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VOLTAGE CONTROL IN DISTRIBUTED ELECTRICITY GENERATION BY USING SYNCHRONOUS CONDENSER

FOREWORD

This thesis was done in VAMK, University of Applied Sciences in the Degree program in Electrical Engineering the Unit for Technology and Communication. The client of this thesis was Wärtsilä Finland Oy Power Plants.

My thesis superior in Wärtsilä Finland Oy was Reijo Leikas, Senior Development Manager and my supervisor at VAMK, University of Applied Sciences was Kari Jokinen, Principle Lecturer. I want to thank everyone who has helped me with my thesis.

Vaasa 30.4.2014

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Sähkötekniikan koulutusohjelma

TIIVISTELMÄ

Tekijä	Mikko Mäkelä
Opinnäytetyön nimi	Jännitteensäätö hajautetussa sähköntuotannossa synkronikompensaattorilla
Vuosi	2014
Kieli	Englanti
Sivumäärä	54
Ohjaaja	Kari Jokinen

Tämän työn aiheena on jännitteensäätö hajautetussa sähköntuotannossa synkronikompensaattorilla. Wärtsilä antoi tämän aiheen koska heillä on aikomus hyödyntää generaattoria myös loistehon tuotantoon silloin kun pätötehoa ei tarvita.

Tehtäväni oli tutustua miten käyttää synkronikompensaattoriin jännitteensäätäjänä. Minkälaisia edellytyksiä on käyttää pysähdyksissä olevan voimalaitoksen generaattoria synkronikompensaattorina ja minkälaisia vaatimuksia se asettaa generaattorin jännitteensäätömenetelmälle. Työssä on myös esitetty ja vertailtu esilaisia jännitteensäätömenetelmiä. Työssä tutustuaan myös minkälaisia säännöksiä ja standardeja on säädetty yleisimmissä Wärtsilän asiakasmaissa.

Avainsanat jännitteensäätö, synkronikompensaattori, hajautettu sähköntuotanto

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ABSTRACT

Author	Mikko Mäkelä
Title	Voltage control in distributed electricity generation by using synchronous condenser
Year	2014
Language	English
Pages	54
Name of Supervisor	Kari Jokinen

The subject of this thesis was the voltage control in distributed electricity generation by the using synchronous condenser. Wärtsilä gave this subject because Wärtsilä attempt to utilize synchronous generator as a reactive power producer when active power production is not needed.

The purpose of this thesis was to discover how to use synchronous generator as a synchronous condenser. What kind of conditions are there to use the generator of the stationary power plant as a synchronous condenser and what kind of possibilities does it sets to the generator voltage control. A few different kind of voltage control solutions are also introduced and differences between them and the voltage control requirements in Wärtsilä`s the most common customer countries.

Keywords voltage regulation, synchronous condenser, distributed electricity

SYMBOLS AND ABBREVIATIONS USED

Abbreviations

AVR	Automatic Voltage Regulation
TSU	Transmission Service Unit
P3B	PLN for distribution and load governing center of as unit of PLN as owner of grid and organizer of electricity system in Java, Madura and Bali island
AESO	Alberta Electric System Operator
AIES	Alberta Interconnected Electric System
AVR	Automatic voltage regulation
HVDC	High-voltage direct current
EMF	Electro motoric force
TSO	Transmission system operator
MV	Medium voltage
HV	High voltage
AC	Alternating current
DC	Direct current

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1 INTRODUCTION

The subject of this thesis is the voltage control in distributed electricity generation by using synchronous condenser. The main purpose of the thesis is to discover how to use synchronous machine as a synchronous condenser and improve electrical network voltage stability. Wärtsilä gave this subject because Wärtsilä attempt to utilize synchronous generator as a reactive power producer when active power production is not needed.

In this thesis the standards and regulations of the voltage control requirements in Wärtsilä`s most common customer countries and different solutions of voltage control methods are studied.

2 WÄRTSILÄ

Wärtsilä is a global leader in complete lifecycle power solutions for the marine and energy markets. Wärtsilä was founded in 1834. In 2013, Wärtsilä`s net sales totaled EUR 4.7 billion with approximately 18,700 employees. The company has operations in more than 200 locations in nearly 70 countries around the world.

2.1 SHIP POWER

Wärtsilä enhances the business of the marine and oil & gas industry customers by providing innovative products and integrated solutions that are safe, environmentally sustainable, efficient, flexible and economically sound.

2.2 POWER PLANTS

Wärtsilä Power Plants is a leading global supplier of flexible baseload power plants of up to 600 MW operating on various gaseous and liquid fuels. The portfolio includes unique solutions for peaking, reserve and load-following power generation, as well as for balancing intermitted power production. Wärtsilä Power Plants also provides LNG terminals and distribution systems.

2.3 SERVICES

Wärtsilä supports its customers throughout the lifecycle of their installations. Wärtsilä provides service, maintenance and reconditioning solutions both for ship machinery and power plants. In parallel with its main service operations Wärtsilä has launched innovative new services that support its customer`s business operations, such as service for multiple engine brands in key ports, predictive and condition based maintenance, and training.

3 INTRODUTION TO VOLTAGE STANDARDS AND CONTROL

Nowadays electricity is necessary for almost all people. The system how electricity is transferred from producers to customer is called a network. It is very important to control the voltage because the supplier has to convey the highest possible quality to the customer with minimum faults. There are standards for these problems and if a fault occurs, there is a set time limit to fix the problem or the electricity distribution is disconnected.

The nominal voltage of 400kV line ranges from 395 to 420kV and in fault situations 360-420kV. The nominal value of 220kV line ranges from 215-245kV and in fault situations 210-245kV. The nominal voltage range of 110kV line is 105-123kV and in fault situations 100-123kV./15/

The nominal voltage of high voltage network in Finland is 110-, 220, and 400kV. The large power plants are connected to these voltage levels. The high-voltage network is responsible for the transmission of electricity over long distances./16/

The medium voltage network **(**1-35kV) transfers voltage from the high-voltage network to distribution transformers, which serve the low voltage networks. Smaller power plants supply electricity to this network. Small and average sized industrial plants and large public and business buildings are connected usually to medium voltage network and are using their own transformers./16/

The low voltage network is responsible for the final distribution of electricity to small consumers (100-1000V). In Europe the medium voltage is converted to 400/230V and delivered to households, industries and offices. In the low voltage network the electricity is transferred from the distribution transformer either straight to the property or via a distribution cabinet./16/

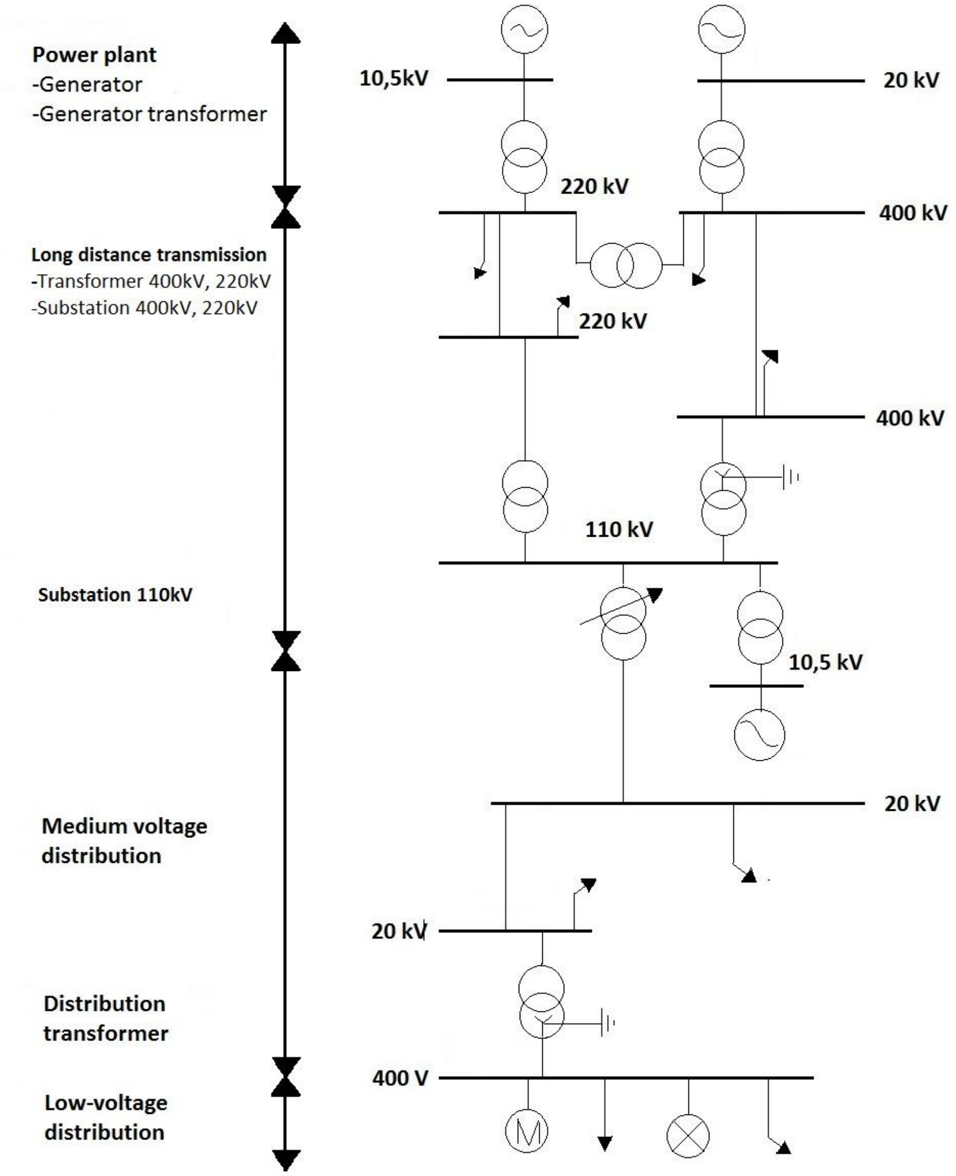

Figure 2. Transmission and distribution network diagram./2/

4 NETWORK VOLTAGE CONTROL REGULATIONS AND STANDARDS

In this chapter the standards and regulations of the voltage control requirements are introduced for Europe, Indonesia and U.S.A which are the most common customer countries for Wärtsilä.

The Grid Code is a set of regulations, requirements and standards to ensure the safety and reliability of the operation and development of efficient system to meet the increasing electricity demand/6/

4.1 ENTSO-E, Europe

ENTSO-E is organization of transmission system operators in Europe. The mission of ENTSO-E is to be the body of transmission system operators of electricity on the European level. The purpose of the ENTSO-E is to improve cooperation in electricity market development of European Union member states. ENTSO-E replaces the previously acted national organizations in European Union. The organization is divided into five groups: Continental Europe, Nordic, Great Britain, Ireland and Baltic. The areas can be seen in Figure 2./1/

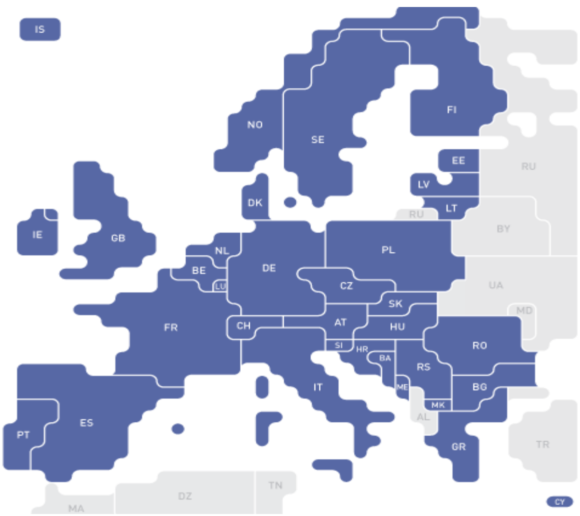

Figure 3. Members of ENTSO-E. /1/

4.1.1 ENTSO-E Draft Requirements for Grid Connection Applicable to all Generators

ENTSO-E has a grid code called ”ENTSO-E Draft Requirements for Grid Connection Applicable to all Generators”. This Network Code defines a common framework of grid connection requirements for Power Generating Facilities, including Synchronous Power Generating Modules, Power Park Modules and Offshore Generation Facilities. It also defines a common framework of obligations for Network Operators to appropriately make use of the capabilities of Power Generating Facilities’ in a transparent and non-discriminatory manner ensuring a level-playing field throughout the European Union. In this thesis is focused on voltage standards and what kind of norm`s there are for voltage regulation./3/

4.1.2 Actions in Voltage Deviation

ENTSO-E have standards for the minimum periods that the power generating module shall be capable of operating when voltage is deviating from the nominal value at the connection point without disconnecting from the network. Table 1 describes power plant actions in all countries that belongs to areas of ENTSO-E when voltage deviation is in within: 110-300kV.

Table 1. Actions in case of a voltage deviation between 110-300kV /3/

Synchronous Area	Voltage Range	Tiem Period for operation
	0.85pu-0.90pu	60 minutes
	0.90.pu-1.118pu	Unlimited
Continental Europe	1.118pu-1.15pu	To be decided by each TSO while respecting the provisions of Article 4 but not less than 20 minutes
	0.90pu-1.05pu	Unlimited
Nordic	1.05pu-1.10pu	60 minutes
Great Britain	0.90pu-1.10pu	Unlimited
Ireland	0.90pu-1.118pu	Unlimited
	0.85pu-0.90pu	30 minutes
Baltic	0.90pu-1.12pu	Unlimited
	1.12pu-1.15pu	20 minutes

ENTSO-E defines the minimum period of time that the power plant should work without disconnecting from the network, when there is a voltage deviation.

When the rated voltage of the connection point is 110kV (eg. Nordic countries) and the voltage deviates 90%-105%, that means voltage 99kV – 115kV, according to Table 1 the operating time of the power plant is unlimited and it will not disconnect from the network. If the voltage rises to 105%-110%, which means that voltage is 115kV-120kV, then the voltage has 60 minutes to recover the allowed voltage level or otherwise the network will be disconnected./3/

ENTSO-E defines the minimum period of time that power plant should work without disconnecting from the network, when there is a voltage deviaton. When the rated voltage of the connection point is 400kV (eg. Nordic countries), then the allowed voltage levels and voltage rises to 90%-105%, that means the voltage 360kV – 420kV. If the voltage deviates from that then some actions are needed after the time specified in Table 2.

Table 2. Actions in voltage deviations between300kV-400kV/3/

Synchronous area	Voltage Range	Time period fo operation
	0.85pu-0.90pu	60 minutes
	0.90pu	Unlimited
Continental Europe	1.05pu-1.0875pu	To be decided by each TSO while respecting the provisions of Article 4 but not less than 60 minutes
	1.0875pu-1.10pu	60 minutes
	0.90pu-1.05pu	Unlimited
Nordic	1.05pu-1.10pu	60 minutes
	0.90pu-1.05pu	Unlimited
Great Britain	1.05pu-1.10pu	15 minutes
Ireland	0.90pu-1.05pu	Unlimited
	0.88pu-0.90pu	20 minutes
Baltic	0.90pu-1.10pu	Unlimited
	1.10pu-1.15pu	20 minutes

4.1.3 Fault-ride-through (FRT)

The fault ride through is a requirement necessary for generators to remain connected to healthy circuits until the faulted element of plant and apparatus has been cleared from the transmission system.

4.1.4 FRT requirements

Grid disturbances such as severe voltage drop caused by short-circuit faults can lead to power-generating units disconnecting from the grid, which may cause instability in the grid. To avoid this, the grid code requires power-generating units to remain connected and continuously operated even if the voltage dip reaches very low values. The depth and duration of the voltage dips are usually defined by a voltage-time diagram. Figure 3 and Table 3 shows an example of FRT requirements during grid faults. The power-generating system must remain connected during the fault even when the grid voltage falls to 0-30% with duration of less than 150-250 ms depending country requirements. The system is allowed to be disconnected from the grid only when the voltage dips are in the area below the limit line. The grid codes also require the system to supply a certain amount of reactive current to support the grid voltage during the fault. It is noted that the limits and ranges for the FRT requirements vary with the grid operators in different countries, but they all share a common background and purpose./22/

Figure 3 and Table 3 describe the lower limit for a voltage-against-time profile by the Voltage at the Connection Point, expressed by the ratio of its actual value and its nominal value in per unit before, during and after a fault. U_{ret} is the retained Voltage at the connection point, during the fault T_{clear} is the instant when the fault has been cleared./3/

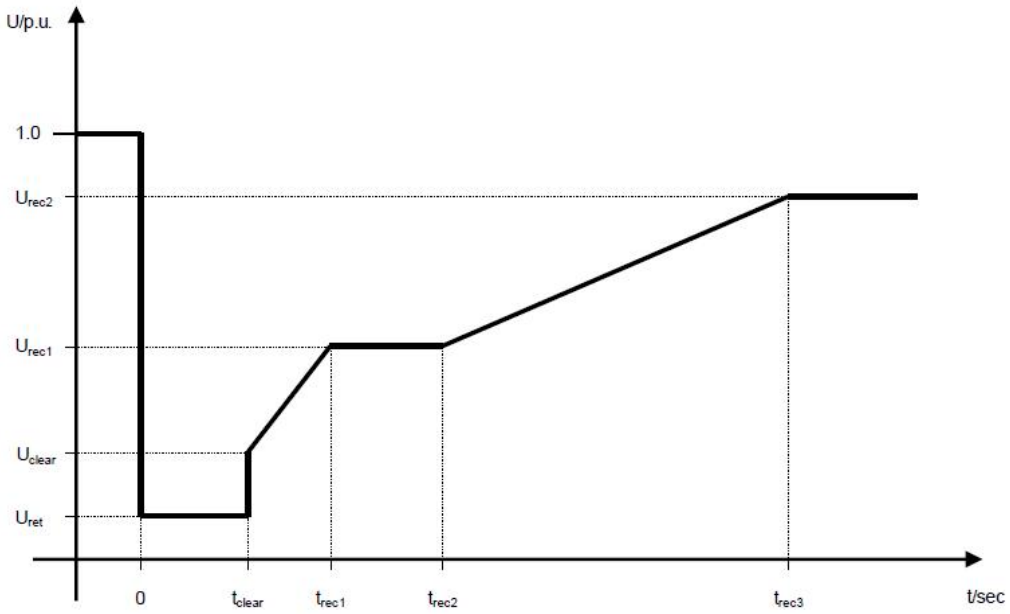

Figure 4. Typical Fault-Ride-Through curve/3/

Table 3. Fault-ride-through parameters/3/

Voltage parameters (pu)		Time parameters (seconds)	
U_{ret}:	0.05.-0.3	t_{clear}:	0.14-0.25
U_{clear}:	0.7-0.9	t_{rec1}:	t_{clear}
U_{rec1}:	U_{clear}	t_{rec2}:	t_{rec1} - 0.7
U_{rec2}:	0.85-0.9 and ≥ U_{clear}	t_{rec3}:	t_{rec2} - 1.5

4.2 GRID CODE of Indonesia (Java-Madura-Bali-Sumatra)

4.2.1 Voltage Control Requirements

To maintain the voltage of the system on the nominal level is required in order to reduce losses of the grid and threat of voltage drop as well as the problem of stability of transient and steady state. Voltage control is also required to avoid damage to the equipment connected to the transmission grid, either too low or too high voltage, can cause damage. Moreover, the unbalance of voltage and harmonics must also be controlled in order to provide satisfactory service to the customers./6/

According to the grid code the control of voltage may be achieved by the following methods:

- Synchronous generators equipped with voltage regulator
- Synchronous condenser
- Static VAr compensator
- Parallel capacitor
- Shunts reactor
- Transformer tap changer

The area control center is responsible for specifying a safe level of operation voltage for all main substations and for submitting such information to the generator and region/sub-region area control centers. The area control center is also responsible for directing the operation of system in such way so that the voltage of system is on the safe level. /6/

4.2.2 Voltage Unbalance

Region/sub-region P3B (Java-Madura-Bali) or Transmission Service Unit TSU (Sumatra) are responsible for balancing the impedance of grid phase in order to limit the voltage unbalance. All grid users must balance phase currents in the connection point in order to limit negative sequence voltage of less than 1%./6/

4.2.3 Voltage Harmonic Distortion (THD)

Total harmonic distortion is a grid code requirement for voltage. All grid users must obey that their contribution to the THD on their connection point is less than 3% from the root-mean-square (RMS) /6/

4.2.5 Grid voltage characteristics

P3B and all grid users shall try as much as possible that the following voltages, at each connection point are met:

Table 4. Limits for the system voltage to be maintained (Java-Madura-Bali)/6/

Nominal Voltage	Nominal Conditions
500 kV	+5%, -5%
150 kV	+5%, -10%
70 kV	+5%, -10%
20 kV	+5%, -10%

Table 5**.** Limits for the system voltage to be maintained. (Sumatra)/7/

Nominal Voltage	Nominal Condition
275 kV	+10% -10%
150 kV	+10% -10%
66 kV	+10% -10%
20 kV	+10% -10%

4.3 U.S.A, AESO

4.3.1 Voltage Fluctuation

Facilities should adhere to the maximum voltage decrease and maximum frequency of occurrence as defined by the curve “Fluctuation Limits” in Figure 3. The voltage fluctuation limits represent the cumulative effects from all services at the point of connection. The curve lines are flat below 4 fluctuations per day, i.e. the voltage fluctuation should not exceed 5% at any time. The facility owner must carry out corrective action if the voltage fluctuations exceed the maximum permissible voltage fluctuation limits. For example once per second is allowed to vary 1% of the root-mean-square (RMS) /8/

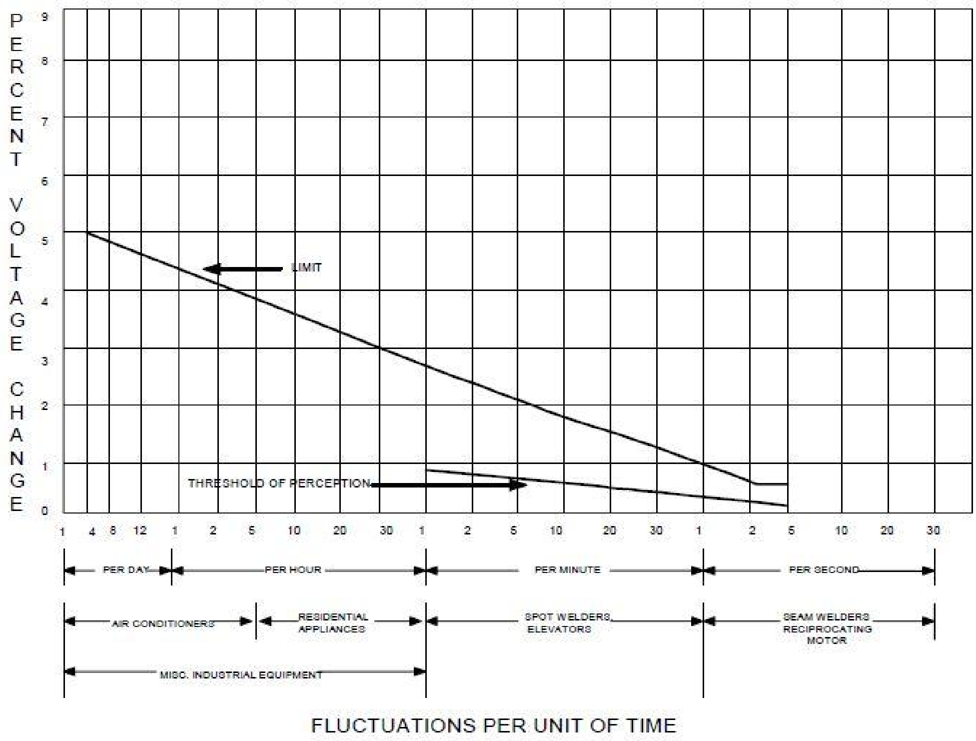

Figure 5. Voltage Fluctuation limits. Ex 1. Voltage fluctuation repeating 2 times per hour shall not exceed 4 percent. Ex 2. Voltage fluctuation of 2 percent shall not occur more frequently than five timers per minute /8/

4.3.2 Voltage Unbalance

Any new three-phase facility must not increase the phase-to-phase voltage unbalance of the system by more than 1% as measured with no load and with balanced three-phase loading. The voltage unbalance on the electrical system under normal operating conditions must not exceed 3%. The voltage unbalance is calculated as follows: /8/

This calculation is defined by NEMA and American National Standard for Electric Power Systems and Equipment – Voltage Rating: /8/

$$\boldsymbol{Unbalance} = \frac{\mathbf{100} * \boldsymbol{deviation\ from\ average}}{\boldsymbol{average}} \tag{1}$$

4.3.3 Voltage Regulation

All generation units, whether synchronous or not, must at a minimum be dispatchable and capable of supplying continuous reactive power at any point within the limits of 0.9 power factor over-excited and 0.95 power factor under excited as measured at the generator unit terminals. The full range of the reactive power capability must be available over the entire MW operating range of the generator at the rated generator terminal voltage as shown by the shaded area in Figure 5. /8/

Each generating unit, under non-disturbance conditions, must be capable of maintaining a constant voltage at the generator terminals within +-0.5% of a set point by continuously modulating its reactive power output within the limits specified above. The voltage set point must be adjustable by the generating unit operator and dispatchable from the AESO system controller within +-0.5% of the nominal generator interface voltage./8/

Unit transformers must have a tapped range so that the maximum unit output can be achieved throughout the system operating voltage range as specified in the project functional specification. At a minimum, unit transformers must be capable of a +-5% voltage range in 2.5% increments.

The combination of the generator and the transformer capabilities must allow for a total operating voltage range +-10%./8/

Generators must operate in an automatic voltage control mode. Excitation systems with stator current limiters are not acceptable for interconnection.

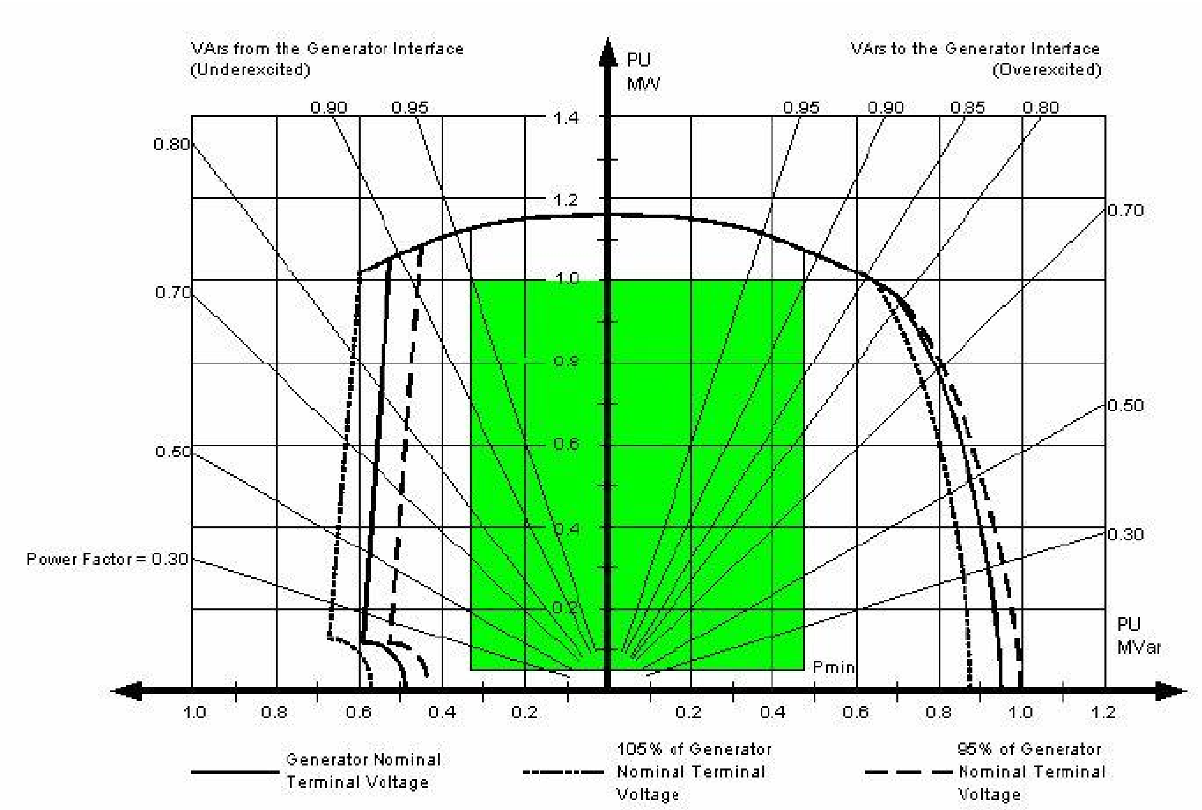

Figure 6. Generator reactive power capability requirements./8/

5 VOLTAGE REGULATION IN ELECTRICAL NETWORK

5.1 Voltage Regulation in Transmission Network

Nowadays there are lot of different solutions for voltage regulation. However voltage regulation is much different between the transmission network and the distribution network. In the transmission network the reactive power plays a big role in voltage differences, because the transmission network resistance is low and the inductance is high. Therefore, there are generators that take care of voltage regulation via reactive power which means that synchronous generator either produces or consumes reactive power. There are also power electronics for voltage regulation e.g. STATCOM and SVC which are introduced later./4/

Voltage drop can be calculated by following formula:

$$\Delta U = U1 - U2 = \text{IRcos}\emptyset + \text{IXsin}\emptyset = RI_{\text{p}} + XI_{\text{qp}} \qquad (2)$$

Reactive current Iq and reactive power Q have a large effect to the voltage drop when Reactance X is big compared to resistance R. See Figure 6.

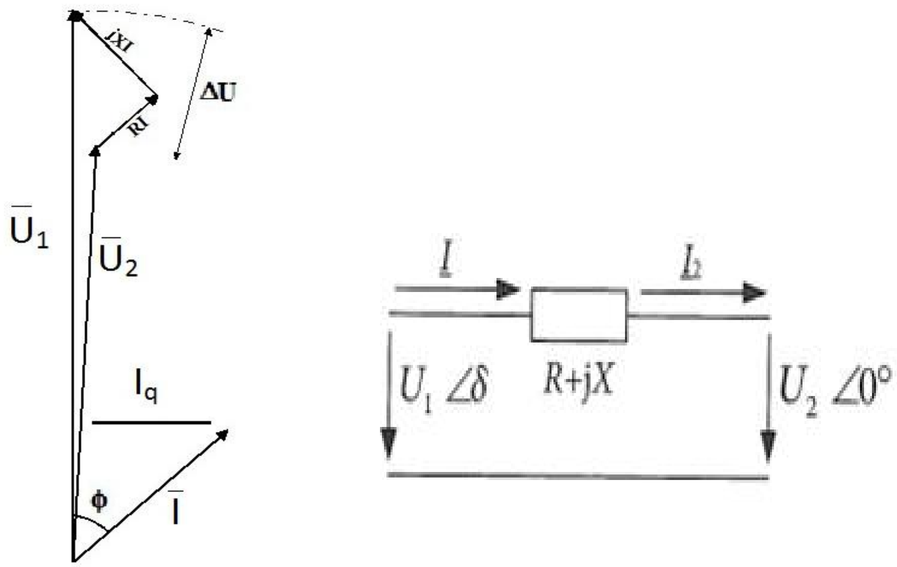

Figure 7. Transmission line vector diagram and equivalent circuit.

Table 6. Typical transmission line conductors.

Conductor type	Voltage level kV	Resistance Ω/km	Reactance Ω/km	Nominal current A	X/R
Duck	110	0,05	0,3	845	6
Finch	110	0,054	0,271	1240	5,01

5.2 Voltage Regulation in Distribution Network

In the distribution network, reactive power does not have so a big effect for voltage because the overhead line and underground cable resistance is much bigger compared to the reactance. In the distribution network the most common voltage control method is to use transformers equipped with on load tap changers. The tap changer is placed on the primary voltage side of transformer. Measurement is connected to the secondary voltage side. The tap changer keeps secondary voltage at the reference level. There are also some sources for reactive power which can be used for voltage regulation however in the distribution network generally there are much fewer ways to affect the voltage in the network.

5.3 Decentralized Power Production Effect on Voltage

5.3.1 Voltage Level Control

Voltage regulation might become challenging in decentralized power production because:

- Decentralized production might have limited features to control reactive power, depending unit size and used technique.
- Sometimes reactive power production capability creates too high additional cost for decentralized power production. Power inverter is often rated

according to maximum active power and there is not enough capacity for reactive power.

- When network is developing and changing continuously, it might require parameter change if voltage fluctuates all the time.
- Renewable power production, like wind- and solar power, do not follow electricity consumption requirements. Produced electricity is consumed near the production plant during the high consumption time, but electricity has to be transferred a longer way during the low consumption time.

The main function of electrical network is to transfer the electric power for consumers. Proper functioning of electrical network requires stable voltage level near the nominal voltage. Also electrical devices connected to network are designed to operate on certain voltage levels.

The operation principles of electrical network have been changing during recent years. One remarkable change is increasing amount of decentralized wind power. The wind power is normally connected to the electricity network as an individual unit or as group of several units. Electricity production of wind power plants is very unstable and these cause fluctuation in the network power flow and this way also in the network voltage level. Normally transformer tap changers are not able to control voltage changes caused by large wind power plants. Therefore large wind power plants have to be equipped with their own voltage control system. This starts to be normal function nowadays, because the sizes of wind power plants are getting larger and larger all the time. Transmission system operators give detailed requirements for reactive power and voltage control at wind power plant connection point. /11/

If a wind or solar power plant is connected to the weak network at a remote location, there can be challenges with both over voltage and under voltage. The power inverter can produce inductive or capacitive reactive power and improve voltage stability. However power inverters have some technical limit coming from the intermediate circuit. Overvoltage compensation is restricted due to intermediate circuit voltage limit and under voltage compensation is restricted due to current limitation. If there is a risk to exceed the over-or under voltage limit, the power plant owner and transmission system operator has to agree, how to handle this kind of situation and who will make additional equipment investments. In some cases the most economical way is to limit power plant production to avoid too high a voltage. Normally this power limitation time is so short on the annual level that it does not influence the overall profitability./11/

Voltage is a local variable, as opposed to frequency, which is common for entire network. This aspect sets some challenges for voltage control, because the voltage level of certain node can be controlled only very near of the node. The transmission network resistance is typically rather low and reactance rather high. Therefore, the voltage difference between two nodes is mainly depending on the reactive power flow between these two nodes. It is important to minimize the reactive power flow in the transmission network, because this way voltage can be kept on a suitable level everywhere in the network and the reactive power transmission capacity can be maximized./11/

The voltage control principles are changing nowadays. Earlier synchronous generators had an important role in the network voltage control, but that role is decreasing nowadays. One reason is that earlier power production and power transmission were handled by the same company, but nowadays these two functions are separated into two independent companies. This new situation means, that voltage control design is not taken into accounts so carefully, when new power plants are designed. Also the old power plant can be closed, if its profit is not on a high enough level anymore. Sometimes it is forgotten, that this power plant has an important role from the voltage control point of view in this area. Because power transmission companies are responsible for the network voltage level, they can be required to purchase reactive power from the power producer or they have to invest in their own voltage control equipment. Recent developments have shown that power transmission operators have started to require reactive power production from all power producers, which are connected to the network./11/

Even if wind power plants have a good capacity of voltage control, they are still not able to replace traditional synchronous generators in voltage control. One reason is that traditional synchronous generators are located near large loading points, where there is also an important electrical network node. While wind power plants are located in areas, where there are good wind conditions, but locations are not from the optimal electrical network point of view. As a result of this, additional voltage control equipment installed in the electrical network will have an important role in the future./11/

6 VOLTAGE CONTROL METHODS

In this chapter some voltage regulation solutions are presented.

The main point in the voltage regulation are:

- To avoid over and low voltage
- To maintain the realiability
- To keep a good quality of electricity
- To minimize losses

6.1 Synchronous Machine Excitation

6.1.1 Excitation and Structure

A synchronous machine has an automatic voltage regulator that controls reactive power. Reactive power is controlled by changing the generator excitation, which has an effect on the generator internal voltage. Synchronous machine excitation is an economical way to keep the connection point voltage at the right level. /2/

The DC field excitation of a large synchronous generator is an important part of its overall designs. The reason is that the field must ensure not only a stable AC terminal voltage, but must also respond to sudden load changes in order to maintain system stability. Quickness of response is one of the important features of the field excitation./18/

In Figure 7 brushless excitation is introduced. Automatic Voltage Regulator supplies DC-current (I_m) to the excitation generator stator winding, where it forms magnetic field. The excitation generator rotor is rotating in the magnetic field and a 3-phase AC-voltage is created to the excitation generator rotor windings. The created AC-voltage is rectified by a rectifier bridge and then connected to the main generator rotor winding, where DC-voltage (U_r) creates an excitation current (I_r), which creates a 3-phase AC voltage to the main generator stator windings (U, V, W)

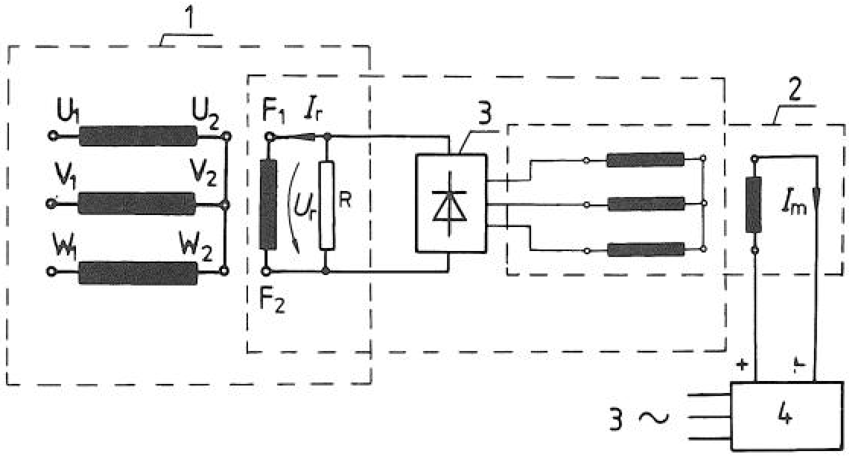

Figure 8. Principle of brushless excitation. (1) Main generator, (2) Excitation generator, (3) Rectifier bridge, (4) Automatic Voltage Regulator /21/

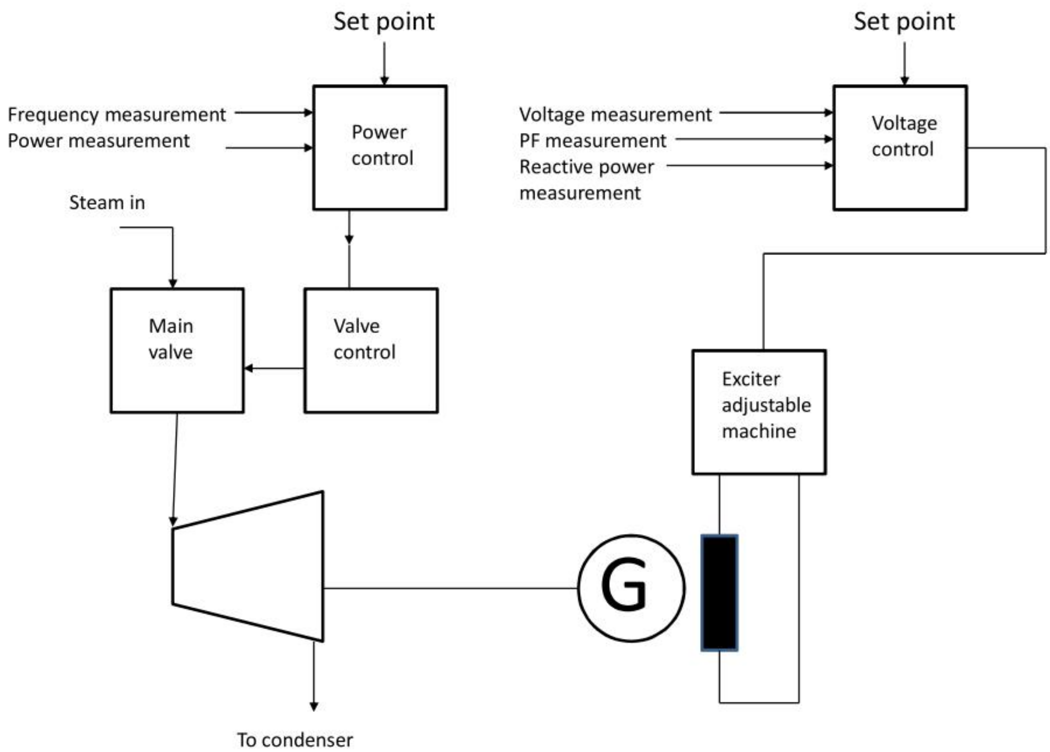

Figure 9. Synchronous generator active power and reactive power control principle. /2/

Vector diagrams and equivalent circuits are widely used for analysis of all AC electrical machines.

In Figure 9 synchronous generator equivalent circuit and vector diagram are demonstrated. Terminal voltage U_v is controlled by changing excitation current I_{ex}. The generator equivalent diagram shows that reactive current I_q has an important role to control terminal voltage U_V. As seen in Figure 9, where is shown how reactive current influences to electro motive force E1, eventhough active current remains the same.

$$\bar{E}=\bar{U}_v+jX\bar{I} \qquad (3)$$

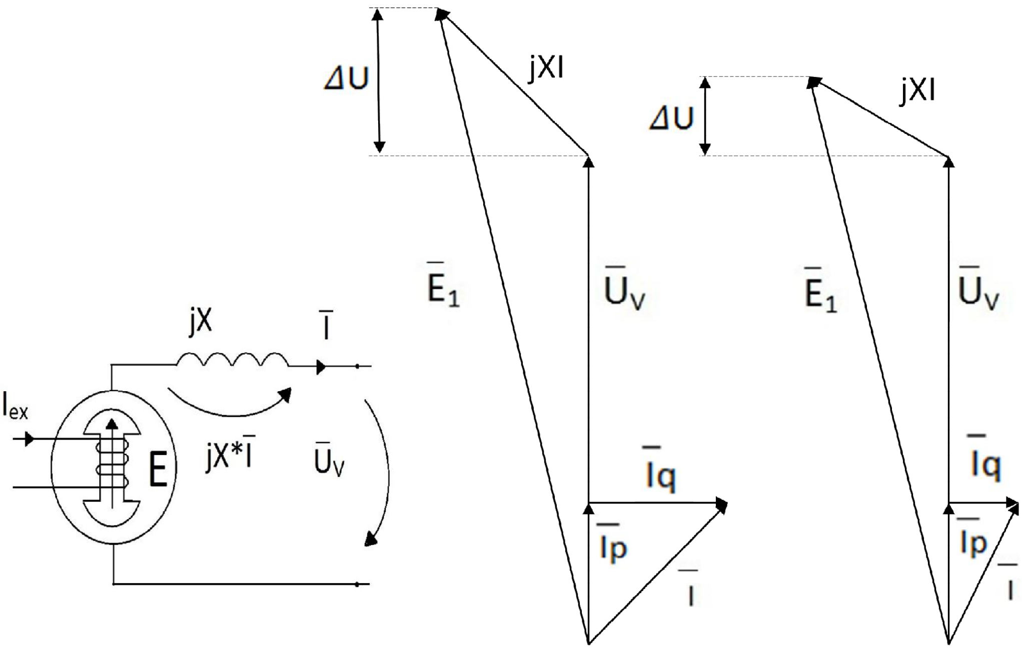

Figure 10. Generators equivalent circuit diagram and vector diagram.

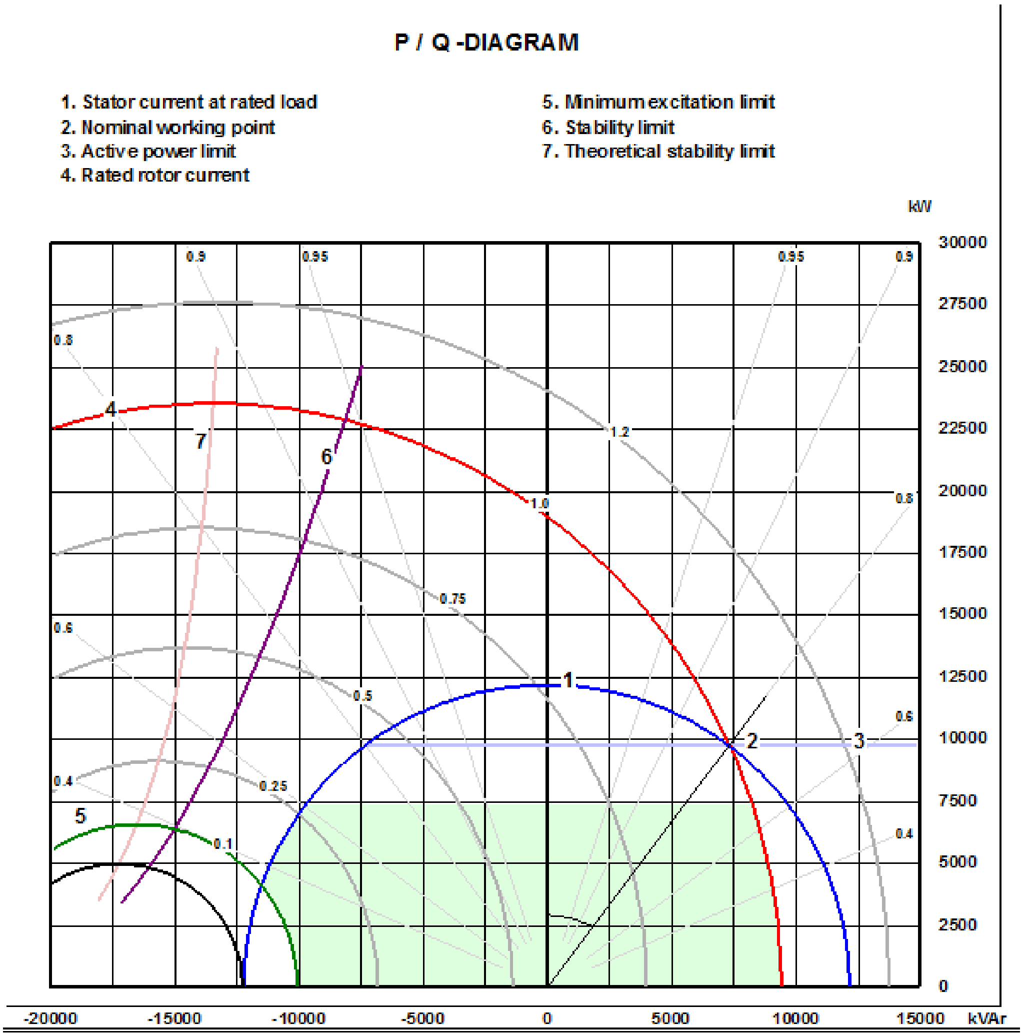

Figure 11. PQ-diagram of the synchronous condenser.

6.1.2 Automatic Voltage Regulator (AVR)

An AVR is a voltage controller for the generator. The AVR is a part of the synchronous machine magnetic circuit. The AVR controls the generators output voltage. AVR can be set to different control modes such as voltage control, reactive power control or power factor control modes.

In order to control the output voltage of the AC generator, the DC field current in the rotor must be controlled to compensate for changes coming from load changes. This adjustment is done automatically by the automatic voltage regulator.

In this thesis work, ABB UNITROL 1000-15 is used as reference AVR.

The main features of the UNITROL:

- Automatic voltage control with adjustable PID controller
- Power factor and reactive current control modes
- Excitation current regulator with PI control
- Various limiter and protection functions
- Reactive power sharing for generators connected in parallel
- Commissioning and maintenance Tool CMT 1000
- Voltage matching prior to synchronization
- Serial communication

6.2 Load sharing methods

When a generator sets are in a paralleled arrangement, the voltage and frequency outputs of the generator sets are normally forced to exactly the same values when they are connected to the same bus. Consequently, the generator set control systems cannot simply monitor its own influence on the bus voltage. If, for example, one set operates at a higher excitation level than the other sets, the reactive load will not be shared equally.

6.2.1 Voltage DROOP

Droop voltage regulation allows the generator voltage to decline by a predetermined percentage of the voltage range as the reactive load changes./9/

Voltage DROOP communicates via voltage level between generators.

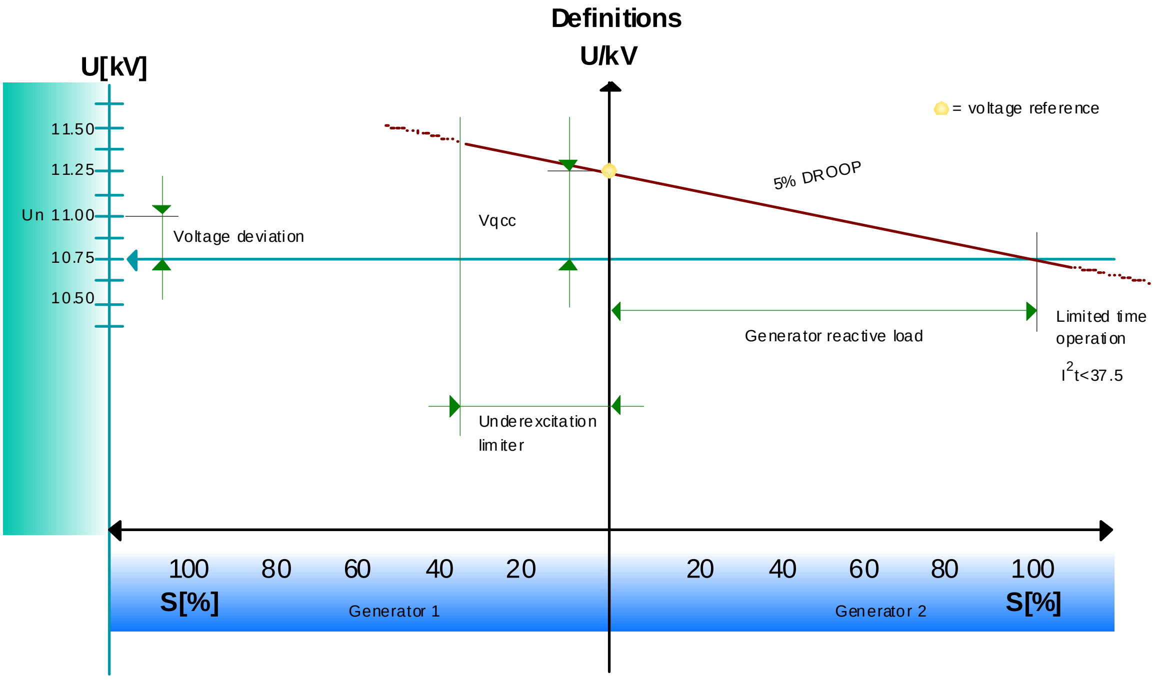

Figure 12. bus voltage will vary as a function of reactive load. The changes in reactive load will be shared equally if the droop settings are the same./10/

6.2.2 Voltage droop compensation (VDC)

In order to share equally the amount of reactive power between parallel connected generators and keep the busbar voltage level at nominal in the island operation the AVR has a special feature called voltage droop compensation control. The units are connected together with a RS-485 bus. In VDC mode all AVR`s operate in the voltage droop. The principle is that each AVR writes the value of its own amount of reactive power to the RS-485 bus. Each unit reads these values and calculates a common average MVAr setpoint, and compensate the effect of voltage droop. Therefore, the voltage level on the busbar is always kept at nominal.

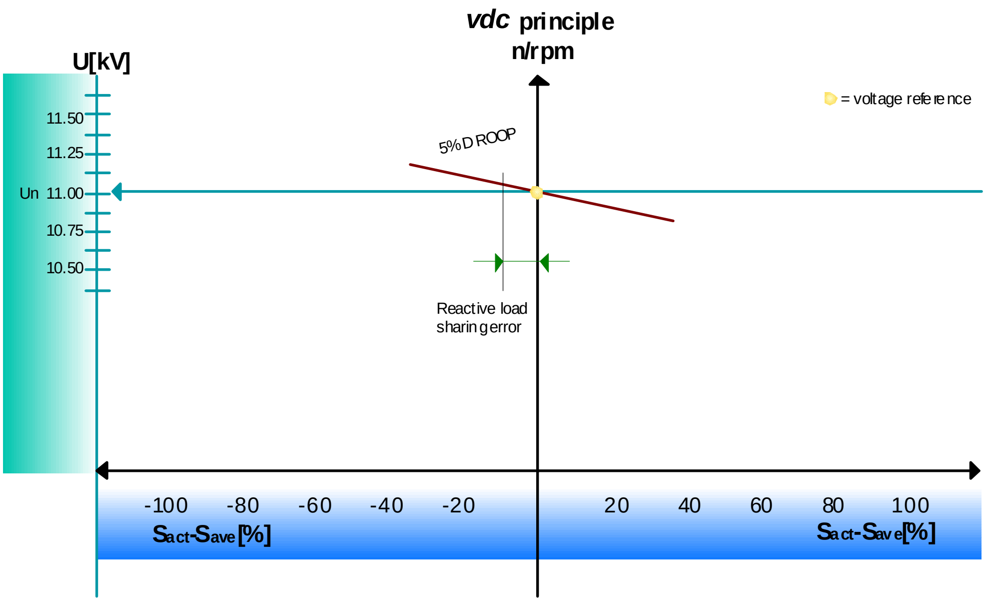

Figure 13. Voltage droop compensation

6.2.3 Power Factor control

Power factor control means that the AVR will adjust the generator excitation current in such a way, that the power factor (cos phi) of the generator output remains constant, independent of changes in the active power output.

When the generator is running parallel with the grid, the power factor control is way to control excitation and reactive load. When in the PF control, the AVR is trying to match the reactive load proportionally to the active load so that the Q/P ratio is maintained. Normally the power factor is a very steady parameter, but if there are rapid changes in the engine active load, this may result in oscillation in the power factor meter as the AVR will try to match the excitation with the varying active load. From the system point of view it is more important to aim at the steady excitation level in order to obtain the constant reactive power output and steady system voltage./10/

6.2.4 VAr control

The VAr-control means that the AVR will adjust the generator excitation current in such a way, that the reactive power of the generator output remains constant, independent of changes in the active power output.

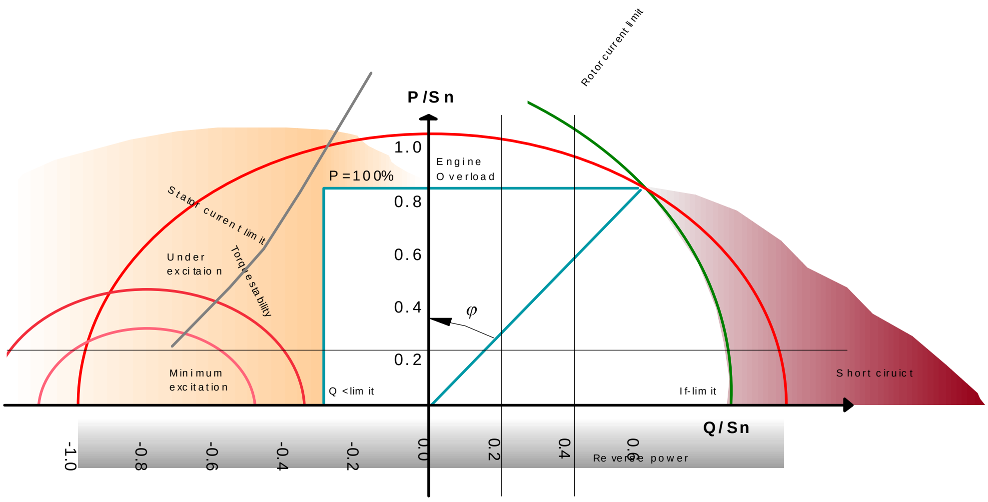

Figure 14. Power Factor-control

6.3 STATCOM

6.3.1 Structure

The STATCOM–static reactive power compensator is a device that produce or consumes reactive power. STATCOM consists of a self-communicating bridge structure (e.g. IGBT) and a DC-circuit. The simplest DC-circuit can be condensator. The device can produce and consume reactive power because the inverter can be turned on/off by the rhythm required. The STATCOM magnitude of the voltage can be adjusted and the voltage level is determining if the device is consuming or producing reactive power to network./2/

6.3.2 Functioning

Producing and consuming reactive power with STATCOM is based on adjusting the inverter output voltage relative to the network voltage, which means that when adjusting the inverter output voltage higher than the network voltage, the reactive current moves towards the network and STATCOM starts to produce reactive power to the network through the connection transformer. Correspondingly when the inverter voltage is smaller than the network voltage, the direction of the current changes and STATCOM starts to consume reactive power. As acting, STATCOM uses active power. If the inverter does not get active power from the network, the switching components depletes the DC-side energy storage./5/

When the network voltage suddenly falls, the difference between output voltage and the network voltage rises, and STATCOM produces more reactive current to the network that tries to support the network voltage./2/

If STATCOM is installed in the middle of the line it keeps the voltage in the connection point the same as the ends of the line. This way it is possible to transmit much more active power than without compensation, but this also effects that the reactive power consumption is higher./2/

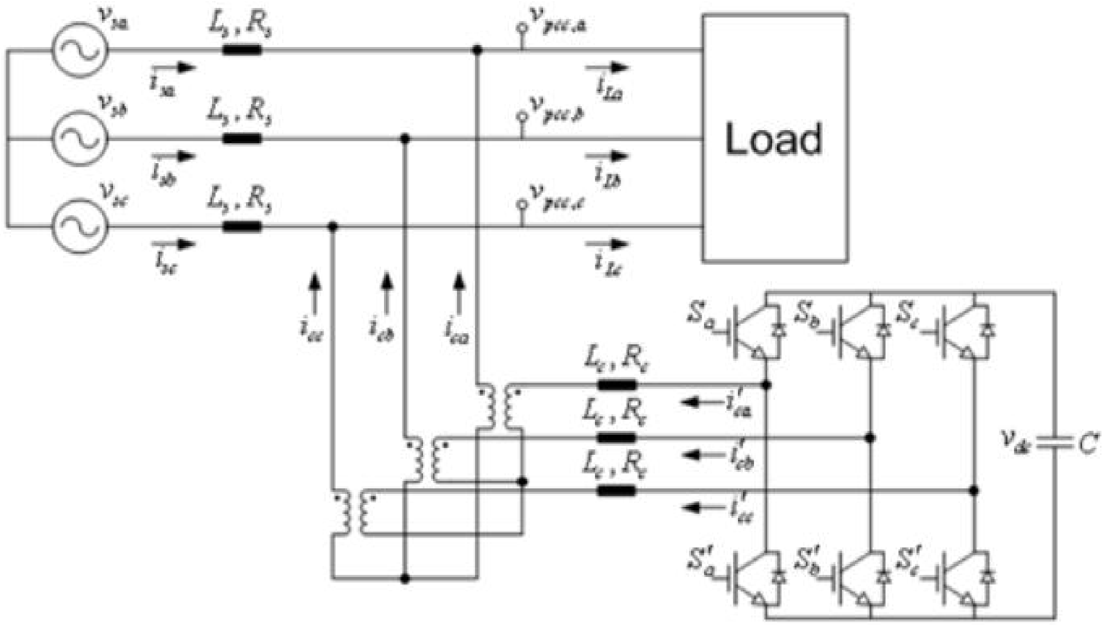

Figure 15. Structure of STATCOM /2/

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6.4 Static VAr compensator (SVC)

SVC is a parallel capacitor and reactor. Capacitance and reactance value can be changed by connecting thyristors. If the susceptance of the capacitors is bigger or smaller than the reactors susceptance, the SVC can control the network voltage either by producing reactive power to the network or consuming it from the network.

When the reactive power increases in the line, also the power angle increases. The SVC can produce active power up to a certain limit and increase active power transmission capacity which means the angle decreases at same active power level.

When the maximum reactive power production limit of the SVC is reached, compensation will not increase anymore and then the situation is the same as if there is parallel fixed sized capacitor in the middle of the line.

The SVC can be also connected to substation, where it can be used as voltage control in continuous mode. Quick control is useful especially after network failures. Due to fast control, the device improves transient stability and can attenuate electro-mechanical fluctuations between network areas. When the SVC is located in a substation, it might in some cases improve electro-mechanical fluctuations attenuation and in some cases it might impair it. Therefore location and control philosophy of SVC have to be done carefully/2/

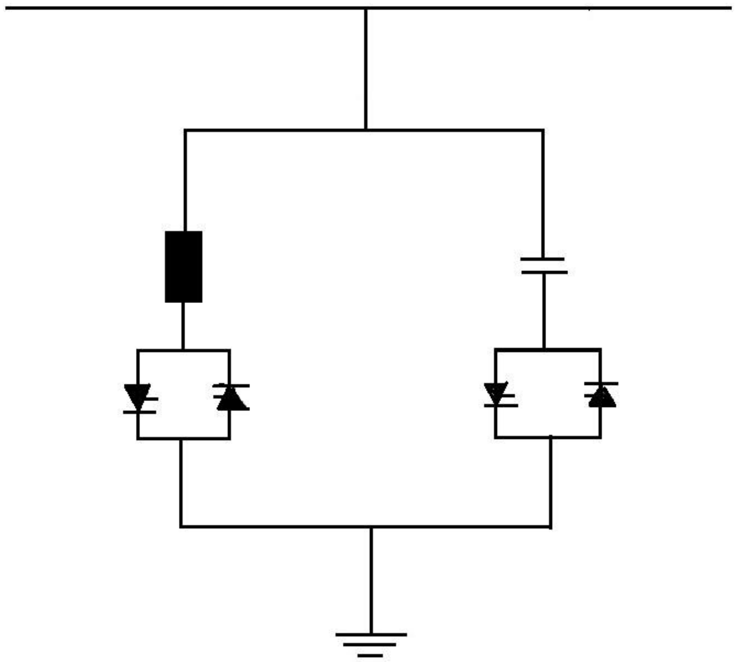

Figure 16. Structure of SVC /2/

6.5 Transformer Tap Changer

The voltage is regulated by changing the ratio of the transformer. With the on-load tap changer it is possible to change the ratio of the transformer even if the transformer is energized and loaded. The on-load tap changer is normally connected to the primary voltage side and voltage measurement is connected from the voltage measurement transformer located on the secondary voltage side. Normally tap changer regulates busbar voltage just after transformer. Modern tap changer controllers have a function, which compensates the power line voltage drop and the voltage can be kept constant on the main load point. The compensation is based on the power flow through the transformer and power line R and X values. Because of this feature the on-load tap changer is suitable for continuous voltage regulation and it keeps the secondary voltage constant. /13/

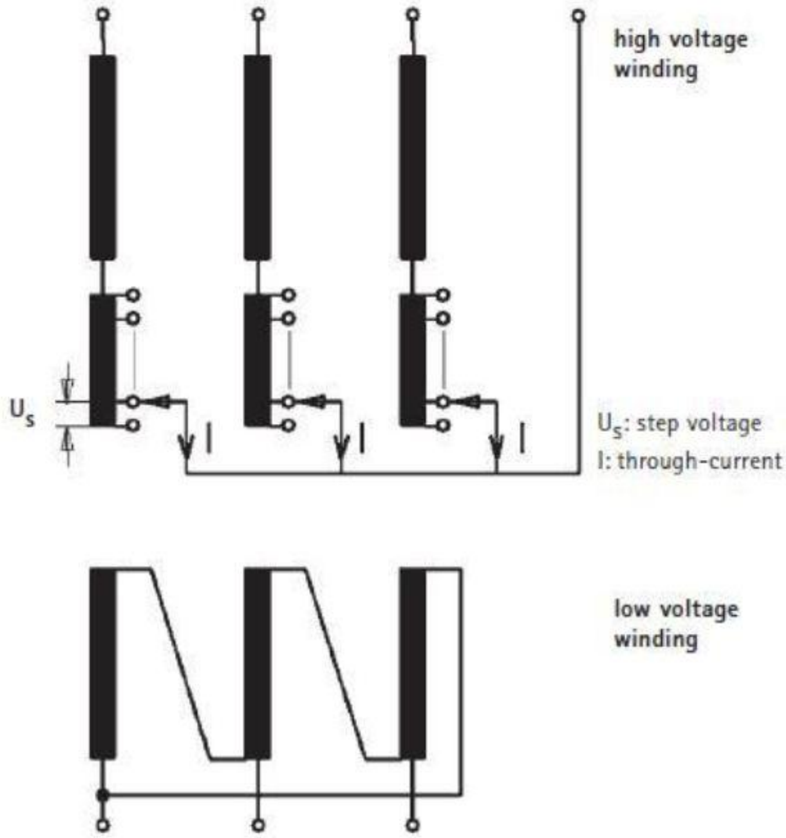

Figure 17. Principle diagram of on load tap changer.

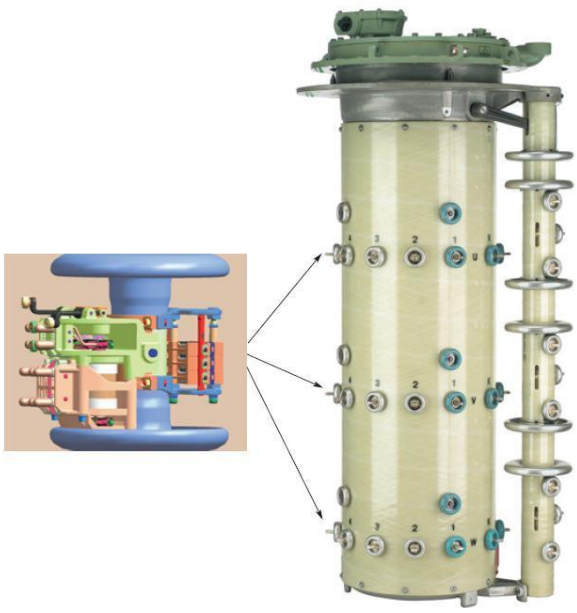

Figure 18. Picture of on load tap changer /2/

The on-load tap changer steps up or down if there is a difference between set point and measured value. There is a dead band around the set point, value where stepping is not done. Usually the change is made step by step. The dead band and delay are needed to eliminate up-and-down voltage regulation too often. If the voltage difference is big enough, the tap changer steps again after the delay. The delay can be from few seconds to some minutes. Normally the step size is 0.5%-1.5%. The dead band is usually twice as much as one step. The on-load tap changer also has a control limit that cannot be exceeded. The transformer with the on-load tap changer is used in the radial distribution network, and it keeps the upstream voltage constant. When the voltage drops in the distribution network, the on-load tap changer reacts after a delay if the voltage difference is big enough. /14/

6.6 Comparison of VAr support technologies

Table 7 shows that the capital cost of the synchronous condenser is the lowest but the cost of losses are the highest. The final decision between techniques has to be calculated based on project specific parameters.

Table 7. Cost comparison of Synchronous condenser, SVS and STATCOM /23/

	Proportional capital cost	Proportional cost of losses
Synchronous condenser	100	100
SVC	113	21
STATCOM	132	33

6.6.1 Synchronous Condenser

Synchronous condensers have several advantages:

- Synchronous condensers contribute to short-circuit power level of the bus to which it is connected
- Condensers reactive power production does not drop rapidly with decreasing system voltage especially if the exciter is a rotating exciter and the auxiliary field for the exciter is fed from a power supply that is not affected by the voltage dip.
- Condensers have high inherent transient overload rating. During power swing there is an exchange of kinetic energy between a synchronous condenser and the power system and if the terminal voltage drops, synchronous condensers can supply reactive power up to two times the rating of the machine for short periods.
- Condensers are easy to maintain and have relatively few parts that could require servicing.
- Condenser can provide continuous control of reactive power output over the complete operating range.

Disadvantages:

- The dynamic response of the synchronous condenser order to increase its output is slow because it takes some time to change the field excitation.
- If the condenser are for some reason or another tripped, it would take a relatively long time to re-start compared with an SVC or STATCOM which could be restarted within seconds. /23/

6.6.2 SVC

Advantages:

- An SVC provides fast and continuously variable capacitive and inductive reactive power supply to the power system.

- An SVC has the lowest losses at zero output and lower losses than synchronous condenser or STATCOM at full output.
- The high speed of response allows the SVC to be used for oscillation damping control and flicker reduction in additional to providing voltage support.

Disadvantages:

- SVC`s cannot respond strongly to severe voltage dips as the reactive power output which comes from statically switched capacitors or fixed capacitors falls off with voltage squared.
- SVC`s have a higher capital cost than synchronous condenser.
- The installation and commissioning of an SVC is more complex than for synchronous condensers. /23/

6.6.3 STATCOM

Advantages:

- Simple equipment configuration with symmetrical output capability.
- Continuous steady state and dynamic voltage support.
- More robust than an SVC with respect to the variation of the network capability.

Disadvantages:

- The cost of STATCOM is normally higher than either SVC or synchronous condensers.
- The losses increase rapidly with output current and would be higher than for a comparably rated SVC at full output. /23/

7 SYNCHRONOUS CONDENSER

This chapter introduces the principles of synchronous condenser as a voltage regulator.

7.1 Principle

The synchronous condenser is a synchronous generator which is operated without a prime mover and the purpose is to produce and absorb reactive power. Re-using the existing generator, its foundation and building, auxiliary systems and grid connections offers an economical source of reactive power capacity. With the automatic voltage regulator, it can automatically control the reactive power output to maintain a constant terminal voltage. An important benefit of a synchronous condenser is that it contributes to the overall short circuit capacity in the network node where it is installed. This, in turn, improves the chances that equipment connected to the network will be able to “ride through” network fault conditions. The machine acts as an enormous 3-phase capacitor whose reactive power can be varied by changing the DC excitation. The excitation control is performed by an AVR which is tuned to match the requirements of the specific application /19/

The operational area and application restrictions may be slightly different for different generator designs. Figure 18 shows the general principle of the synchronous condenser mode of a generator. In the generator mode the active power capability shown in the vertical direction of the diagram is always restricted by the mechanical input power from the prime mover (2). The reactive power capability shown in the horizontal direction in the diagram is in the area restricted by the stator (1), rotor (3) current limits and the minimum excitation limit (4) of the generator. In the synchronous condenser mode, here illustrated by the green line, the operation is restricted by the minimum excitation limit (4) and the rotor current limit (3).

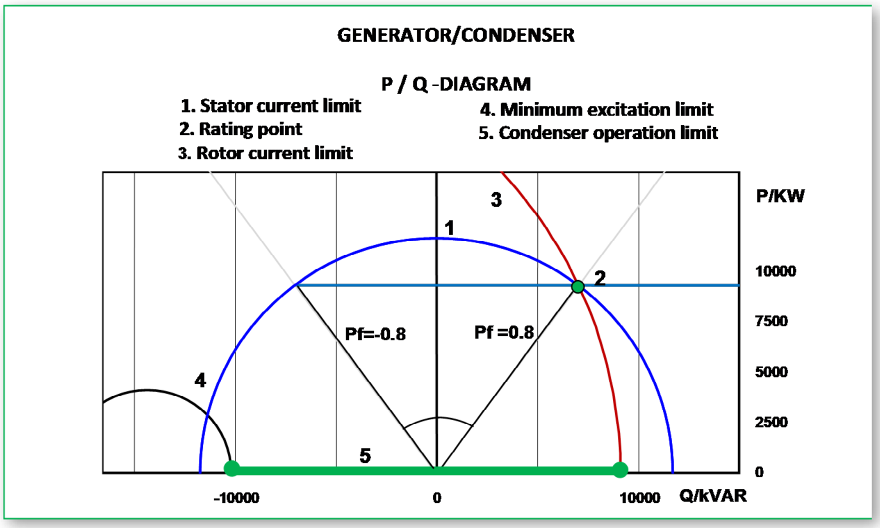

Figure 18. P/Q diagram of synchronous generator. Green line represent synchronous condenser mode./19/

7.2 Applications

During power swings there is an exchange of kinetic energy between a synchronous condenser and the power system. During such power swings, a synchronous condenser can supply a large amount of reactive power. It has about 10 to 20% overload capability for up to 30 minutes. The synchronous condenser has an internal voltage source and is better able to cope with low system voltage conditions. Peaking power generation units can be operated as synchronous condensers if required. Such units are normally equipped with clutches which can be used to disconnect the prime mover from the generator when active power is not required from them. Recent applications of synchronous condensers have been mostly at HVDC converter stations connected to weak systems. /19/

Nowadays synchronous condensers are specially designed to meet the needs of hybrid renewable power systems. During high wind period, the prime mover can be turned off, and the generator as in synchronous condenser handles voltage control. /19/

If the system cannot furnish the required starting power, a pony motor is used to bring them up to synchronous speed. Once the synchronous machine is on-line, the pony motor is de-energized./19/

Advantages using an integrated synchronous condenser:

- When active power is not needed and while the prime mover is in stand-by mode can voltage control and reactive power support can continue in the synchronous condenser mode.
- No additional voltage control infrastructure is needed at the plant connection point.
- The machine inertia support to stabilize the power system during disturbances, load fluctuations or variability of renewable generation output.
- A synchronous machine produces a high amount of reactive power for a short time period in response to a system fault.

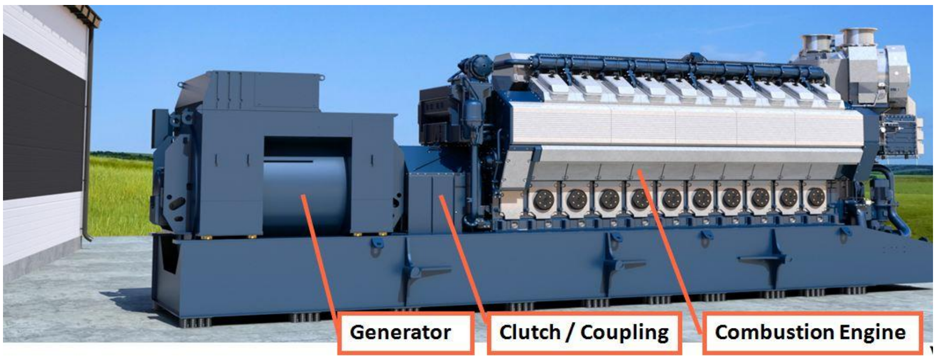

Figure 19. Combustion engine generating set with synchronous condenser feature./19/

8 WÄRTSILÄ SOLUTION

This chapter introduces Wärtsilä solutions how to disconnect the generator from engine.

8.1 Clutch

The generating set with a synchronous condenser function has to be provided with a clutch installed between the prime mover and the generator. The design of a clutch can be seen in Figure 22 and its engaging principle. The connection between the two clutch halves, which are equipped with friction plates, and the outer part is established by driving the clutch halves outwards pneumatically by compressing air bought through the generator shaft. The compressed air flows through the shaft and into the clutch, as illustrated by the red arrows in Figure 20. To provide the needed air flow an integrated compressor is needed which can be placed at the non- drive end of the generator.

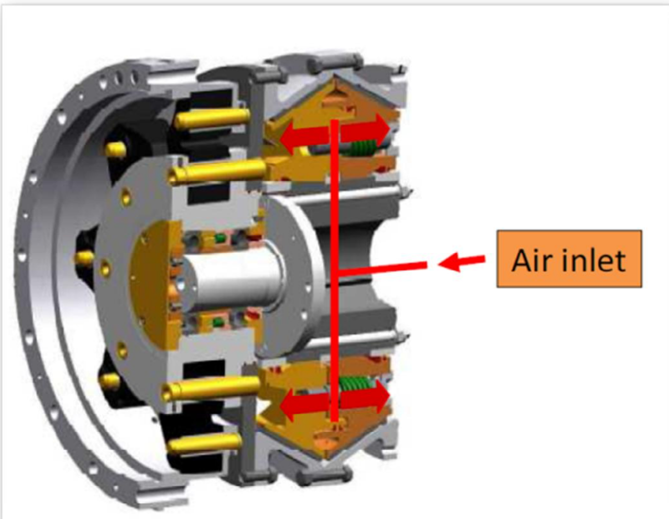

Figure 20. Clutch-coupling. /19/

The clutch is engaged during the engine start-up and can be disengaged as the generating set has been accelerated up to nominal speed and the generator has been synchronized with the grid. Re-engaging, in case active power is needed, is done only when the rotating speeds of engine and generator are again the same. This leads to minimal wear of the friction plates allowing very long service intervals for the clutch.

As soon as the generator is disengaged from the engine, the engine can be shut down and the generator can continue operating as a condenser. Again, whenever the active power is required, the engine is started and accelerated up to the speed representing system frequency, which allows the clutch to be engaged. After this the generating set is ready for the power production.

8.2 Operation Modes

The main purpose of the synchronous condenser function included in Wärtsilä generating set is to improve voltage balance, even though active power production is not needed. It is recommended to use the same generator excitation control mode continuously regardless of prime mover operation. This way the voltage can be kept on the constant level continuously. The starting and stopping of the prime mover does not influence the generator terminal voltage and reactive power production.

When the generating set is operating in the synchronous condenser mode, then possible excitation control modes are voltage control and reactive power control. Because the power factor control is not possible in the synchronous condenser mode, it has to be avoided also in the normal generating set mode.

When AVR is set to the voltage control mode, it keeps the generator terminal voltage on the constant level according to the set point. Sometimes it is possible, that the constant voltage point is on the HV busbar step up on the transformer high voltage side. Then the cascade control method has to be utilized, where AVR takes care of the generator terminal voltage, but a PLC gives a new voltage set point for AVR based on the HV busbar voltage.

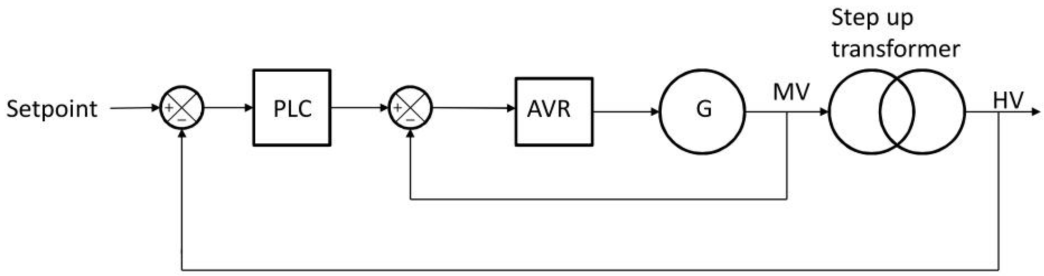

Figure 21. Principle of Cascade control

The electrical network operator can also require constant reactive power production. Then AVR has to be set to the reactive power control mode and the generator produces certain amount of reactive power based on the set point. In this mode the network operator likes to get help to gain the reactive power balance and the final voltage control is made by another method, such as the power transformer tap changer.

9 CONCLUSION

The subject of the thesis was voltage control in distributed electricity generation by using synchronous condenser. The use of synchronous condenser only as a voltage regulator has been reduced since it is not so cost-effective. There is lot of decentralized power production which is not in continuous use. The purpose of the thesis was to discover how to use synchronous machine as a synchronous condenser and improve electrical network stability and to compare synchronous condenser to other solutions of voltage control methods since nowadays there are lot of different kind of solutions.

All voltage control methods are based on adjusting reactive power. Wärtsilä attempt is to utilize already existing synchronous generator as a reactive power producer when active power is not needed. Synchronous generator spins freely and it is used only if needed.

There are also lot of advantages using synchronous generator as voltage controller as presented earlier. A synchronous machine can, irrespective of running generator or condenser mode, produce a high amount of reactive power for a short time period of time in response to a system fault. This can be very valuable for assisting system stability by supporting the system voltage during and after disturbance. A high short circuit level or ratio is also essential in controlling the allowed harmonics level in power system. A synchronous machine is an internal voltage source, this means unlike with a capacitor/reactor bank or SVC, the value of reactive power from a synchronous condenser can be continuously adjusted even with reduced system voltage. Reactive power from a capacitor bank or SVC decreases with decreasing voltage, while a synchronous condenser can increase its current as voltage decrease.

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