the electrical grid are described.

Methods that are used for synchronization in power plants are investigated and by combining these with the requirements related to a flexible testing system, a solution is compiled. Requirements in this case are that the system must be able to manage variating voltage and frequency. An investigation in automation was also done to save time on installation for a new generating set.

The thesis resulted in a solution with multi voltage transformers and a frequency converter together with several busbars. Synchronization possibilities are located on different places in the distribution line, depending on requirements for the synchronization, modifications can be done to fulfill the function.

Language: English Key words: Synchronization, Generating set, Switchgear

EXAMENSARBETE

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Abstrakt

Detta examensarbete om synkronisering av generatorer gjordes åt Wärtsilä Finland Oy vid motorlaboratoriet i Vasa. Syftet med arbetet var att få bättre kunskap om synkronisering samt att undersöka vilka faktorer som har en inverkan på detta. Samtidigt skulle en lösning för synkronisering av Gensets i en flexibel testmiljö planeras.

Teorin för detta examensarbete omfattar de krav som ställs för en synkronisering. För att skapa en bättre överblick av synkronisering är även komponenter relaterade till eldistributionen beskrivna, från Genset till elnätet som det ansluts till.

Metoderna om hur synkronisering görs i kraftverk undersöks och genom att kombinera dessa med fordringar relaterade till ett flexibelt testsystem, sammanställs en lösning. Fordringarna i det här fallet är att systemet måste klara av varierande spänningar och frekvenser. För att spara tid vid installation av ett nytt Genset undersöktes automationsmöjligheter.

Undersökningen resulterade i en lösning med mångspänningstransformatorer och en frekvensomvandlare tillsammans med ett mångsidigt skensystem. Synkroniseringsmöjligheter är placerade på olika ställen i distributionslinjen. Beroende på fordringar för synkroniseringen kan modifikationer göras för att få till en fullständig funktion.

Språk: engelska Nyckelord: synkronisering, kraftverk, ställverk

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Nimike: Generaattorien synkronointi verkkoon joustavassa testausympäristössä

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Tiivistelmä

Tämä opinnäytetyö generaattoreiden synkronoinnista on tehty Wärtsilä Finland Oy:lle Vaasan moottorilaboratoriossa. Työn tarkoituksena oli saada parempaa tietoa synkronoinnista ja tutkia, mitkä tekijät vaikuttavat tähän. Samalla piti suunnitella ratkaisu, miten Gensettien synkronointia tehtäisi joustavassa testausympäristössä.

Opinnäytetyön teoria sisältää synkronointivaatimukset. Paremman synkronoinnin yleiskuvan luomiseksi, kuvataan myös sähkönjakeluun liittyviä komponentteja Gensetistä siihen sähköverkkoon, johon se on liitetty.

Menetelmiä, joilla synkronointi suoritetaan voimalaitoksissa, tutkitaan ja yhdistämällä ne joustavaan testausjärjestelmään liittyviin vaatimuksiin kootaan ratkaisu. Tässä tapauksessa vaatimukset ovat, että järjestelmän on hoidettava vaihtelevia jänniteitä ja taajuuksia. Ajan säästämiseksi uuden Gensetin asennuksessa tutkittiin automaatiomahdollisuuksia.

Työn tuloksena saatiin ratkaisu monijännitemuuntajilla ja taajuusmuuttajalla yhdessä monipuolisen kiskojärjestelmän kanssa. Synkronointiominaisuudet sijaitsevat jakelulinjassa eri paikoissa. Synkronoinnin vaatimuksesta riippuen voidaan tehdä muutoksia täydellisen toiminnon saavuttamiseksi.

Kieli: englanti Avainsanat: synkronointi, voimalaitos, kojeisto

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1 Introduction

This thesis considers synchronizing of generating sets to grid in a flexible testing environment and is made for Wärtsilä Finland Oy at the Engine Laboratory in Vaasa.

The common set-up in engine testing with synchronous generators is that the engine loading is done on the electrical grid. When running fixed frequency and voltage that correspond to the electrical grid it is possible, but today there are also situations when load banks are used to complete the system. Load banks are flexible to use but the produced energy is wasted unnecessarily so a new more flexible method is required.

A generating set is synchronized to the grid by some means, it is very critical that this synchronizing is done correctly otherwise severe damage can occur in the system. The goal is to have the engines into the test cells and running as fast as possible, minimizing the installation time.

1.1 Background

Wärtsilä is moving its business from Vaasa City to Vaskiluoto where a new Smart Technology Hub (STH) is under construction. The new STH is planned to be as environmentally friendly as possible and therefore all the generated power must be taken care of. This means that engines which are on test run or in laboratory use should be connected to grid, independent of size and specs. Problems occur then because the voltage on each generating set may be on different level in different engine cells. Therefore, the switchgear must be built to handle different voltages from different engine cells at the same time and be connected to the local grid. The voltage difference can be adjusted by multi-voltage transformers partially, but the synchronization of the power sources to grid is still complicated. To prevent mistakes there must also be included a working interlocking system.

1.2 Purpose

The purpose with this thesis is to get deeper knowledge in synchronizing, what factors have an impact on this and what impact do the multi-voltage systems have on the synchronization. Also, to investigate how installation and synchronization can be done in a fast and safe way in a fast changing and flexible testing environment. Moreover, to collect information inside and outside the organization about current solutions, evaluate these and plan a solution that

based on the investigation would be the best one. A time saving point is also to investigate how much can be automated from a safety perspective.

1.3 Employer

Wärtsilä was established in 1834 in the county of Karelia, the business started then with a sawmill. Since that Wärtsilä have been involved in many business areas and companies. Nowadays it is a global leader in smart technologies and complete lifecycle solutions for the marine and energy industry. The company wants to maintain high quality and cost efficiency and therefore constantly seeks new ways to go forward. By focusing on digitalization and investing in R&D they secure and strengthen their position on the market.

Wärtsilä operates in over 200 locations in more than 80 countries around the world with approximately 19,000 employees. Net sales totalled 5.2 billion EUR in 2018 and the company is listed on Nasdaq Helsinki. Jaakko Eskola is titillated as President & CEO of Wärtsilä Corporation. [1]

2 Theory

This chapter will consider necessary theory about power generation and the transmission of electricity to the electrical grid. To be aware of the process all the way from the power source to the consumers is important for a good understanding in this topic. Therefore, this theory will go through the whole chain and give a describing section about components that are used. Synchronization can be seen as the most important thing in this chain, at least from the generating side seen. If a breaker is closed at a wrong moment it may cause severe damage due to high currents and forces.

2.1 Generating Set

Wärtsilä is producing generating sets (gensets) for marine industry and power plants worldwide. A genset consists of a diesel, gas or dual fuel engine connected to a synchronous generator via a flywheel and coupling, mounted on a common baseframe with conical rubber mounts. The smaller gensets are popular in tug boats and as auxiliary to power plants for example. For power generating and in large ships bigger gensets, for instance W46 engines are used. W46 is named after Wärtsilä and the cylinder bore of 46 cm. The new Wärtsilä 31SG has also been introduced to the market with low emissions and over 11 MW output on a Wärtsilä 20V31SG genset. This engine has a V shape and consist of 20 cylinders with a bore of 31 cm. SG stands for spark ignited gas, which means that this is a pure gas engine. If the engine name ends with a D, it is a diesel engine and if it ends with DF it is a dual fuel engine that goes on both gas and diesel.

The benefit with gensets in marine use, as diesel-electric propulsion is that engines can run on optimal speed to be as efficient as possible instead of running on various speed with use of gearboxes and shafts to the propellers. An engine that runs on various speed needs a wide torque range to difference from the genset solution that can be optimized on a fixed speed.

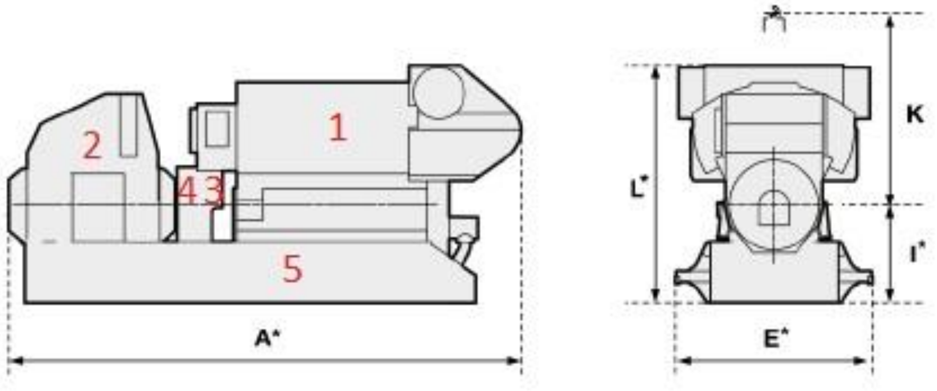

Figure 1: Wärtsilä 31DF Genset [2]

Explanation of numbers and letters in figure 1:

1 Engine
2 Generator
3 Flywheel
4 Coupling
5 Baseframe
A Total length of the generating set.
E Total width of the generating set.
I Distance from the bottom of the common baseframe to the crankshaft centreline.
K Minimum height from the crankshaft centreline when removing a piston.
L Total height of the generating set.
The values are variating depending on quantity of cylinders and generator choice.

As example a Wärtsilä 31DF genset with a 10V31DF engine have a length on 9,75 m, a height on 4,9 m and the weight is around 100 ton. [2]

2.1.1 Generators

A generator is an electrical machine that converts mechanical energy into electrical energy. There are various types of generators such as alternating current generators, direct current generators, vehicular generators, and so on. The alternating current generators can also be split into two categories, synchronous and asynchronous. The difference between these two is the construction that determines the function and rotating speed.

An asynchronous machine is easier built and therefore also cheaper. The most common electrical machines are asynchronous motors, but they are rarely used as generators. This

machine is made to work with a nominal speed. Depending on load, the speed can be both over and under nominal speed. For generator use the machine needs to be accelerated up to nominal speed before it can start to generate power. The power generates when the machine goes over the nominal speed with help of an external force, for example a turbine. With use of an asynchronous machine as generator there is often a need for a gearbox to increase the speed on the driving shaft. A mechanical break is also necessary in case of overspeed that can result in excitation losses.

The main use for synchronous machines is as generators at power plants. The name synchronous comes from that the rotor rotates with synchronous speed against the grid connected. An advantage with this generator type is that it generates electricity from a few rpm and up to a little bit over nominal speed. The synchronous generator has maximum torque with synchronous speed which means that the speed stays constant when the load changes, while the load stays under maximum capacity for the generator.

The synchronous generator consists, like typical generators of a rotor and a stator. The rotor is a large electromagnet that rotates in the stator. Rotors are made with magnetic poles and are laminated to reduce eddy current losses. The stator is found in the chassis and consists of windings that induces a 3- phase voltage of the rotating magnetic field from the rotor. Magnetization of the rotor is done by a DC current in two different ways. Supply DC power by slip rings and brushes from an external source or supply DC power by a brushless exciter. Large generators are using brushless exciters and they are mounted on the same shaft as the rotor. The exciters function is like the generators, but the parts is on the contrary. The shaft works as stator and generates a 3- phase current that rectifies to DC before it can be used. Another option is to use permanent magnets that produces magnetic fields for the rotor. Magnetization in the rotor is necessary for the function. Without magnetic fields in the rotor there are no forces that creates currents in the stator windings.

Voltage regulation for the output current is regulated by the excitation current for the rotor. Higher excitation current means stronger magnetic fields and therefore higher output voltage and contrariwise for lower excitation current. Permanent magnet generators have a disadvantage here because of the air gap flux that cannot be controllable, which means that the voltage is hard to regulate.

For a synchronous generator, the synchronous speed can be calculated if you know the electrical grids frequency and pole number for the generator.

The formula is:

$$N_s = \frac{120 * f}{P}$$

Where:

N_s = Synchronous speed, rpm

f = Frequency, Hz

P = Number of poles

120 is a constant for the time (seconds/minutes) and pole pairs, to get the speed in rpm.

The poles P is always in pairs, which means that the maximum speed is 3000 rpm at 50 Hz and to run a diesel engine on 750 rpm requires an 8 poles generator to get synchronous speed.

$$P = \frac{120 * 50Hz}{750rpm} = 8\ poles$$

The synchronous generator starts to generate electricity when the rotor angle is in front of the stator rotating magnetic field. If the generator slows down, it will take power instead and work as a motor. [3]

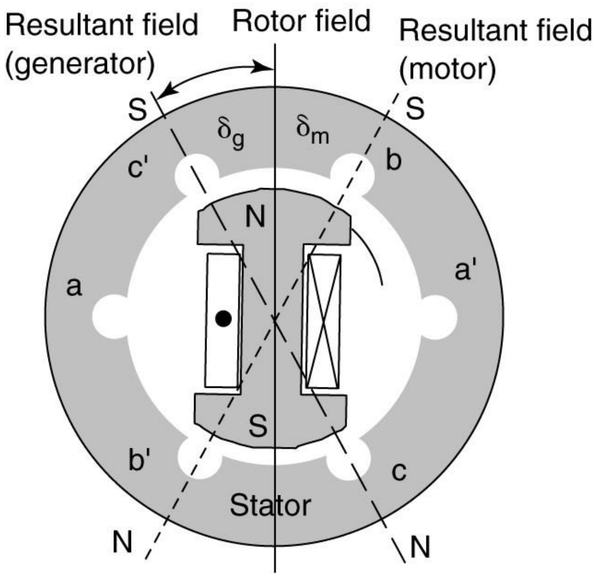

Figure 2: Function of a synchronous machine [13]

In the picture above the difference between generator and motor operation is shown for a synchronous machine. The rotor is rotating counter clockwise in this case.

2.2 Transformers

Without transformers, it would not be financially possible to transfer electricity through countries or longer distances. Every electrical grid includes transformers to increase the voltage after the power plants to reduce currents. After transmission the voltage is lowered again for the consumers use. Transformers can be divided into two types, single phase and three phases. Single phase transformers are often seen in homes as implement for illuminations etc. but in this case with electrical transmission they are mostly used for instrumental transformation. Three phase transformers are most common as power transformers in electrical grids and manage huge amounts of electricity. Due to this an old transformer, can be more expensive than a change to a new one with lower losses.

Transformer construction consists of windings and a core. Insulation vary of the position and use of the transformer and is either with oil or dry isolated. The number of windings and core shape vary between transformer types, but the main function is same for all of them. The primary winding creates a magnetic flux in the core when electricity passes through. This flux goes around in the high magnetic permeability core and in the secondary winding a voltage is induced. An ideal transformer according to Faraday's law, induces a voltage in each winding proportional to its number of winding turns since the same flux passes through both windings. A real transformer has of course losses caused by the magnetic flux and in the metal core but that is not treated now. In Figure 3 below the function of a one phase transformer is shown.

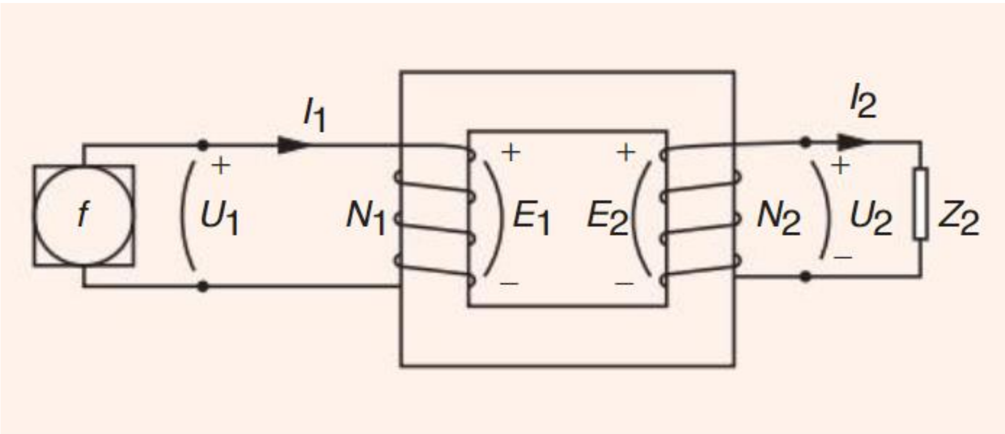

Figure 3: Transformer function description [3]

If this was an ideal transformer the connection between the values could be calculated with a formula of:

$$\frac{I_1}{I_2} = \frac{U_2}{U_1} = \frac{N_2}{N_1}$$

A three-phase transformer can be connected in different ways between the windings to obtain different output voltages and phase angles depending on needs. [3]

2.3 Frequency converter

Produced electricity have a frequency related to the rotating speed of the generator and this frequency is not always equal to the electrical grid's frequency. It can also be that an electrical motor needs to be run on variating speed or a specific speed not equal to the grid's frequency. Then there is need for a frequency converter that converts the powers frequency to another frequency that can be used.

Simply described, frequency converters can be sectioned into three parts: rectifier, DC bus and inverter. These parts are described below including a figure of the process.

The rectifier converts the AC sine wave into DC by using diodes that only passes through the positive side of the sine wave.

The DC bus filter the AC "ripple" voltage from the converted DC. The filtration is done by an inductor and capacitors to get a smoother DC before the inverter section.

The inverter part makes AC sine waves from the DC and this is done with high speed switching transistors. [3]

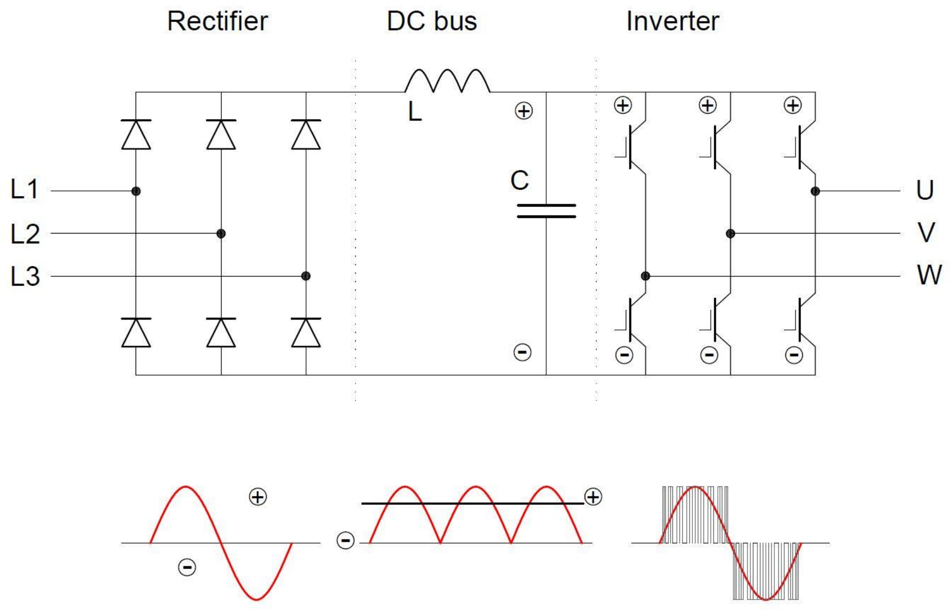

Figure 4: Frequency converter process

2.4 Switchgear

To control the generated power there is a need for a switchgear. A switchgear includes units to control, protect and isolate electrical equipment. Switchgears are shared into different voltage levels, low, medium, and high voltage. In Wärtsiläs testing environment, equipment in medium voltage range is used.

The significant parts in a switchgear are; circuit breakers, disconnectors, earth knives, busbars, measurement transformers, fuses and protection relays.

All switchgears are not identical to each other so the contain of equipment inside can variate a lot from case to case. The construction is anyway the same with dimensions and formats for a certain model type. [4]

2.4.1 Circuit Breakers

Circuit breakers (CB) are used to break the current that flows through a system. They are used as safety equipment when the current flow gets too high or as a safe way to just cut off the currents for service works etc. Without CB, there would not be any ways to control the

electricity. The CB can be operated manually or on distance with signals from a protection relay or synchronization relay as example.

If a short circuit should occur, it will result into very high currents that the breaker must be able to manage. These currents can be thousands of amperes and to handle these there are two common options of CBs for medium and high voltage, vacuum and SF_6 gas insulated.

The vacuum CB is constructed with vacuum around the metal connectors. Vacuum extinguishes the arc between the contact surfaces in the breaker mechanism because of its particle free property.

The SF_6 gas CB contains sulfur hexafluoride gas that have unique properties to extinguish the arc in the breaking moment. The construction is made with a cylinder and piston principle so the gas compresses in the opening moment and blows forward through the formed arc guided by nozzles and in that way extinguish it. The function is described with a picture below. [5]

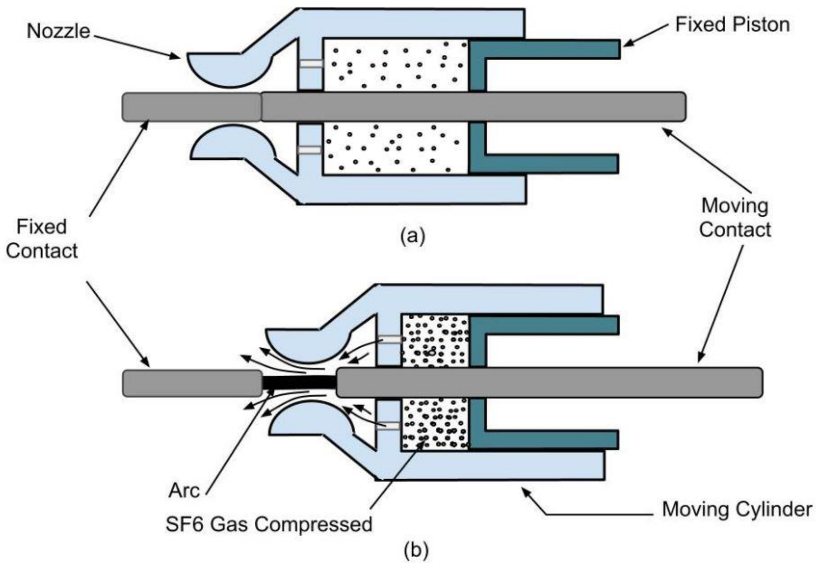

Figure 5: Description of SF6 gas use in CBs

2.4.2 Disconnector

Disconnectors are used to ensure that the electrical circuit is completely de-energized and to make it visible for the maintenance personnel that the circuit is open. A disconnector is similar to a breaker but cannot break a loaded circuit as a CB and can only be used as a complement. Disconnectors are used as a safety complement in switchgears to allow safely service work without the risk that the CB closes and begins to conduct power. To operate the disconnectors the circuit must first be opened by a CB and then controlled manually or automatically. To secure a safe work disconnector can also be locked in open position.

2.4.3 Earth switch

Earth switches are used to provide extra safety to working personnel, both on the electrical side and the mechanical side with the engines that are connected via generators. Even after the CB and disconnectors are opened there can be some residual charges on the bus which can be dangerous under maintenance. Therefore, are earth switches used to secure that the transmission line is connected to ground. Earth switches can be operated manually or be automated, so they close when the CB opens.

2.4.4 Busbars

To distribute power in electrical installations between supply points and output circuits, busbars are used. These are made of copper or aluminum and used instead of cables to get more compact and simple solutions in switchgears and power stations. When planning busbars, currents needs to be calculated to decide dimensions. Small busbars give much losses due to resistance and large busbars takes much space and costs more to build. To get more flexibility in a switchgear there can be double busbars. Then it is possible to guide power from different supplies to different circuits in same time. Busbars can also be coupled together to get more connection points for the distribution. The coupling is then done with a circuit breaker either with deenergized busbars or energized by synchronization. [4]

2.4.5 Instrument transformers

When the voltage is on medium voltage level and the currents goes up over 1000 A it comes a need for transformers to lower the levels. Then the instrumentation transformers with high accuracy class are useful. These transformers are used for instrumentation, measuring or to

get an isolated secondary side. In testing environments, it is common that different relays are used for different equipment. For example, transformers for protection equipment does not need to be exactly accurate but needs to tolerate fast changes. Instead transformers for measurement have high requirements on accuracy. Typical accuracy classes can be 0,5 % on instrumentation and 0,2 % measurement.

2.4.5.1 Current Transformer (CT)

To measure the current flow in the conductors or busbars there must be a current transformer between the power side and the measuring side to lower the current into small standardized values. The most common setup is a 5 A current on secondary side when there is a nominal flow through the primary winding. With 500 A, nominal current on the primary side it’s a transformation with 100 times.

2.4.5.2 Voltage Transformer (VT)

Voltage transformers are used like CTs but instead of transforming currents, its voltage that transforms. The most common setup for voltage transformers is to transform voltage on primary winding into 110 volts on the secondary winding. 110 V and $110/\sqrt{3}$ V is standardized values that most of the control equipment uses.

2.4.6 Protection relays

Relays are programmable units that monitor circuits and associated equipment. When changes outside the preset values are detected, the relay starts to operate according to the settings that are chosen. It can be to start a timer for a function, make an alarm or something else from the relays setting list.

Relay protection is mostly built as a system where many relays works together and completes usually with instrumental transformers and circuit breakers. When a fault occurs, and is observed by the protection relays, an open signal is sent to the CB that belong to this circuit to avoid damage. Protection is normally divided into separate protection areas to enable flexible changes and to pretend that big sections affects in case of faults.

A possible section division on a power plant could be a section per generating set with transmission line to the switchgear or per busbar if a fault occurs on outgoing line. [3]

2.5 Electrical grid

To distribute generated power to the consumer an electrical grid is necessary. This grid considers power generation, substations, transformers, transmission lines and consumers. Power plants generate electricity that transfers over to substations with high voltage. Substations split the transmission into separate sections and transform voltages if necessary. Transformers near the consumers lower the voltage into low voltage that fits the customers. Consumers in industry, trading and farming are more special customers that can get their electricity straight from medium voltage grid.

The Finnish electrical grid is built with a head grid on high voltage level, 110 kV- 400 kV. High voltage is used to lower the currents and, in that way, reduce losses that can be high. In this case on a total length of 22 500 km. To widen this grid, distribution grids with medium and low voltage is used. The MV grid, 1- 70 kV, have a total length of 140 000 km and the LV grid under 1 kV have a total length of 240 000 km. Due to high costs for cables in the ground, main part of the Finnish grid is built with conductors in air. [6]

2.6 Synchronization

When connecting a synchronous generator to an electrical grid an accurate synchronization must be done to secure a safe coupling. If the synchronization fails, large equipment damage can occur. There are four conditions that must be met before the circuit breaker can be closed. These four are listened and described below.

Voltage Magnitude
Frequency
Phase angle
Phase Sequence

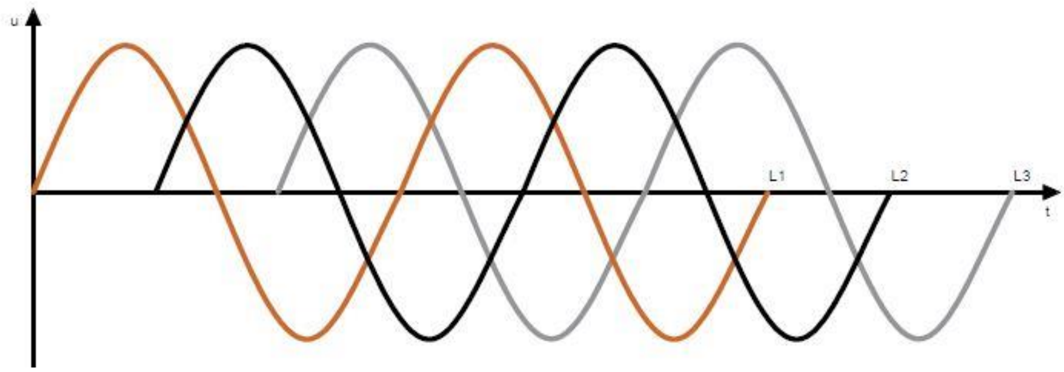

Figure 6: Description of a 3-phase voltage

Voltage Magnitude

AC voltage alternates in polarity and can be plotted as a sinusoidal waveform, this means a positive and a negative pulse per period per phase. By measuring the height of the peaks, the peak voltage can be defined. If peak-to-peak value of the waveform is more interesting the measuring must be done between the opposite peaks.

The electrical grid consists of a sinusoidal voltage with a fixed magnitude. To synchronize a generator to grid requires that the voltage magnitudes are equal. If there are differences in the magnitude it will result in a high reactive power flow. If the generator is overexcited so that the voltage is higher than the grid voltage it will generate reactive power and opposite if the generator is under-excited it will take reactive power.

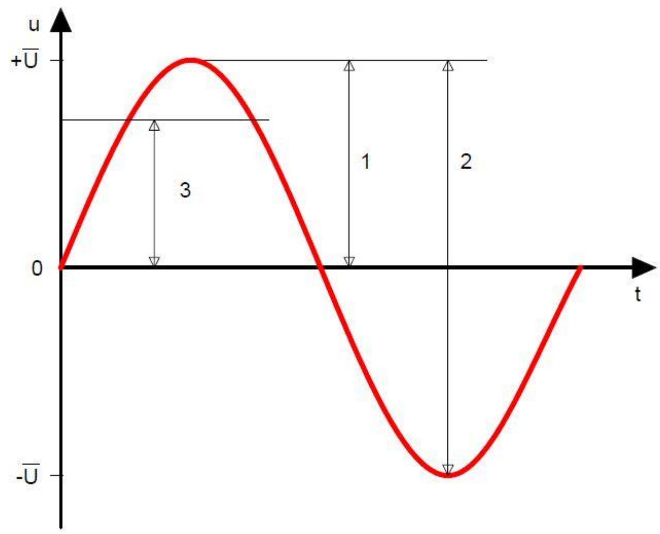

Figure 7: Magnitude measurement options

Explanation of numbers in figure 5:

1 Peak amplitude (Û)

2 Peak-to-peak amplitude (2Û)

3 RMS, Root Mean Square amplitude (Û/√2)

Frequency

The AC voltage waveform can be divided into pieces where a positive and a negative wave forms a period. This period length determines the frequency of the voltage. Normally in electrical grids 50Hz and 60Hz is used. A 50Hz voltage have a 20ms period which means 50 periods per second.

If the generator is rotating slower than the grid and the circuit breaker is closed, the grid would try to speed the generator up. The generator would be out of step and the rotor and stator would be slipping poles which will lead to damage.

To see the eventual frequency difference of the generators and the grids voltages a synchroscope is used. The figure below describes a situation where the generator goes too fast and produces a voltage with higher frequency than the grid has. “X” in the figure is a period length that needs to be the same between the voltages to synchronize the generator to grid.

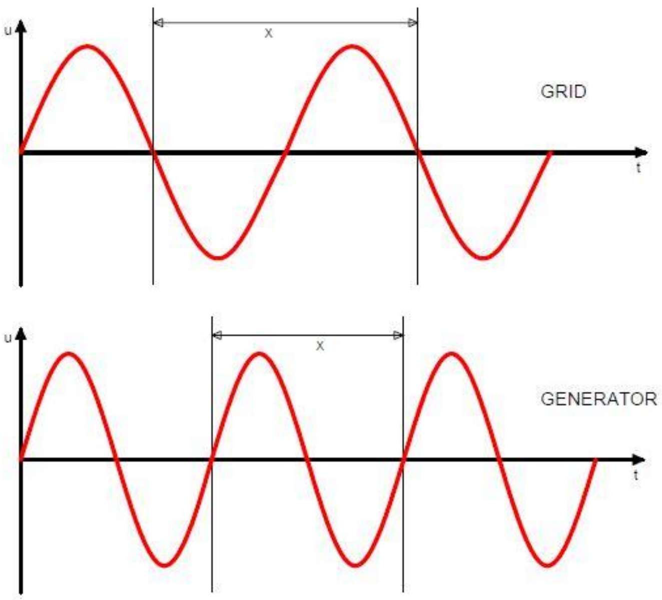

Figure 8: Frequency difference

Phase angle

The angle between the generator voltage and the grid voltage is called phase angle and it can be between 0 and 180 degrees. The phase angle is received by comparing the voltages positions in the zero crossings or in the peaks of the waveform.

The phase angle must be zero before the breaker is closed, otherwise it will be as in the wrong frequency case with high destructive forces on the generator. If the generator voltage is before the grid voltage it will be as the generator goes too fast and the grid would try to slow it down to come into step, and opposite if the generator is after the grid. The worst case will be if the phase angle is 180 degrees, meaning that the generator is exactly out of phase. The phase angle difference is described in the figure below. The length of “x” is the difference and it is normally measured between the peak-tops or in the zero-passing moments.

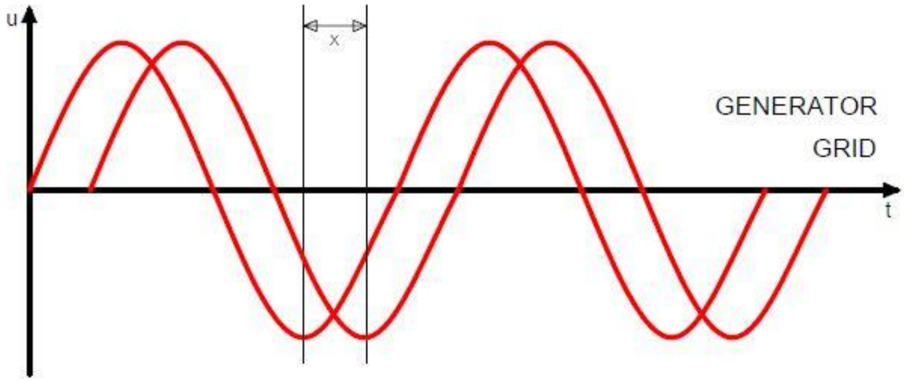

Figure 9: Phase angle difference

Phase Sequence

The three phases, (L1, L2, L3) coming from the generator have a rotation, phase sequence that must be equal to the phases of the electrical grid. If the sequence is wrong the synchronization cannot be done, and it will be a disaster if the circuit breaker closes.

The rotation direction of the generator is always the same so the only reason that the sequence would be wrong is that generator or transformer leads would be interchanged during maintenance. In the fast-changing testing environment at Wärtsilä it is especially important to have control on this when generating sets are often changed and the conductors need to be removed.

The figure below shows a situation where the phase sequence between the grids and the generators voltages is wrong. To be synchronized, two conductors from the generator must be switched to match the sequence that the grid has.

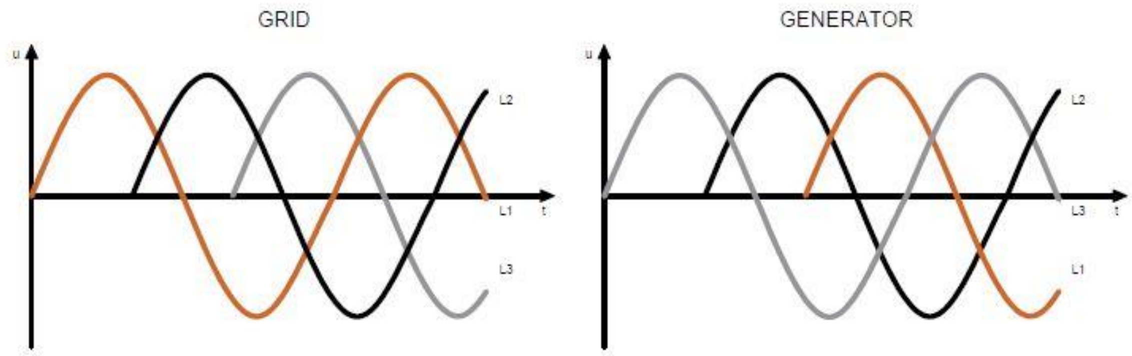

Figure 10: Phase sequence fault

In the figure, grids phase sequence is L1- L2- L3 and for the generator it is L3- L2- L1 which means that the rotations are not equal.

Poor synchronization has impact on both generating set and the connected electrical system. Improper phase and frequency matching will lead to a situation where the electrical grid with high rotational forces will pull the generator in to right position. These forces are critical for the rotor, driving shaft and engine. Due to these forces a dangerous increase in current can damage the windings and this is worse when the phase matching is poor. Voltage magnitude is related to the excitation as mentioned earlier and if the generator voltage is higher than the grids voltage the generator is over excited. Synchronization in this situation will lead to a high reactive flow to grid from the generator and this may lead to high mechanical shock for the generator, both stator and generator shaft. If the produced voltage is lower than grids voltage it will reverse current to rotor from stator and slip poles. This will damage the windings if the currents are high. [7]

2.6.1 Synchroscope

To have control over the synchronization moment in manual synchronization, a synchroscope is a helpful device. Synchroscopes are available in different sophisticated models. Single-function synchroscopes are only showing the phase angle and frequency so if using them voltmeters are necessary too. As on upgrade there are multi-function synchroscopes with check synchronizing relays for circuit breaker closing.

The synchroscopes have a circle with LEDs that shows frequency and phase angle. It is only one LED at a time that lights but if it rotates the generator voltage frequency is too fast or too slow. If the LED lights 12 o’clock both frequency and phase angle is equal to the grids voltage and the φ OK LED will light. However, if the LED stays still on another position the

phase angle must be corrected. The voltage of the generator has two LEDs also that shows if the voltage is too high or too low against the grid voltage.

If all conditions are inside the frames of the settings that have been programmed for the unit, the SYNC LED will light, and the relay gives permission to the circuit breaker to close.

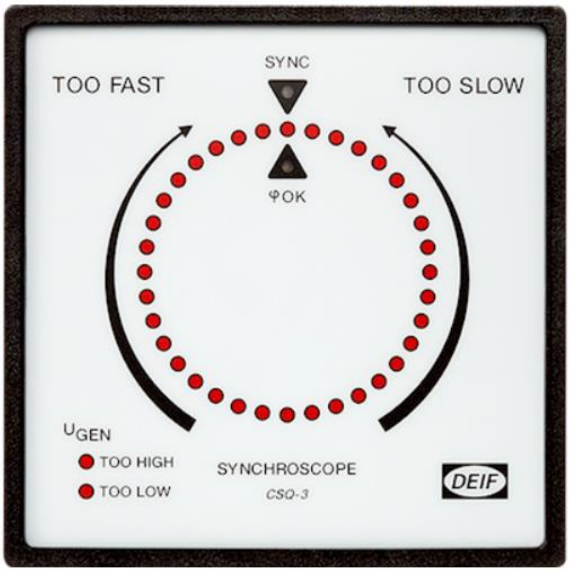

Figure 11: Deif CSQ-3, Multi-function synchroscope [8]

For automatic synchronization there are synchronizers that automatically sends signals to the AVR (Automatic Voltage Regulator) and engine control system in generating set cases. In this way, the synchronizer operates by itself to get to acceptable values and closes the circuit breaker when the requirements are met. [8]

As an alternative to the external synchronizers an AVR with support for synchronization can be used. An example for this type is the UNITROL 1020 AVR produced by ABB. The UNITROL 1020 is a multifunctional unit for excitation systems that also includes synchronization features and load sharing for two generators connected in parallel. To complete the functions, UNITROL is communicating with the engine control system.

3 Methods

In the new STH there will be testbeds for generating sets like the setup that are used today. The produced power is transferred via cables from the testbeds to a switchgear that guides the electricity forward to right destination. Synchronization is now done with the generator circuit breaker to the 10 kV busbar in the switchgear. If a generating set has another voltage output a transformer is needed between the generator and the switchgear or it must be connected to load banks.
The difference between the old system and the new is that the produced power will now be sent to the local grid in all situations. To build a system that can control different generator setups in same time from different testbeds, sets high demands on synchronization. To better understand the context around synchronization better, some different methods and options for synchronization will be described.

The ground everything is built on is standards, even maintenance and use of the equipment is related to standards. This means that standards according to a project and location of it should be followed. By focusing on synchronization now, standards are not much treated to keep it simpler.

3.1 Standards

Standards related to synchronization is mostly for components that are used and the components construction. Normally standards are used to keep same accuracy and quality between components in a system and to maintain an appropriate safety level. Below are examples of standards from International Electrotechnical Commission (IEC) that can be related to electrical equipment in power plants.

- IEC 62271 High-voltage switchgear and control gear
- IEC 60044 Instrument transformers
- IEC 60076 Power transformers
- IEC TR 60616 Terminal and tapping markings for power transformers
- IEC 61558 Safety of power transformers, power supplies, reactors and similar products
- IEC 60255 Measuring relays and protection equipment
- IEC 61810 Electromechanical elementary relays

These standards include insulation classes, nominal current and voltage levels, maintenance requirements etc.

For synchronization there are accuracy regulations for the four conditions described in chapter 2.5 above. IEEE Standard 67 describes operation and maintenance of large generators and also discusses synchronizing requirements. In this standard the synchronization limits are:

- Angle ±10 degrees
- Voltage 0 to +5 percent
- Slip ±0.0067 Hz

The phase sequence must always be right, and it is mostly expected to be understood and normally not explained additionally.
These limits are meant to protect the generator and not to apply to the prime mover design. Due to this, wider limits are often applied to match better with the engine control system and the voltage regulator that may have difficult to get the output voltage within these limits.

A maximum frequency difference of ±0.0067 Hz is not easy to reach so normally the slip limit is increased to around 0.3 Hz for generating sets. [9]

3.2 Synchronization options

In power plants synchronization can be done in different places in the distribution line depending on the situation and wanted function. Normally gensets in a power plant generates power on the same voltage level. In situations like that the synchronization can easy be done for the gensets separately or together with a breaker for the whole busbar. In testing environment, the gensets can produce different voltages at same time and then it becomes more difficult to have different synchronization places due to variating voltages for control equipment. Below are typical synchronization options in power plants described.

3.2.1 Generating set synchronization

The most common synchronization method is synchronization generating sets separately to a busbar or a load, even called live bus synchronization. In the figure below three generating sets (G1-G3) are connected to a busbar via circuit breakers (Q0) and disconnectors (Q1). The busbar is then directly connected to the load, the local grid for example.

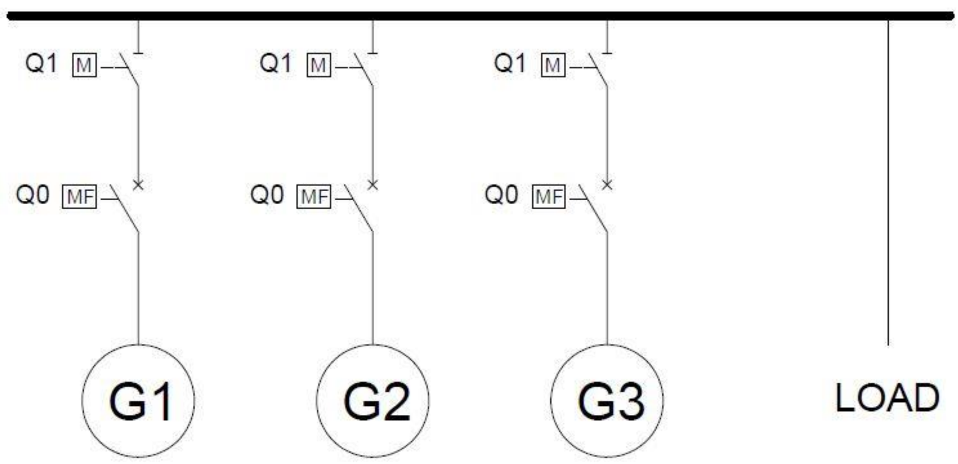

Figure 12: Example of generating set synchronization

To compare this method with other methods, advantages and disadvantages must be gone through to make clear the functionality. Starting with the pros, this method is very flexible although it is simple. For engine testing it is a big advantage to be able to synchronize a generator without considering other generating sets. In power plants it is also easy to add or remove generating sets depending on power need and in that way, be able to run the engines in use on optimal effects and save on fuel consumption.

The disadvantages with this method are the time it takes from stand still to generating requested power output for the power plant. This is because of one generating set in the time are synchronizing to the busbar. For normal power plants this does not need to be a problem that it takes same seconds longer to start up because they have time to wait but for smaller power plants that are meant as backup, the startup time is important.

3.2.2 Dead bus synchronization

For critical plants or large-scale power plants dead bus synchronization is a good option due to fast start up. The system is described in the figure below. It is very similar to the live bus synchronization above but instead of direct contact to the load there are a circuit breaker Q0 between the busbar and the load. Dead bus means that the circuit breaker ($Q0_{LOAD}$ in this case) is open and the busbar is deenergized.

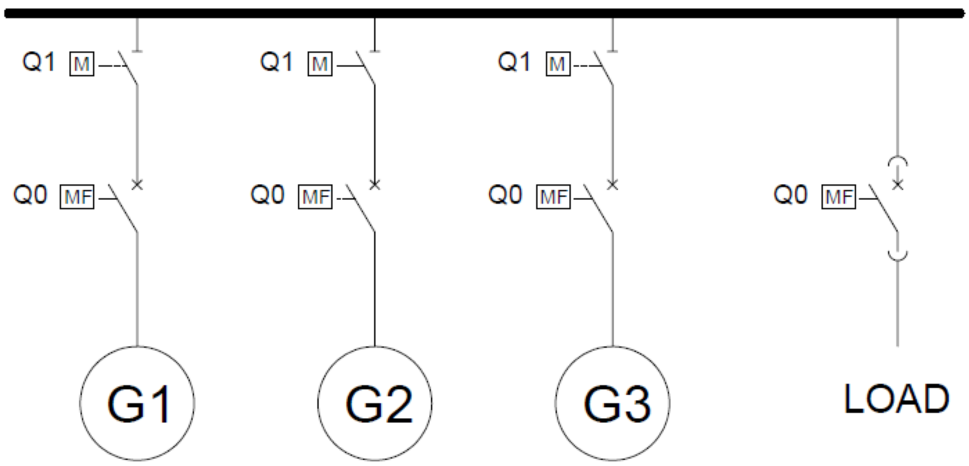

Figure 13: Example of dead bus synchronization

The synchronization technique is as follows:

- Start-up command given to gensets
- Circuit breaker $Q0_{LOAD}$ opens
- All generator breakers closes
- Engines start with generator magnetization off
- When the last engine reaches its nominal speed, generator magnetization order is done simultaneously on all the generators
- Gradual voltage increase

If a generator has not reached nominal speed following a delay, it will be uncoupled and later synchronized by the live bus synchronizing method.
While the speed is increasing on the generators a remanent voltage, approximately 10% of the nominal voltage is delivered. This voltage is not enough to synchronize the generators together but when the magnetization order is executed simultaneously on the generators, voltage is smoothly increasing and synchronizing them together naturally. For this method

it is necessary to use an advanced generating set controller and the same voltage regulator for all of the generating sets to secure they follow the same commands.

After this procedure the busbar is energized with nominal voltage and the synchronization between busbar and load is possible.

The advantages for this method are time saving in the startup moment when using many generating sets. This is through to the synchronization between the generators direct from start of the engines. The disadvantages are that it also needs synchronization possibilities for each generating set to the live busbar so it is quite similar to the generating set synchronization option. Under the start-up time it will also cause currents between the generators that can activate sensitive protection systems. [10]

3.2.3 Plant synchronization

A more uncommon method is also plant synchronization. This method is more appropriate for smaller power plants due to its complicated function. For small power plants with only one busbar it is like the dead bus synchronization method. But when having many generating sets connected to different busbars in a power plant, the regulation of the output voltage for a synchronization becomes more difficult when all generators are involved. This method is rarely used but the possibility exists.

3.3 Development

The electrical system used today with complement of load banks needs to be replaced with a new system that can control all possible situations in engine testing with loading on grid. The challenges that the load banks have handled until now are variations in frequency and voltage. To be able to synchronize the generating sets to grid in these situations there are needs for frequency converters and transformers.

If generating sets are tested by simulating propulsion cases the frequency is variating and needs to be converted to 50 Hz before a synchronization to grid. Same situation occurs if generating sets are producing power of 60 Hz that is a common frequency in many countries around the world. To make the produced powers frequency equal to the 50 Hz grid there must be a frequency converter involved. These are expensive in this power size, so the amount needs to be held narrow.

Voltage on the produced power can be variating depending on purpose of use for the generating set and often also related to the power output. To transform these voltages there are need for a transformer. As standard a normal transformer transforms a specific voltage to another specific voltage, 6,6 kV to 11 kV as example. So, using a normal transformer should mean that there are need for one transformer per voltage step. Instead multi voltage transformers could be used. These can transform different voltages on secondary side to a specific voltage on the primary side. Voltage change for the secondary side is done by changing connection combinations for the windings as well as different tapping options for fine tuning.

As a conclusion, a frequency converter together with a multi voltage transformer completes the requirements very well.

3.3.1 Automation

As mentioned in the theory, synchronization consists of four conditions that must be met, voltage magnitude, frequency, phase angle and phase sequence. The synchronization equipment that are used today is controlling voltage magnitude, frequency and phase angle by communicating with the AVR and the engine control system. Phase sequence is normally not changed so the synchronization systems mostly do not include the function. In testing environment at Wärtsilä generating sets are changed regularly and then the phase sequence must be controlled so the phases have not been interchanged. Today this is done by taking out the circuit breaker from its cubicle and voltage difference over the CBs place is controlled with hot-sticks when synchronization is simulated. If the sequence is right it will be about 0 V difference between the measuring points; (L1-L1), (L2-L2), (L3-L3). If the sequence is wrong two conductors must be switched. When right sequence is ensured the CB can be replaced.

This is a long process to do every time a new generating set is connected to the system. To avoid this process, a phase sequence relay could be placed in series with the sync check relay to secure that an incorrect close signal cannot be sent to the CB. An example of relay for this is DEIF RMT-111Q96 that is meant for check and indication of correct and incorrect phase sequence of a shore connection that is unchanged. The relay is common on vessels to secure right phase sequence when switching from own supply to the harbors supply. On the left side in the figure below the connection for this relay is shown. The relay compares the generators phase sequence against a preset rotation of L1, L2 and L3. When the power is off,

or the phase sequence is wrong, connection point two and three is closed. Then when the phase sequence is right, the relay will switch and close connection point one and two instead. So, when wiring the synchroscopes synchronization signal in series with the relay, an incorrect close command is prevented from reaching the circuit breaker. A disadvantage with this relay is that it does not work with 110 V so it will need own voltage transformers for 230 V or 400 V, alternatively find a similar relay that support 110 V.

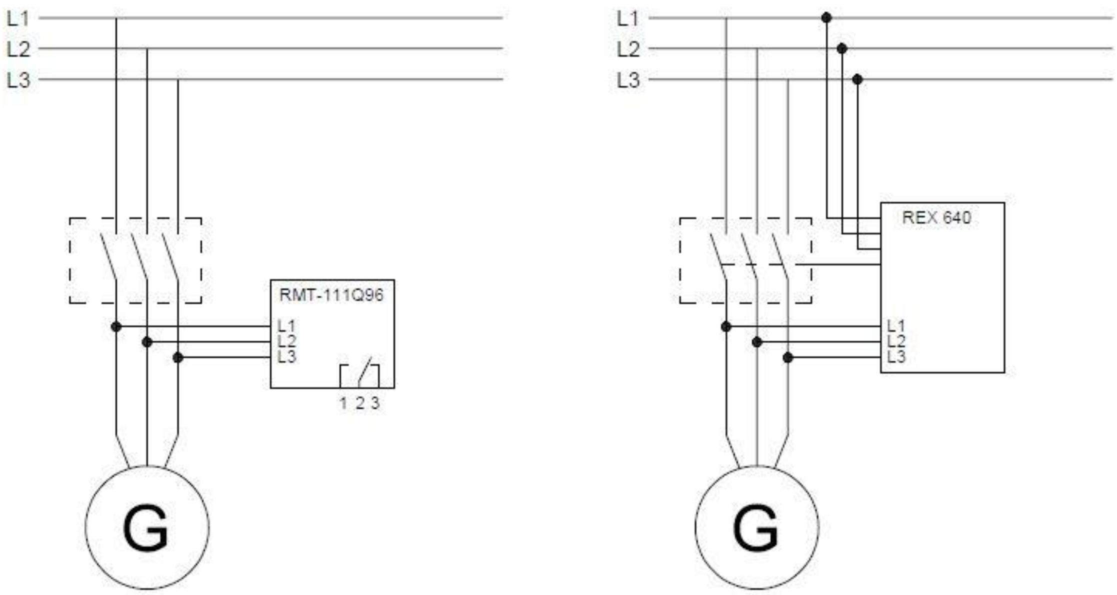

Figure 14: Phase sequence check

Another option would be to use ABBs new relay REX 640 which is an all in one relay based on application packages. According to ABBs explanation the synchronization application that is available cannot detect a wrong phase sequence. But with adding “negative sequence over voltage protection” package, the relay can block the synchronization signal to the circuit breaker if the sequence is wrong.

On the right side in the figure above, the measurement points for the relay are shown. Compared to the RMT-111Q96 relay this REX 640 relay uses both generator voltage and voltage on the busbar for the control.

Both of these options require that all connections stay unchanged on the measurement side and only the generator couplings are changed when generating sets are changed on the testbeds. The first time the system is taken in use or if some couplings are changed that can have impact on the measurements, the phase sequence must be checked with the hot sticks to secure that the wirings are right.

4 Conclusions

The easiest way would be to have a multi voltage transformer and frequency converter per testbed for the generating sets but due to high costs and space requirements this is not possible in this case. Instead, some compromises need to be done to be able to build a new system that supports today's requirements better. In the figure below an example is shown of how this system could be built in a little more reasonable variant. The number of testbeds for STH is not decided yet so this example is probably just a part of the whole system. Due to statistics the biggest part of generating sets to be tested are 11 kV, 50 Hz followed by 6.6 kV. After these comes a big part 13.8 kV, 60 Hz and the rest are split into smaller groups. This statistic gives an overview of the main use for the system and some priorities for it.

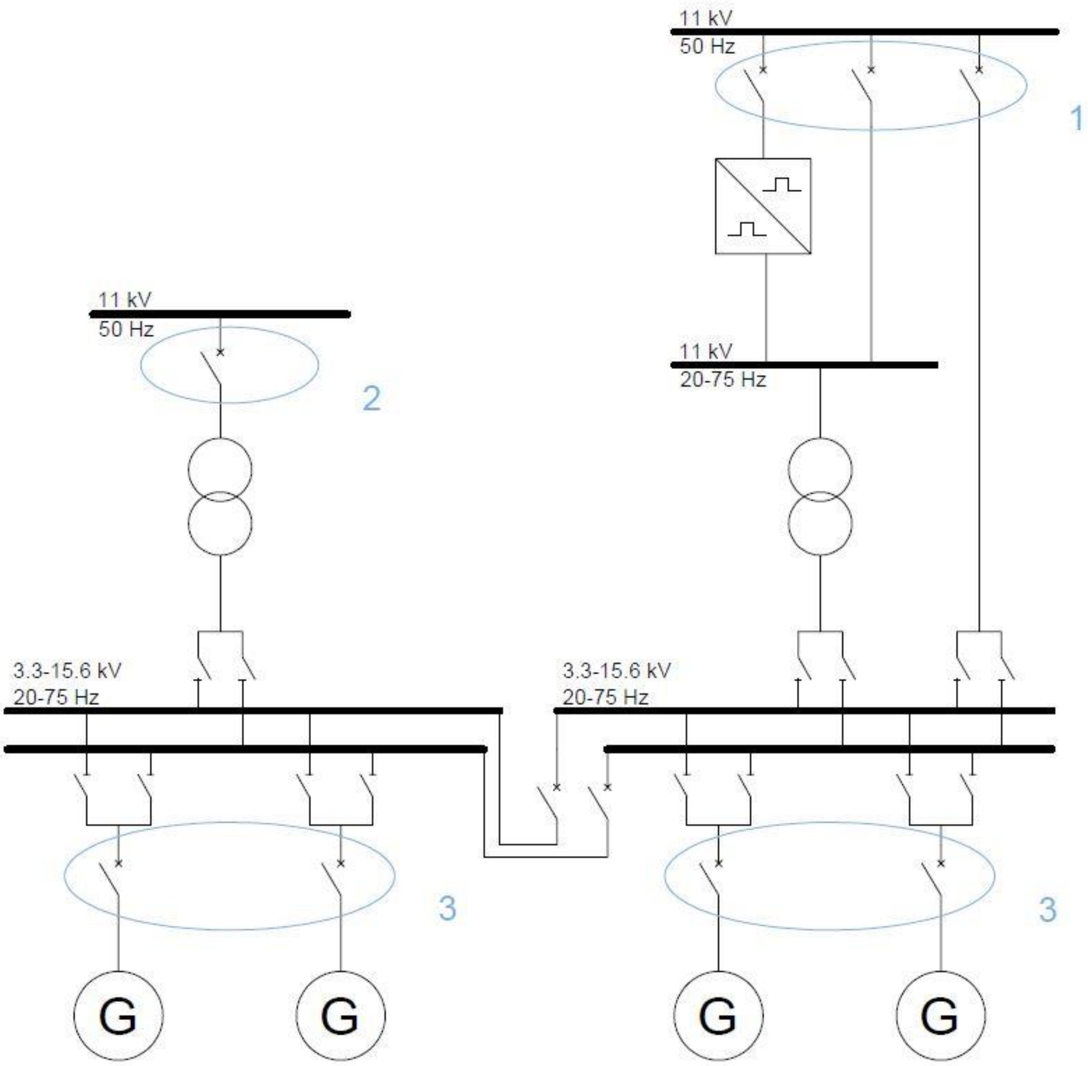

Figure 15: Example setup for a multi voltage system

If the medium voltage system was built like the setup in the figure above, it could cover a big part of requirements related to the flexibility in the new STH. To describe the setup better, the four generating sets are located in separate rooms or testbeds. The generated power is distributed via cables to switchgears. There goes the power through a circuit breaker and guided into one of the busbars by the disconnectors. These switchgears have double busbars to get better flexibility in the distribution between the generators and output circuits. Depending on voltage and frequency, different ways can be chosen with the disconnectors, busbars on this level can also be coupled together by CBs. Normally the frequency is between 25 and 60 Hz but to secure that the system can manage all situations there must be margins, therefore are some of the busbars marked with 20 - 75 Hz.

If the generated power has a voltage of 11 kV and 50 Hz it can be sent straight to the top busbar via the CB in circle 1. With another voltage, the generated power must go through one of the two multi voltage transformers before reaching a 11 kV busbar.

If the frequency is variating or otherwise different from the standard 50 Hz, the power must be guided through the frequency converter. The frequency converter is located after a multi voltage transformer to be able to manage all possible voltages that are used in the system.

Synchronization can either be done on the 11 kV side or direct after the generating sets where the voltage can be variating. The benefit with synchronization on the 11 kV side (circle 1 & 2), is that the voltage is always 11 kV. This helps a lot when the synchronization equipment can serve in all situations without modifications. A disadvantage for this synchronization is when a generating set is synchronized to grid via a specific route through the system, this route is then reserved. This means that it is not possible to add a new generating set to this route without synchronizing it with the generator breaker (circle 3).

By synchronizing with the generator breakers will lead to a more flexible use. Due to the variating voltage it is complicated to get a working synchronization system for this. The equipment that are meant for synchronization is made for 110 V nominal voltage, so the same voltage transformers will not support this. So, for this method more transformers are needed and an interlocking system that can manage more voltage variations to secure that mistakes cannot be done.

A smart solution would be to combinate these two alternatives. By having the 11 kV synchronization as first choice and by specifying the switchgears cubicles into different voltage ranges for incoming power, to be able to run two generating sets on same route

through the system. This could be done so 6.6 kV have synchronization possibilities from two testbeds, 11 kV from two and 13.8 -15.6 kV from two as example. This would be a cost-efficient way to get more flexibility and due to more testbeds in the final solution there will be more possibilities for variations between the testbeds.

To secure that the system is safe to use, it needs an interlocking system that protects from incorrect equipment operation. This system must include signals from all circuit breakers, disconnectors, busbars and earth switches to be complete. An interlocking system is like an agreement between the equipment. If a generating set is producing a specific voltage and is connected to a busbar, the interlocking system prevents another generating set to synchronize to the same busbar if the voltage is unequal. Other basic functions are that a circuit breaker should not be able to close if an earth switch is closed or that disconnectors are not allowed to be controlled when the circuit breaker is closed.

5 Discussion

The purpose with this thesis was to get more knowledge in synchronization and an understanding in which factors have an impact on it. At the same time, also to plan a solution for synchronization of generators in a flexible testing environment for generating sets and investigate how much can be automated in the installation. I think the purpose was fulfilled very well and from the solution I have got, it is possible to correct things depending on priorities later on. Especially the synchronization location when it is clearer what the requirements are for this.

When I started working on this thesis, I knew what synchronization was and roughly how it is done. Even with some knowledge from before it has been a challenging task and contained much problem solving and investigations to clear out things. By writing this thesis I have learned much more about synchronization and how a medium voltage system is built and how everything is working together as a solution.

Internal solutions have been discussed on meetings and external ideas are searched on internet from companies involved in medium voltage systems.
Information about components are taken from companies' websites and by contacting them with questions. Through this I have also gained better knowledge in the real business life and how projects are performed.

Planning of the electrical distribution system for the new STH is a large project that requires opinions from experts in this area together with workers that will be using it onwards. Based on my investigation hopefully something is interesting and useful. For further development interesting parts of the solution can be investigated more when it can be related to a specific case. When the number of testbeds is desired, and the electrical system is clearer, it is also possible to develop the interlocking system.

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