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AUTOMATIC CONTROL OF THE STEP-UP TRANSFORMER TAP CHANGER AND GENERATOR AUTOMATIC VOLTAGE REGULATOR

Master's Thesis for the degree of Master of Science in Technology submitted for

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PREFACE

This thesis was made for Wärtsilä Oy Energy solutions. The topic was interesting but challenging. To understand the aim of the thesis I had to have a great understanding of the whole Wärtsilä power plant system topology. I would like to thank Mr. Anders Paavola and my instructor Mr. Srinivasa Raju Addala for giving me the opportunity to write this thesis. I also want to thank them for all the support and guidance.

I also want to thank Mr. Hannu Hautala for providing me with information about RET670 relay, and Mr. Ilari Ristolainen, Mr. Juuso Simolin and Mr. Bengt Johansson for helping me understand the simulation model.

From the University of Vaasa I would like to thank Professor Seppo Niemi, Professor Kimmo Kauhaniemi and D.Sc. Birgitta Martinkauppi for all the help.

The final thanks goes to my family and friends and the people at Project service team that have made my time great here.

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SYMBOLS AND ABBREVIATIONS

ANSI	American National Standards Institute
ATCC	Automatic Tap Changing Control
AVR	Automatic Voltage Regulator
GOOSE	Generic Object Oriented Substation Event
HV	High Voltage
IEC	International Electrotechnical Commission
IED	Intelligent Electronic Device
LV	Low Voltage
MV	Medium Voltage
NEMA	National Electrical Manufacturers Association
OLTC	On Load Tap Changer
PLC	Programmable Logic Controller
RCC	Remote Control Centre
SCADA	Supervisory Control And Data Acquisition system
SM	Synchronous Machine

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ABSTRACT

In the modern power systems advanced automation is the first choice for all operations. At the same time when the automation level is advanced, safety and security are also vital. In this thesis automatic voltage control between two active controllers is analysed with all needed safety interlocks and limiters. The switching operations in a grid can result in large voltage fluctuations for which the power plant controllers need to be smoothly designed/adjusted so that there is minimum impact on the power plant equipment and its auxiliaries. The aim of this thesis is to achieve smooth operation between the transformer IED and generator automatic voltage regulator. With the IED it is possible to control voltage level through the transformer tap changer. The generator automatic voltage regulator controls the output voltage level of the generator. The purpose is to respond to grid voltage fluctuations which are caused by reactive load demands.

When grid voltage varies the automatic controls should react in a smooth way so that the transformer IED changes tap position automatically to large voltage fluctuations and the generator automatic voltage regulator responds to smaller voltage fluctuations. This action is achieved by setting right parameters to the transformer IED’s automatic voltage control function. The automatic controllers that are going to be used are RET670 transformer IED and generator automatic voltage regulator Unitrol.

The thesis includes a theoretical study about generator, step-up transformer and protection systems used in Wärtsilä power plants. The thesis studies also RET670 and Unitrol product manuals. The results are achieved by communication and meetings with power plant system experts, product specialists and information gathered from product manuals. Testing of results are done with Matlab/Simulink Wärtsilä Power plant model. The results show that automatic voltage control is possible. This thesis gives a guideline for a real case power plant project were automatic voltage control is going to be used.

KEYWORDS: Automatic voltage regulator, on-load tap changer, automatic voltage control

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ABSTRAKT

I moderna kraftverk är avancerad automatisering det främsta valet för alla operationer. När automationsnivån är avancerad är säkerheten och reliabiliteten det viktigaste. Denna avhandling behandlar automatisk spänningsregulation mellan två automatiska styrenheter samt alla deras nödvändiga säkerhetsspärrar. De omkopplingar som görs i ett elnät kan resultera i stora spänningsvariationer där kraftverksstyrenheter smidigt måste regleras så att kraftverksutrustningen och dess hjälpmedel påverkas minimalt. Syftet med denna avhandling är att uppnå en smidig samverkan mellan transformatorns relä och generatorns automatiska spänningsregulator. Med relät är det möjligt att styra spänningsnivån genom transformatorns lindningskopplare medan generatorns automatiska spänningsregulator styr spänningsnivån hos generatorn. Målet är att svara på elnätets spänningsvariationer som orsakas av reaktiv belastning.

När spänningen varierar bör de automatiska styrenheterna reagera på ett smidigt sätt så att transformatorns relä byter position på lindningskopplaren vid stora spänningsvariationer och generatorns automatiska spänningsregulator verkar på mindre spänningsvariationer. Denna samverkan uppnås genom att ställa in rätt inställningar på transformatorns relä som styr den automatiska spänningsreglerfunktionen hos lindningskopplaren. De automatiska styrenheter som kommer att användas är RET670 transformatorns relä och generatorn automatiska spänningsregulator Unitrol.

Examensarbetet innehåller en teoretisk studie om generatorn, transformatorn och reläskydden som används i Wärtsiläs kraftverk. Avhandlingen studerar också RET670 och Unitrols produktmanualer. Resultaten har uppnåtts genom kommunikation och möten med kraftverksexperter, produktspecialister och genom information som samlats från produktmanualerna. Resultaten är simulerade med Wärtsilä kraftverks modell i Matlab/Simulink. Resultaten visar att automatisk spänningskontroll är möjligt. Denna avhandlings anvisningar kan användas när automatisk spänningskontroll ska användas i ett kraftverksprojekt

NYCKELORD: Automatisk spänningsregulator, Automatisk spänningskontroll, lindningskopplare

1 INTRODUCTION

1.1 Company introduction: Wärtsilä

Wärtsilä is a global leader in complete lifecycle power solutions for the marine and energy markets. By emphasizing technological innovation and total efficiency, Wärtsilä maximizes the environmental and economic performance of the vessels and power plants of its customers. In 2014, Wärtsilä net sales totaled EUR 4,779 million with approximately 17,700 employees. The company has operations in more than 200 locations in nearly 70 countries around the world. Wärtsilä is listed on the NASDAQ OMX Helsinki, Finland. Wärtsilä has three main areas of business: Energy solutions, Marine Solutions and Services & Support.

Wärtsilä Energy solutions is a leading global supplier of flexible baseload power plants of up to 600 MW operating on various gaseous and liquid fuels. Wärtsilä portfolio includes unique solutions for peaking, reserve and load-following power generation, as well as for balancing intermittent power production. Wärtsilä Energy solutions also provides LNG terminals and distribution systems. In addition to the technical advantages, Wärtsilä fast track deliveries of complete power plants, together with long-term operation and maintenance agreements, provide Wärtsilä customers with complete solutions– in urban areas as well as in the most demanding remote environments. As of 2014, Wärtsilä has 55 GW of installed power plant capacity in 169 countries around the world.

1.2 Thesis background

Power generation requires control, protection and monitoring. The goal is to keep stable grid frequency either 50 Hz or 60 Hz. Stable frequency is achieved by running an engine by a constant speed. System output voltage is determined by the grid demand. Generator voltage is controlled with excitation. To control excitation current, an automatic voltage regulator (AVR) is used. A step-up transformer is used to increase the voltage from Medium Voltage (MV) -system to High Voltage (HV) -system. An on-load tap changer (OLTC) is applied on the secondary winding (HV) of the step-up transformer. The OLTC enables that tap changing can be operated under voltage and load. Tap position is changed depending on the secondary voltage to keep the primary voltage at the correct level. The secondary voltage changes depending on the grid conditions. Today transformer tap changer control is manual in Wärtsilä power plants. My role was to investigate the use of automatic tap changing control instead of manual control. Prediction of my thesis is that in the future tap changing would be automatic and the operator does not have to control the tap changer manually by pushing raise or lower button in the power plant control system.

1.3 Objective, scope and structure of the thesis

The subject for this thesis was provided by Wärtsilä Finland Oy, Energy solutions, Project services. The objective for the thesis is to achieve automatic voltage control between two active controllers. This is achieved by using RET670 Intelligent Electronic Device (IED) for the step-up transformer tap changer control and to make a smooth interface between the RET670 IED and the generator AVR. It is important to keep the MV-system steady to protect the equipment at LV-system. The thesis will also investigate the advantages and disadvantages with automatic voltage control.

RET670 IED that is already used for transformer differential protection and tap changing in Wärtsilä power plants. The tap changing commands raise or lower is done manually through Supervisory Control And Data Acquisition (SCADA) system from a remote place or locally directly on the RET670 relay. RET670 includes an automatic tap changing control function block that could be implemented and it would be possible for Wärtsilä to start using this function instead of manual control.

Wärtsilä synchronous generators have brushless excitation systems that are controlled by an AVR Unitrol 1000-15 or Unitrol 1020. Unitrol keeps the generator in its limits and enables load sharing of parallel running generators. The power plant control method depends on whether the power plant will run isolated from other systems (Island Mode) or as utility system connected to for example national grid (Parallel Mode). In Parallel Mode the active power control with frequency support is used for the engine, which means that the engines will have a steady output and respond to frequency fluctuations. The generator AVR uses power factor control in Parallel Mode. In Island Mode the engine is run in isochronous load sharing mode, which means that active and reactive power is controlled. The generator will run in voltage droop compensation control which means the generators share equally the reactive power by AVR communication and the voltage at busbar is kept at nominal value.

The thesis structure is built up in the following way: Chapter 2 will describe the Wärtsilä power plant electrical system in general. The following Chapters 3-4 will explain about the generator AVR, step-up transformer and protection systems used in step-up units. Automatic voltage control is described in Chapter 5. Chapter 6 explains the interface between generator AVR and differential relay, and the results are simulated in Matlab/Simulink. Chapter 7 contains recommendations for further actions and Chapter 8 draws the conclusions.

2 WÄRTSILÄ POWER PLANTS

2.1 General

Energy demand increases continuously. The use of fossil fuels creates carbon emissions that lead to global warming and this has resulted in concerns about the future. By using renewable sources like wind and solar, carbon emissions will be reduced. The problem with wind and solar power is that the power they produce depends on weather conditions. By making power systems adjustable, able to maintain dynamic capacity, and capable to handle frequent fast starts, stops and load ramps the Wärtsilä engines can be combined with renewable sources (Power Plants Solutions 2014).

Figure 1. Wärtsilä smart power generation with energy efficiency, fuel flexibility and operational flexibility (Power Plants Solutions 2014).

2.2 Power plant electrical system

The majority of power plants are used for base load production in industrial applications as well as in utilities. In addition, they are used as standby and emergency power sources. Power plants can be used for both Island Mode and Parallel Mode with grid. The structure of electrical system depends on type of application, plant capacity, and grid or consumer connection as well as on the technical solutions (Wärtsilä ELWIS (ElectricalWisdom) 2015).

The power plant electrical system consists of equipment for:

- Power generation
    - – Generators
- Power distribution
    - – Switchgears
    - – Transformers
    - – Cables
    - – Earthing
- Control, supervision and protection of above mentioned systems

In the following figure, we see a picture of a typical power plant electrical system arrangement.

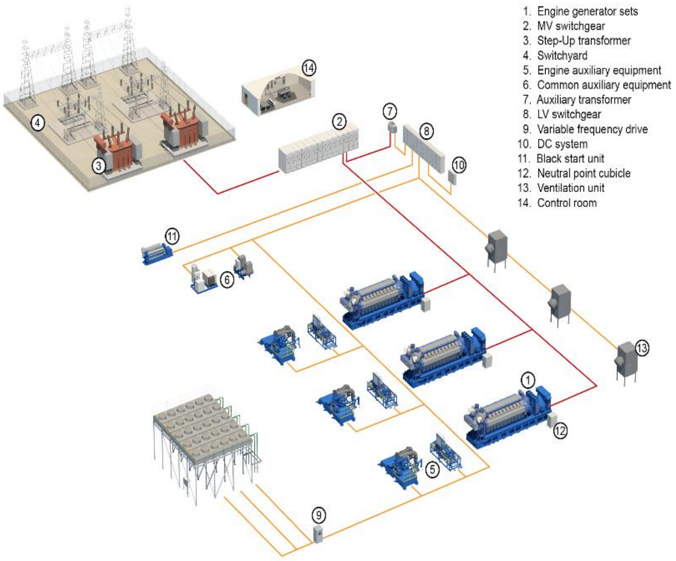


Figure 2. Typical arrangement of a power plant (Wärtsilä ELWIS (ElectricalWisdom) 2015).

The electrical system is divided into three different systems depending on voltage level. High voltage (HV) 35 kV to 230 kV, Medium voltage (MV) 1 kV to 35 kV and Low voltage (LV) 0,1 kV to 1 kV. Parallel running generating sets are usually connected to the MV switchgear. The advantages with multiple parallel connected generating sets are reliability, flexibility, expandability, ease of maintenance and serviceability, cost effectiveness and quality performance. Short-circuit current limits the number of generators that can be connected to the same bus. In Fig. 3 a typical single line diagram of electrical system in a power plant is shown. In the single line diagram there are two MV buses, and each MV bus has six generators. The MV buses are connected to the HV bus with step-up transformers. Auxiliary transformers are connected to the MV bus and steps down the voltage to 400 V from 15 kV for the LV equipment.

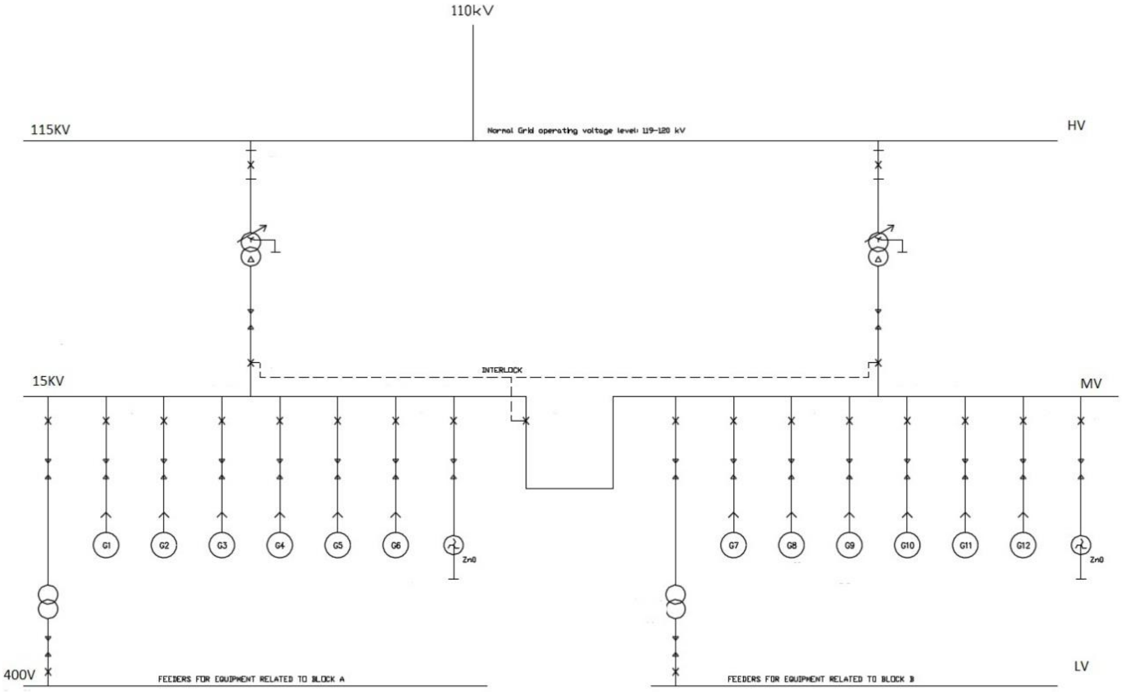


Figure 3. A single line diagram of a power plant electrical system (Wärtsilä 2015a).

The following chapter will describe the generator and transformer used in Wärtsilä power plants.

3 GENERATOR AND STEP-UP TRANSFORMER

This chapter will tell about the generator and step-up transformer that are used in Wärtsilä power plants.

3.1 Generator technical information

Synchronous generators are used in Wärtsilä power plants. The generators shall be constructed according to ISO and IEC standards. IEC stands for International Electrotechnical Commission (IEC) and ISO stands for International Organization for Standardization (ISO). Standards that have to be approved when selecting a generator are listed in Appendix 1.

The standard generator shall be capable of operating when the power factor cos φ varies between 0,95-0,8. The power factor is the ratio between real power (kW) and apparent power (kVA). The closer to 1,0 the power factor is the better the capability of the generator to transfer energy to the load are. The standard network frequency is either 50 Hz or 60 Hz depending on the location. Standard MV voltage levels are 6 kV, 11 kV, 15 kV for 50 Hz and 6,6 kV or 13,8 kV for 60 Hz. The nominal engine speed depends on frequency and the number of poles in the generator. For example, if frequency is f = 50 Hz and number of pole pairs P = 4 the rotation speed of engine will be $N = f \cdot 60$ s/4 = 750 rpm. For example, Wärtsilä 34SG nominal speed is 750 rpm. The ambient temperature of the generator is 50 °C and the maximum temperature rise is 90 °C. Medium speed generators have two ring lubricated sleeve bearings with self-lubrication and cooling. The protection class for enclosure is IP 23 when a generator is running and IP 20 when it is in standby mode. The standard rotating direction is counter clockwise (Wärtsilä ELWIS (ElectricalWisdom) 2015). The generator is air cooled self-ventilated with air inlet filters cooling method IC0A1, which means the generator takes the cooling air from the close environment through the air filter, through generator parts, and exhausts it back to the environment. No external cooling systems are needed (ABB 2012a).

3.2 Generator excitation system

Brushless excitation system is used in Wärtsilä generators. The chosen system use booster current transformers and power transformers for excitation power supply and AVR voltage sensing. In the following figure brushless excitation system with Unitrol 1020 connection diagram is shown (Wärtsilä ELWIS (ElectricalWisdom) 2015).

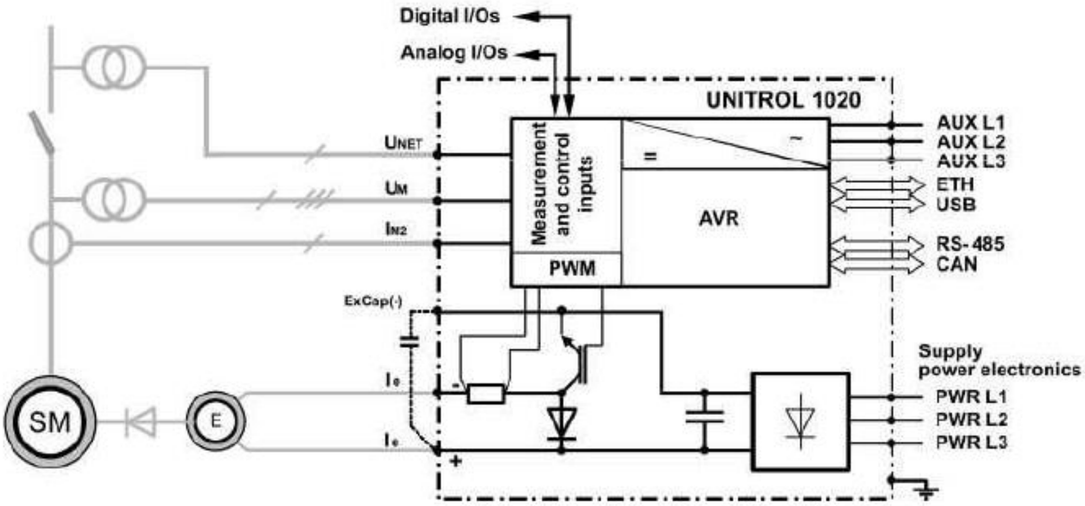


Figure 4. Brushless excitation system with AVR Unitrol 1020 (ABB Ltd 2012).

The Unitrol 1020 measures the network voltage U_{net}, machine voltage U_{m} and machine current I_{m}. The excitation current I_{e} is raised or lowered depending on the given voltage setpoints. Ethernet, USB, CAN and RS-485 are used as communication ports.

The excitation system reliability is high and its duty is to:

- stabilize power oscillations
- share reactive power with other generators connected in parallel
- response quickly in case of network disturbance
- keep the generator in synchronous mode
- operate the generator with its operating limits
- maintain the network voltage

- maintain the generator voltage

The generator voltage is determined by the excitation current I_e and the rotational speed n. If the machine rotates at nominal speed the excitation current decides the induced voltage E_p. In the following figure no-load characteristics operating behaviour of a synchronous machine is shown. I_{eo} (no-load field current) is raised until the generator nominal voltage is reached.

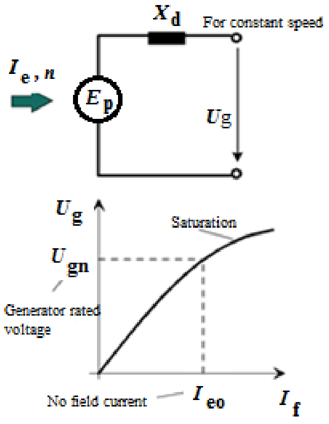


Figure 5. No-load characteristics, operating principle of synchronous machine (ABB 2007).

The generator rotor and power units of the excitation system are designed for a specific operating point which is decided by the nominal excitation current. For the generator to operate safely various limiters are used. Field current limiter is used to protect the generator from overload. To protect the generator from under-excitation a stability limit is used. The theoretical stability limit is reached at a load angle $\delta = 90°$. In Fig. 6 we will see how the safe operating area is determined by over-excitation and under-excitation limiters and the active power of the maximum engine output.

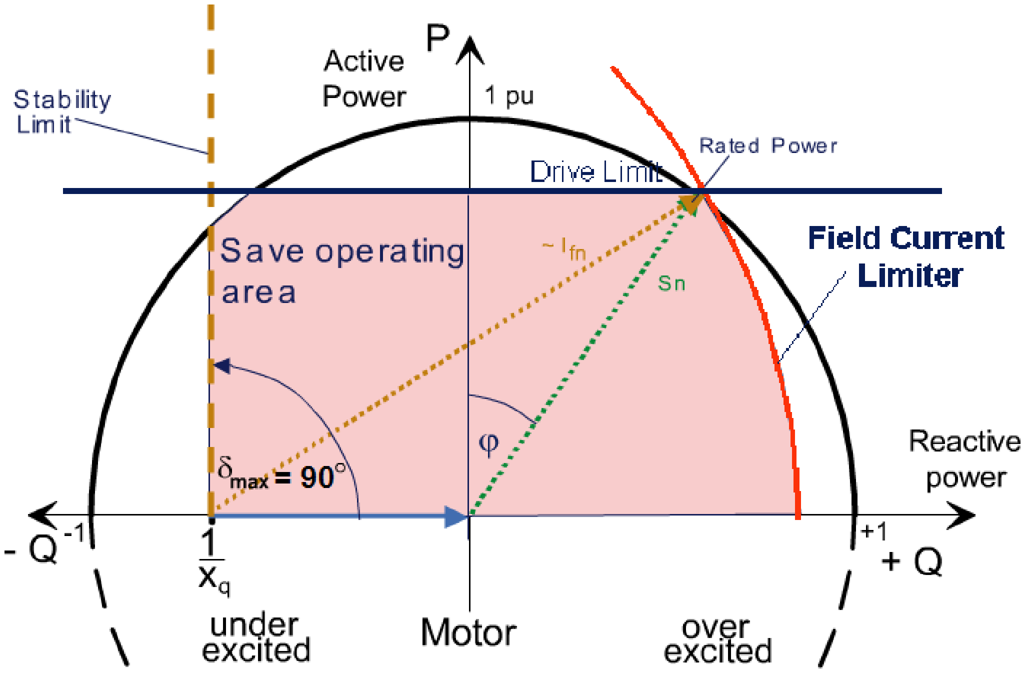


Figure 6. Safe operating area of a synchronous machine (ABB 2007).

For a generator without load, the load angle is δ = 0°. When the machine takes up active power, the load angle increases. When the generator is operating, a force F_{drive} is generated by the rotor. To prevent the rotor from accelerating a counterforce F_{syn} is created by magnetic fluxes influenced by excitation system to keep the generator in synchronous mode (ABB 2007). See Fig. 7 for different load angles.

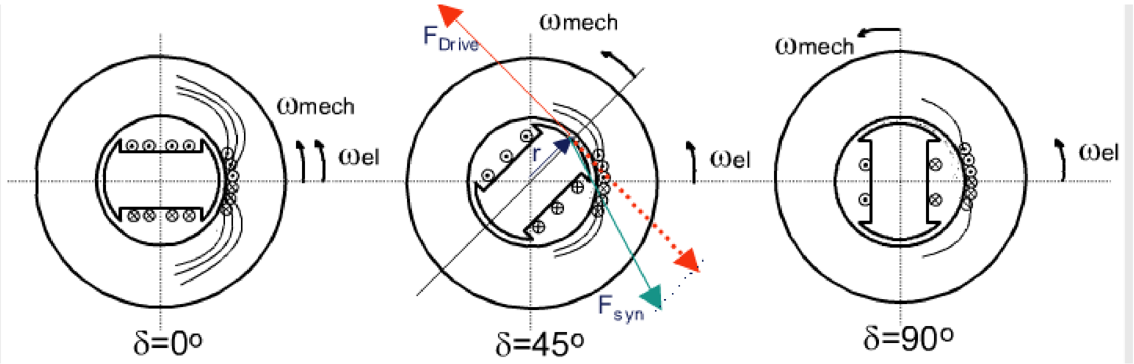


Figure 7. Defining the load angle (ABB 2007).

When active power P increases the ω_{mech} increases due to $P=\omega \cdot r$. Maximum torque T that can be generated is when the load angle is 90° due to $T=F \cdot r$, r is the rotor radius.

ω_{mech} is the mechanical angular speed and ω_{el} is the electrical angular speed (ABB 2007).

3.3 Step-up transformer

The step-up transformers purpose is to take the voltage from a generator voltage level and "step it up" to a transmission voltage level. Step-up transformers are usually YNd connected which means that the winding on the high voltage side is Y-connected, the winding on low voltage side is d-connected, neutral is connected to the high voltage side. The reason for this set-up is to keep the zero sequence impedance of the transformer low. Y-connection is beneficial on the HV-side, because then it is possible to place the tap changer on neutral end which is usually solidly earthed. This leads to that the tap changer operates at lower voltage and the voltage differences between phases will be smaller. With d-connection the current through windings on LV-side is also smaller because the line current is divided by the square root of three.

When choosing step-up transformer, the following four main considerations are important (ABB 2010: 46)

- Short circuit impedance
- Secondary high voltage rating
- Transformer MVA rating
- Primary low voltage rating

The ratio of a transformer can be changed by adding turns or subtracting turns from either the secondary or primary winding. By selecting transformer tap the number of turns in the transformer winding is selected (Vibhute, Rupali, Holmukhe, Chaudhari & Hasarmani 2011).

The ratio can be adjusted with off-circuit tap changer or on-load tap changer (OLTC). OLTC makes tap changing possible under load. Tap changing is usually done in the Y-connected high voltage side of the transformer ensuring that reactive power exchange between generator and power system is not restricted. Voltage ratio of a transformer is normally specified in no-load condition and is directly proportional to the ratio of the number of turns in windings. When the transformer is loaded the voltage on the secondary side changes depending on the angle φ between the voltage and current, the value of secondary current, the short circuit impedance of the transformer and its active and reactive components (ABB 2010: 46).

The following figure shows the relationship between voltages in no-load and load conditions. U_{20} is no-load voltage, U_2 is voltage when load is connected and ΔU_2 is the voltage drop. u_r and u_x are the active and the reactive short-circuit voltages at rated current related to the related voltage U_{20}. This is visualized in Fig. 8.

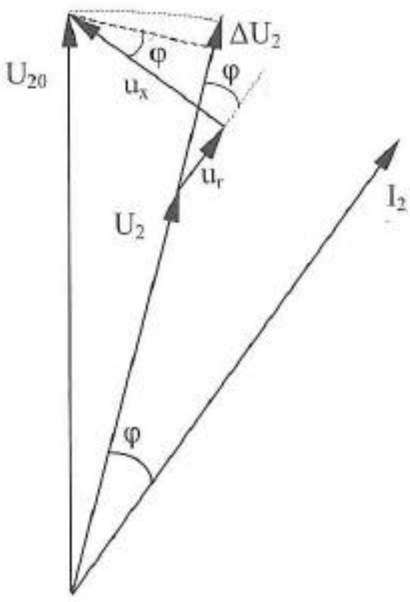


Figure 8. Vector diagram of relationship between no-load voltage (U_{20}) and load voltage U_2 (ABB 2010: 14).

Voltage drop is calculated in the following way:

$$\Delta U_2 = I_2 \cdot r \cdot cos\varphi + I_2 \cdot sin\varphi + U_{20} - \sqrt{U_{20}^2 - (I_2 \cdot r \cdot sin\varphi - I_2 \cdot x \cdot cos\varphi)^2} \qquad (1)$$

To calculate the relative voltage drop at any relative loading: $n = \frac{I_2}{I_{2n}}$ the following formula is used:

$$\frac{\Delta U_2}{U_{20}} = n(u_r \cdot cos\varphi + u_x \cdot sin\varphi) + 1\sqrt{1 - n^2(u_r \cdot sin\varphi - u_x \cdot cos\varphi)^2} \tag{2}$$

For example n = 1 u_r = 0,01 u_x = 0,06 cos φ = 0,8 inductive

$$\frac{\Delta U_2}{U_{20}} = 1 \cdot (0{,}01 + 0{,}8 + 0{,}06 \cdot 0{,}6) + 1 - \sqrt{1 - 1^2 \cdot (0{,}01 \cdot 0{,}6 - 0{,}06 \cdot 0{,}8)^2}$$

$$= 0{,}045 \tag{3}$$

$$\Delta U_2 = 0{,}045 \cdot U_{20} \tag{4}$$

$$U_2 = \Delta U_{20} - U_2 = (1 - 0{,}045) \cdot U_{20} = 0{,}955 \cdot U_{20} \tag{5}$$

With these transformer values the voltage on secondary terminals decreases to 95,5 % compared to the voltage level at no-load. Installation planners and users have to take in consideration the voltage variation when specifying the transformer data. Voltage drop is caused by the consumption of active and reactive power in the transformer. IEC and ANSI standards differ, in IEC the input power is the rated power and in ANSI the output power is the rated power. From the following figure we can see that the voltage drop is smaller with a bigger power factor, the voltage drop also increases when short-circuit reactance increases (ABB 2010).

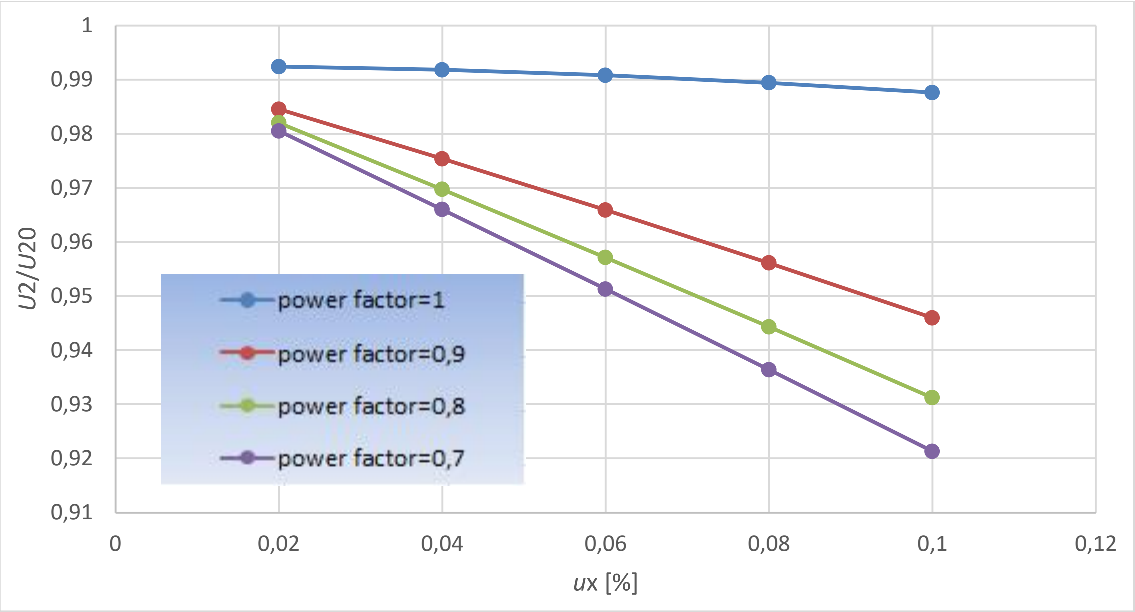
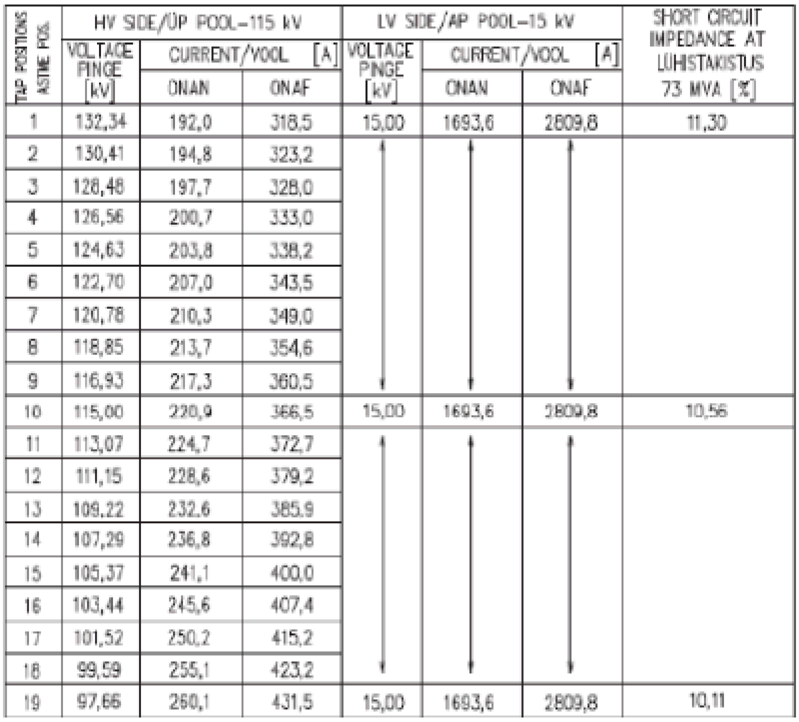


Figure 9. Transformer voltage drop with different power factors and short-circuit reactances (ABB 2010).

3.4 On-load tap changing control

To meet system voltage variations an on-load a tap changer is used. The control of a tap changer is not done by the tap changer itself, relay systems in the station are in charge of its control (ABB 2010). The regulating range depends on the transformer. Range is determined from the amount of steps. For example, transformer rated voltage is 115/15 kV and the tap changer is on the HV side. If tapping range is ± 9 · 1,675 % the transformer has 19 tap steps and the percentage is the voltage raise/drop calculated based on the tap position on the nominal value for example 115kV. Maximum voltage is 115 kV+ (9 · 1,675 %) = 132,34 kV and minimum voltage is 115 – (9 · 1,675 %) = 97,66 kV. In Fig. 10 transformers tap position details are shown.



TAP POSITIONS ASTME POS.	HV SIDE/ÜP POOL–115 kV			LV SIDE/AP POOL–15 kV			SHORT CIRCUIT IMPEDANCE AT LÜHISTAKISTUS 73 MVA [%]
	VOLTAGE PINGE [kV]	CURRENT/VOOL [A]		VOLTAGE PINGE [kV]	CURRENT/VOOL [A]		
		ONAN	ONAF		ONAN	ONAF	
1	132,34	192,0	318,5	15,00	1693,6	2809,8	11,30
2	130,41	194,8	323,2	↕	↕	↕	
3	128,48	197,7	328,0				
4	126,56	200,7	333,0				
5	124,63	203,8	338,2				
6	122,70	207,0	343,5				
7	120,78	210,3	349,0				
8	118,85	213,7	354,6				
9	116,93	217,3	360,5				
10	115,00	220,9	366,5	15,00	1693,6	2809,8	10,56
11	113,07	224,7	372,7	↕	↕	↕	
12	111,15	228,6	379,2				
13	109,22	232,6	385,9				
14	107,29	236,8	392,8				
15	105,37	241,1	400,0				
16	103,44	245,6	407,4				
17	101,52	250,2	415,2				
18	99,59	255,1	423,2				
19	97,66	260,1	431,5	15,00	1693,6	2809,8	10,11

Figure 10. Voltage levels depending on tap position (Wärtsilä 2015a).

There are many methods to control the tap changer. Most commonly used is an AVR device. Another way is to use an intelligent electronic device (IED). By using SCADA it is possible to control the IED or AVR from a remote place. (Sichwart, Eltom & Kobet 2013).

The purpose of tap change control is to keep voltages at all buses in acceptable ranges. When the generator operates at constant voltage unnecessary OLTC operations and voltage fluctuations are avoided (Viawan & Karlsson 2008). Today Wärtsilä power plants use SCADA to control the tap changer. With SCADA it is possible to give raise or lower commands from a remote control center manually depending on measured voltage levels.

This thesis will investigate the use of an IED RET670 for tap changing in step-up units. The RET670 is already used for differential protection of the transformer. The IED control can be local at the substation or remote at the control centre. Control can also be done manually at the transformer but this is not preferred, as it is normally used only for maintenance purpose.

RET670 relay includes an automatic voltage function block that could be used instead of the manual control. The automatic voltage block monitors the voltage level and it will send a message when it notifies that the MV is not in range. The message is received by the tap changer mechanism to make a tap change position. More about RET670 automatic voltage function block is described in Section 5.2. For short-time voltage fluctuations a time delay can be used to prevent unnecessary tap change operations. More about automatic tap changing will be explained in Chapter 5. (Gao & Redfern 2010).

In the following chapter protection of MV-system will be presented. The chapter makes it easier to understand what limits are used for undervoltage and overvoltage conditions.

4 PROTECTION OF MEDIUM VOLTAGE (MV) SYSTEM

Protection of a MV system is needed for human safety, to protect equipment and to limit the stress on connected equipment. Protection systems are also used for avoiding total power plant blackouts. The main idea of protection system is to locate a fault as fast as possible and disconnect the malfunctioning unit without unstabilizing the network. This chapter will describe which protections are used in MV-systems. The protection systems and their time limits are significant for knowing the working range automatic tap changing.

4.1 General information

Generator and transformer act as one unit when there is a fixed electrical connection between them. Different relays trigger circuit breakers to quickly disconnect the unit with failure to protect the rest of the system. This may cause higher voltage on the generator terminals which will lead to over-excitation of the transformer. The overvoltage protection of the low voltage winding is important because of large difference in the voltage and insulation levels, magnitude of transferred transients and overvoltage from the high voltage to the low voltage side. The current is very high between the generator and transformer. To prevent short circuits, bus ducts are used for each phase conductor. The high current with strong magnetic fields creates circulating currents. The losses from these circulating currents cause overheating. Therefore it is important that the bus ducts are correctly measured at the transformer end to lessen the heating problem (ABB 2010: 47).

4.2 Protection standards

There are two different types of power system device function numbering standards. American National Standards Institute (ANSI) and International Electrotechnical Commission (IEC) (My Electrical Engineering 2012). Which standard is used depends on the country/location. ANSI uses numbers when IEC uses symbols. Notations of ANSI and IEC standards are compared in Appendix 2.

4.3 Short-circuits and earth faults

The most common faults in power systems are short-circuits and earth faults. Short-circuits and earth faults have different fault types. Fig. 12 shows one-phase, two-phase and three-phase short circuits as well as single-phase, two-phase and double earth faults. It also displays line break down and single phase earth fault on the load side. One-phase short circuit means that there is short-circuit between one phase conductor and the ground. Two-phase short circuit means that there is a fault between two phase conductors. Three-phase short circuit means that there are faults between all phase conductors. Single-phase earth fault means that there is a fault between the ground and one phase conductor. Two-phase earth fault means that there is a fault between two phase conductors and a fault between a phase conductor and the ground. Double earth fault means that there is a fault between the ground and two separate phase conductors.

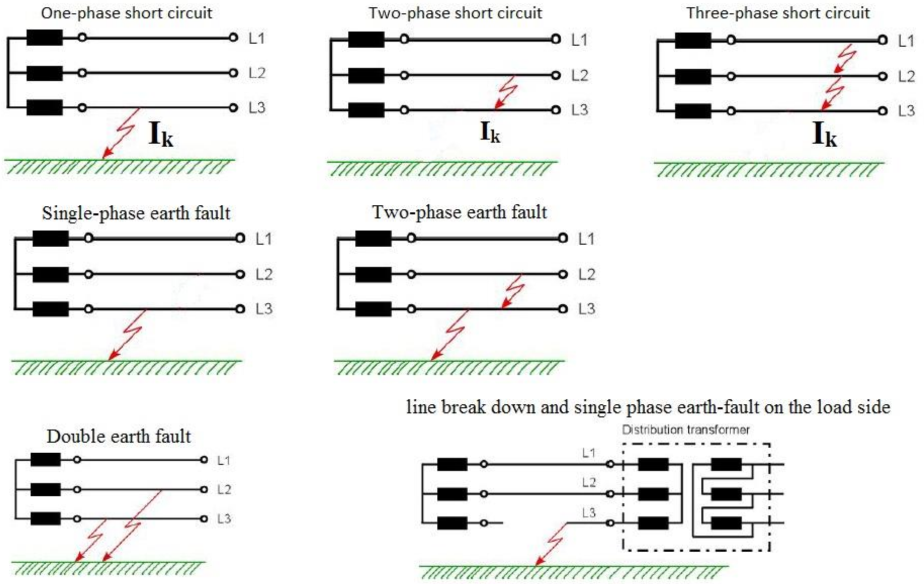


Figure 11. Different short-circuits and earth faults between phase conductors L1-L3 (Wärtsilä 2015).

Short circuits are caused by aging of insulation, mechanical damage to insulation due to environmental stress, arc from overvoltage (e.g. caused by lightning), and unintentional or intentional mechanical damage. Fault currents cause arcs that can damage mechanical parts and be dangerous for humans, voltages between components that are dangerous, disturbance voltages near to the fault, and damage to different components caused by thermal stress. These faults lead to loss of system stability, temporary load peaks, and undervoltage in the undamaged parts of the network. An earth fault is when a fault between live part and earth occurs, for example, when a tree or vehicles touch the over headlines or when the overhead lines falls down to the ground. Other causes are flashovers to earthed parts, isolators with weak insulation and cable faults caused by damage or aging (Wärtsilä 2015).

4.4 Generator protection

Many different electrical and mechanical faults can occur in a modern generating unit. The amount of protection installed depends on the value of the machine and the value of the plant output determined by the plant owner. Problems that you have to take into consideration are the following (NPAG 2011):

- Stator electrical faults
- Overload
- Overvoltage
- Unbalanced loading
- Overfluxing
- Inadvertent energisation
- Rotor electrical faults
- Loss of excitation
- Loss of synchronism
- Failure of prime mover
- Lubrication oil failure
- Over-speeding

- Rotor distortion
- Difference in expansion between rotating and stationary parts
- Excessive vibration
- Core lamination faults

The stator winding neutral point is usually earthed to make protection of stator winding easier. Earthing also protects against overvoltage. High voltage generators use earthing through impedance to limit earth fault current to a suitable level. Where a step-up transformer is applied, the generator and the lower voltage winding of the transformer can be treated as an isolated system that is not influenced by the earthing requirements of the power system. If the generators capacity is over 1 MVA differential protection is used (NPAG 2011).

The generator is protected with a REG670 relay and a RET615 relay. The REG670 is used for protection, control, and monitoring of generators and generator-transformer blocks from relatively small units up to the larger generating units. RET615 is an advanced protection and control IED for two-winding power transformers and power generator-transformer blocks. The RET615 is used in back up purpose for the REG670. Functions that are applied in RET615 and REG670 in a protection diagram of a generator are shown in the Appendix 3.

4.5 Step-up transformer protection

The transformer protection varies depending on application and importance. Different transformer faults are the following:

- Winding and terminal faults
- Core faults
- Tank and transformer accessory faults
- On-load tap changer faults
- Abnormal operating conditions
- Sustained or uncleared external faults

Winding failures caused by deterioration of insulation is statistically the most probable cause for the transformer failure. On-load tap changer is the second most probable fault instigator. Tap changing faults can depend on the malfunction of a mechanical switching mechanism, high resistance load contacts, insulation tracking, overheating, or contamination of the insulating oil. The third most common is the fault on transformer bushings which is caused by general aging, contamination, cracking, internal moisture, loss of oil, vandalism, or wild animals (Grigsby 2007). Table 1 shows what kind of protection methods are used for typical transformer faults.

Table 1. Transformer fault types and the corresponding protections (NPAG 2011).

Fault type	**Protection used**
Primary winding phase-earth fault	Differential; Overcurrent
Secondary winding phase-phase fault	Phase-phase fault differential
Interturn fault	Differential, Buchholz
Core fault	Differential, Buchholz
Tank fault	Differential, Buchholz; tank-earth
Overfluxing	Overfluxing
Overheating	Thermal

In the following figure protection logic diagram for the step-up transformer is shown.

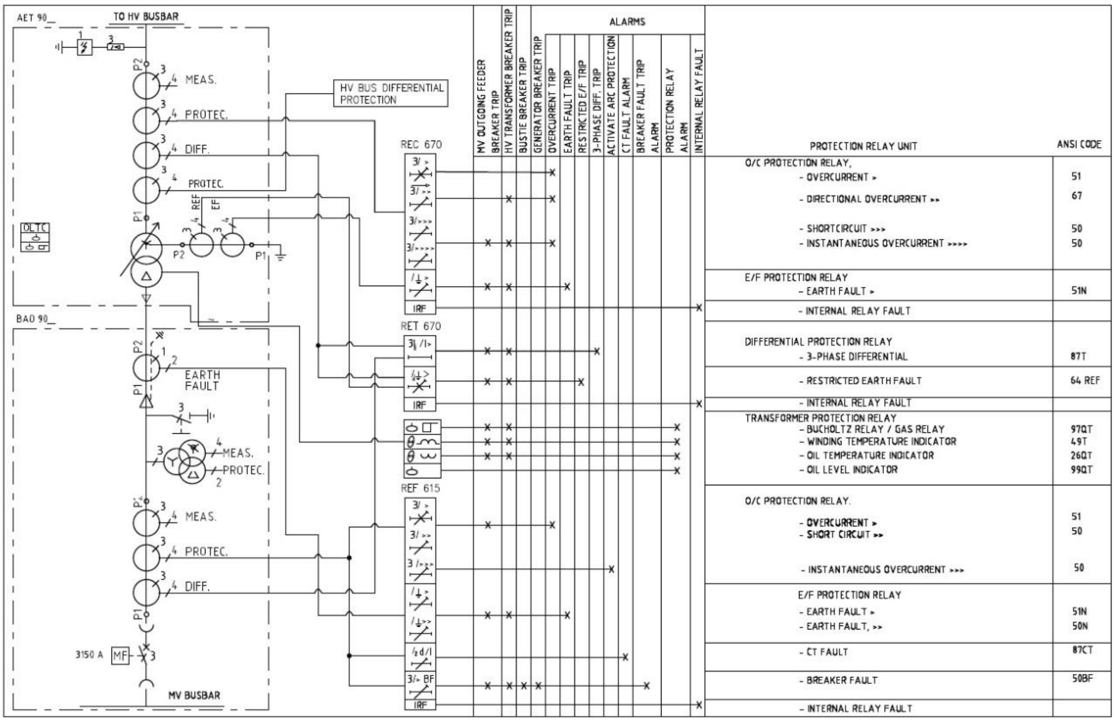


Figure 12. Step-up transformer logic protection diagram with REC670, RET670, and REF615 protection relays (Wärtsilä internal 2015a).

In the logic protection diagram the protection from MV-side to HV-side is shown. The main purpose is to protect the step-up transformer. The protection consists of REC670, RET670 and REF615 relays.

The REC670 is used for the control, protection and monitoring of different types of bays in power networks (ABB Ltd 2015). RET670 provides fast and selective protection, monitoring and control for two- and three-winding transformers, autotransformers, step-up transformers and generator transformer, block units, phase shifting transformers, special railway transformers, and shunt reactors. RET670 has a fast, low-impedance differential protection function with very low requirements on the current transformers (CT). REF615 provides feeder over current and earth-fault protection for distribution networks. REF615 is available in nine standard configurations and will therefore suit the most common feeder protection and control applications (ABB Ltd 2015). The transformer also needs a protection gas relay called Buchholz relay named after the inventor. Oil functions as insulation and cooling in a transformer, so it is important to control oil level, oil temperature and winding temperature. Functions that are used in REC670, RET670, REF615 and Buchholz relay in step-up transformer are shown in Appendix 4.

RET670 differential relay is used for step-up transformer protection. The RET670 has a fast low-impedance differential protection function with very low requirements on the CT:s. Differential relays are connected on both sides of the transformer, see Fig. 13. (Guzman, Fischer & Labuschagne 2009).

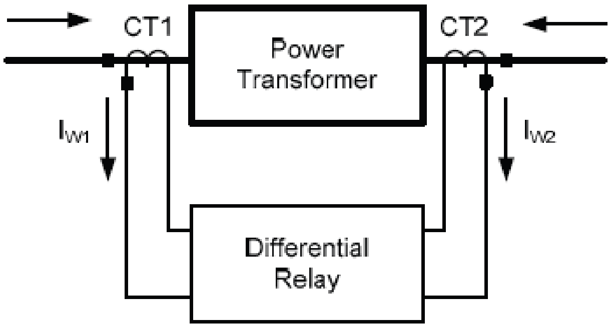


Figure 13. Differential relay connection. (Guzman, Fischer & Labuschagne 2009)

RET670 provides fast and selective protection, monitoring and control for all types of transformers. RET670 is capable to handle from a single up to eight parallel transformers. It is also possible to protect several objects with a single RET670 for example transformer and its connected transmission line. RET670 tap changer control function includes line drop compensation and load shedding function. Fig. 14 shows an application with RET670, which for instance is able to measure voltage on both sides, measure currents on bus feeders and monitor breaker statuses with a single device (ABB Ltd 2015).

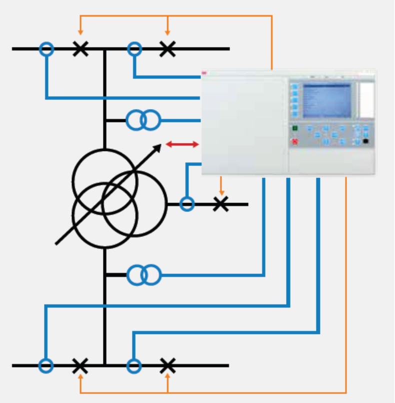
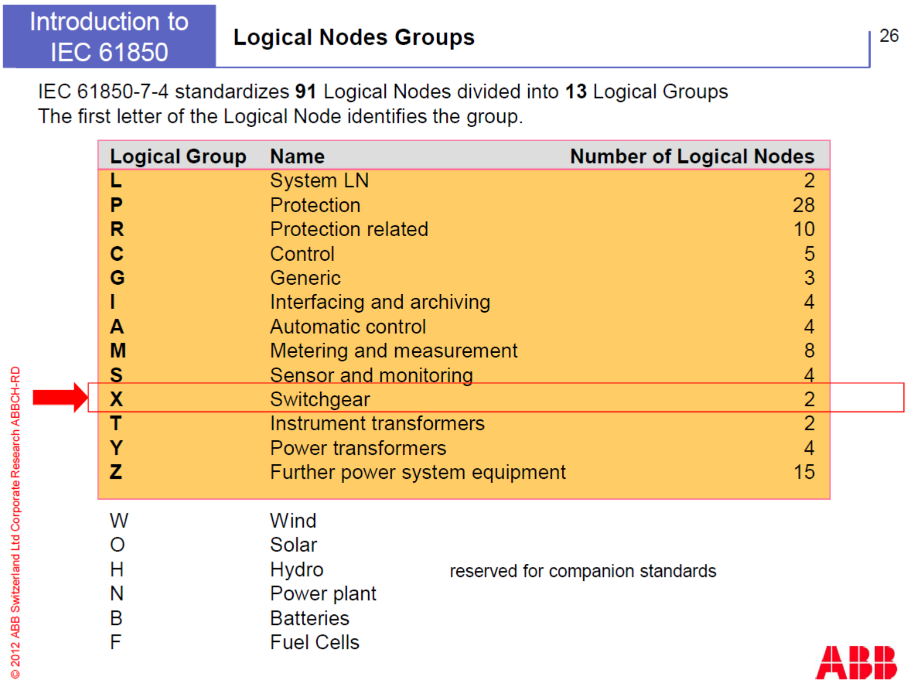


Figure 14. Application example with RET670 voltage measurement, current measurement and breaker monitoring (ABB Ltd 2015).

RET670 is designed for implementing all aspects of IEC 61850 standard. IEC 61850 standard specifies communication between IEDs for the automation of substations. GOOSE messages are used for communication between IED devices and communication from IED devices to a substation computer. IED devices consist of logical nodes. Each logical node consists of multiple data groups and each data group has multiple data attributes. There are many benefits of using IEC 61850 standards, for example, wiring can be greatly reduced and thereby the need of copper is reduced. Interoperability is also achieved with less wiring (Sichwart, Eltom & Kobet 2013). Fig. 15 shows what kind of different IEC 61850 logical nodes groups there are.



Introduction to IEC 61850

Logical Nodes Groups

26

IEC 61850-7-4 standardizes **91** Logical Nodes divided into **13** Logical Groups
The first letter of the Logical Node identifies the group.

Logical Group	Name	Number of Logical Nodes
L	System LN	2
P	Protection	28
R	Protection related	10
C	Control	5
G	Generic	3
I	Interfacing and archiving	4
A	Automatic control	4
M	Metering and measurement	8
S	Sensor and monitoring	4
X	Switchgear	2
T	Instrument transformers	2
Y	Power transformers	4
Z	Further power system equipment	15

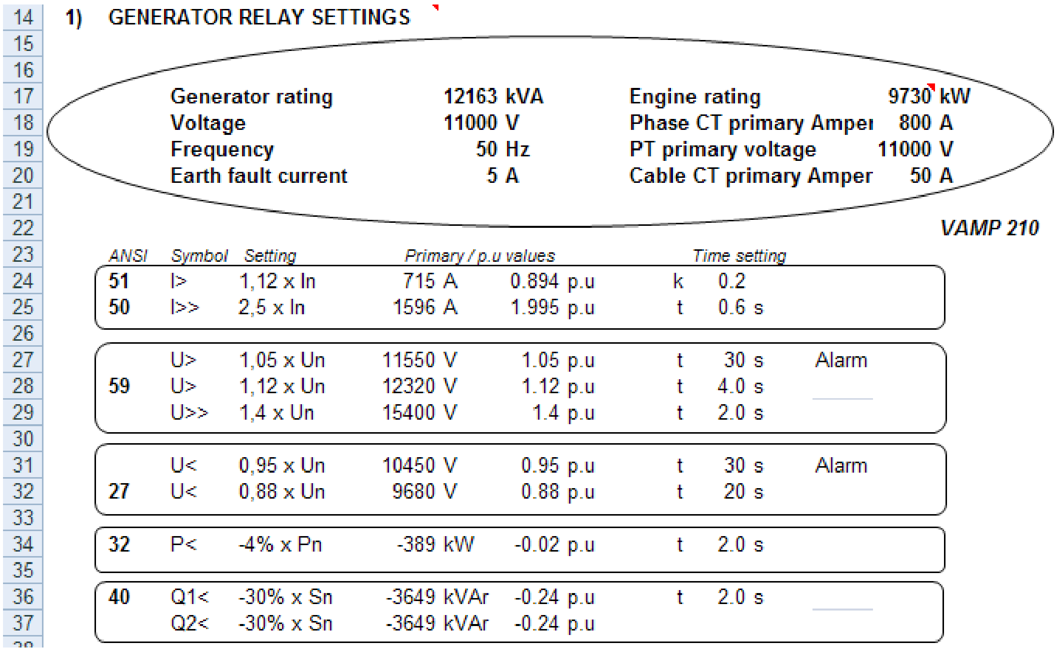
W	Wind	reserved for companion standards
O	Solar	
H	Hydro	
N	Power plant	
B	Batteries	
F	Fuel Cells	

Figure 15. Logical nodes group (Sichwart, Eltom & Kobet, 2013).

GOOSE messaging has become more and more available for protection and automation devices. Network communication between devices is more flexible than communication by network cables. Communication can also be applied in several multifunctional IEDs. With GOOSE messages it is possible to send a set of data attributes. Data attributes can, for example, be circuit breaker position status value. The device that has information of interest, sends a GOOSE multi-casted message that other devices can retrieve, and read the sent information. (Sichwart, Eltom & Kobet, 2013)

4.6 Wärtsilä default relay settings

Default relay settings are defined to protect equipment. Maximum and minimum limits define the range the generator and transformer are able to work safely. In the following figure, Fig. 16, Wärtsilä default relay settings for generator are shown. Maximum accepted overcurrent is 1,12 times nominal current (inverse time). If the current is 2,5 times above the nominal current for more than 0,6 s the relay will trip instantaneously. Maximum accepted overvoltage is 1,05 times nominal voltage and if the voltage is above this limit for 30 s, the relay will alarm. If it is above 1,12 times nominal voltage, the relay will trip after 4,0 s. Minimum undervoltage is 0,95 times nominal voltage. The relay will alarm after 30 s if voltage is under 0,95. The relay will trip after 20 s when voltage is 0,88 times nominal.



1) GENERATOR RELAY SETTINGS

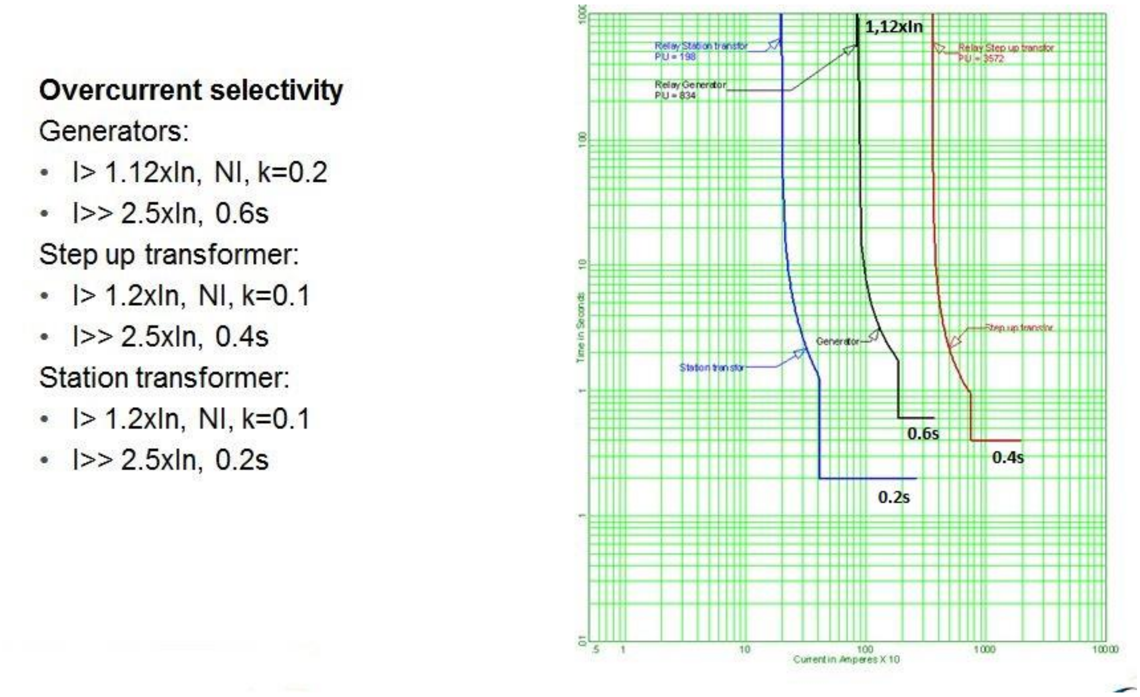
Generator rating	12163 kVA	Engine rating	9730 kW
Voltage	11000 V	Phase CT primary Amper	800 A
Frequency	50 Hz	PT primary voltage	11000 V
Earth fault current	5 A	Cable CT primary Amper	50 A

VAMP 210

ANSI	Symbol	Setting	Primary / p.u values		Time setting		
51	I>	1,12 x In	715 A	0.894 p.u	k	0.2	
50	I>>	2,5 x In	1596 A	1.995 p.u	t	0.6 s	
	U>	1,05 x Un	11550 V	1.05 p.u	t	30 s	Alarm
59	U>	1,12 x Un	12320 V	1.12 p.u	t	4.0 s	
	U>>	1,4 x Un	15400 V	1.4 p.u	t	2.0 s	
	U<	0,95 x Un	10450 V	0.95 p.u	t	30 s	Alarm
27	U<	0,88 x Un	9680 V	0.88 p.u	t	20 s	
32	P<	-4% x Pn	-389 kW	-0.02 p.u	t	2.0 s	
40	Q1<	-30% x Sn	-3649 kVAr	-0.24 p.u	t	2.0 s	
	Q2<	-30% x Sn	-3649 kVAr	-0.24 p.u			

Figure 16. Current, over- and undervoltage, active power and reactive power generator relay settings.

So that the right protection will work at the right time different time settings are used for the generator, step-up transformer and the station transformer to achieve selectivity (see Fig. 17). Selectivity means that the breaker closest to the fault should work first and minimum time discrimination between two relays is set to 0,2 s for definite time function. Standard inverse and definite time functions are used to achieve selectivity.



Overcurrent selectivity

Generators:

- I> 1.12xIn, NI, k=0.2
- I>> 2.5xIn, 0.6s

Step up transformer:

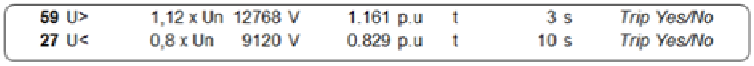
- I> 1.2xIn, NI, k=0.1
- I>> 2.5xIn, 0.4s

Station transformer:

- I> 1.2xIn, NI, k=0.1
- I>> 2.5xIn, 0.2s

Figure 17. Protection overcurrent selectivity (Wärtsilä 2015b).

The blue line is the station transformer setting trips after 0,2 s, the black line is the generator setting trips after 0,6 s and the red line is the step-up transformer setting trips after 0,4 s. Generator protection shall be the last in order to cause trip. Outgoing breaker time delay is therefore set to have lower time limit 3 s to trip before generator breaker 4 s.



59 U>	1,12 x Un	12768 V	1.161 p.u	t	3 s	*Trip Yes/No*
27 U<	0,8 x Un	9120 V	0.829 p.u	t	10 s	*Trip Yes/No*

Figure 18. Switchgear over- and undervoltage protections.

When setting the generator protection settings, generator AVR settings have to be considered as PQ-limiter, under-excitation and over-excitation limiters.

The following chapter will describe automatic voltage control.

5 AUTOMATIC VOLTAGE CONTROL

This chapter will tell about how generator and step-up transformer voltage is controlled automatically.

5.1 Generator automatic voltage regulator

For controlling voltage level, Wärtsilä generators are supplied with ABB Unitrol 1000-15 or Unitrol 1020 automatic voltage regulators (AVR). Unitrol 1020 is a newer model with the same functions. The following operation modes that can be used are: Voltage Droop, Power factor or Voltage Droop Compensation. (Wärtsilä ELWIS (Electrical-Wisdom) 2015). Power factor control is used when operating the power plant parallel with grid, by controlling generator excitation so that the reactive power is matched proportionally to the active power. Intention of voltage droop is to control the power plant system voltage by controlling the generator field excitation. The Voltage Droop is calculated from the power plant reactive load so the bus voltage will vary as a function of reactive load. Voltage Droop compensation (VDC) is used in Island Mode. In VDC each generator AVR are connected to a reactive load communication bus. Each AVR writes their own amount of reactive power to the communication bus which each AVR reads and then calculates a common average reactive power set point. In this way reactive load is shared and the voltage droop is compensated (Wärtsilä internal 2011).

Unitrol 1000-15 is an AVR for synchronous generators which maximum output current is 15 A and the power input can be from an AC or DC source. Standard functions are:

- Voltage regulator with PID control algorithm
- Power factor cos φ regulator with PID control algorithm
- Reactive power regulator with PID control algorithm
- Excitation current regulator with PI control algorithm
- Internal digital references value
- Bumpless change-over for all modes of operation

- Soft-start function
- Reactive current droop for network operation
- Reactive power sharing between parallel by RS-485 bus
- Volts-per-hertz limiter
- Three-step delayed maximum excitation current limiter
- Reactive current limiter as a function of active power (P/Q)
- Stator voltage limiter
- Master slave reactive power sharing
- Undervoltage detection to activate external current boost for short-circuit support
- Open-loop control of output voltage for test purposes
- Built-in step test function
- Stand-by mode for redundant backup channel system
- Alarm and trip signals

Unitrol 1000-15 has four digital inputs, four digital outputs, three analog inputs and two analog inputs. It also has a RS-232 serial interface for PC connection and a RS-485 used for reactive power sharing when two or more generators are connected in parallel. It has also a CAN bus for controlling local extension devices. Unitrol has an easy panel to set all the parameters and user-friendly software CMT1000 (Commissioning and Maintenance Tool). Unitrol 1000 is displayed in Fig. 19.

Figure 19. Unitrol 1000 operation panel with four buttons and display (ABB2007).

The voltage can be controlled in three different modes:

- Reactive power control, Q-control (Default)
- Voltage control, U-control (Optional)
- Power factor control, Pf-control (Manual)

Q-control is for adjusting the amount of produced reactive power according to a set-point by increasing or decreasing AVR voltage reference signal to reach the reactive power production requested. Q-control requires that active power management mode is active, remote control mode is active, and voltage control mode is disabled. The reactive power produced is measured on the upper side of the step-up transformer. Pf-control is intended for manual operation of individual generating sets only (Wärtsilä 2015).

U-control is controlling the AVR voltage set point to achieve target voltage at the sub-station high voltage side. The following figure shows the principle of voltage control arrangement.

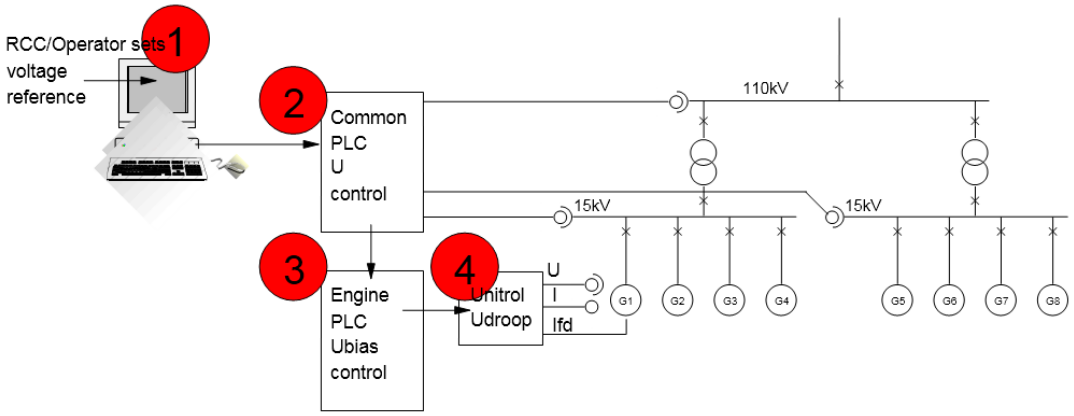
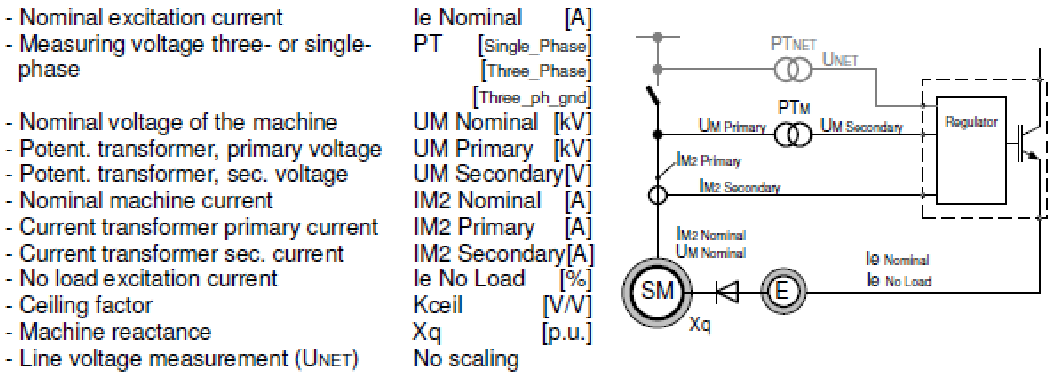


Figure 20. Voltage control set-up from a remote control centre through PLC (Wärtsilä 2015).

System operating voltage set point is set by RCC/operator. Voltage bias signal is given to PLC’s. PLC voltage reference controller handles the control of the bias signal to the Unitrol AVR with a 4−20 mA output signal setting the generator voltage reference. Unitrol operates automatically in the voltage droop mode (Wärtsilä 2015).

Standard AVR systems that are offered are single channel systems and dual-channel systems. Dual-channel systems purpose is to provide higher security in case of failure. In the following figure parameters used in Unitrol AVR are shown.



- Nominal excitation current	Ie Nominal	[A]
- Measuring voltage three- or single-phase	PT	[Single_Phase] [Three_Phase] [Three_ph_gnd]
- Nominal voltage of the machine	UM Nominal	[kV]
- Potent. transformer, primary voltage	UM Primary	[kV]
- Potent. transformer, sec. voltage	UM Secondary	[V]
- Nominal machine current	IM2 Nominal	[A]
- Current transformer primary current	IM2 Primary	[A]
- Current transformer sec. current	IM2 Secondary	[A]
- No load excitation current	Ie No Load	[%]
- Ceiling factor	Kceil	[V/V]
- Machine reactance	Xq	[p.u.]
- Line voltage measurement (UNET)	No scaling	

Figure 21. Description of AVR parameters (ABB 2015).

The voltage level is raised by raising excitation current, see Fig. 22 (ABB 2015).

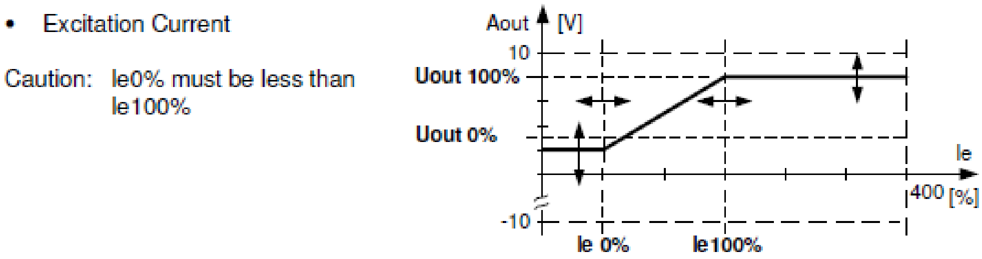


Figure 22. Voltage level depending on the excitation current (ABB 2015).

Following limiters are available for different purposes:

- V/Hz limiter
- IeMinimum current limiter
- IeMaximum current limiter
- PQ limiter
- Boost-output
- UM limiter

UM limiter makes it possible to limit minimum machine voltage and maximum machine voltage. UM limiter is only available in power factor mode. Its voltage matcher function makes it possible to raise a voltage to the level of the line voltage. In Fig. 23 minimum voltage level is 90 % and maximum voltage level is 110 %. The voltage is raised to match the line voltage U_{net}.

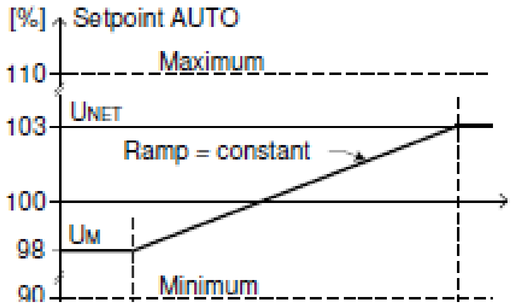


Figure 23. Voltage matcher (ABB 2015).

In the following picture voltage droop compensation control is shown. To share the amount of reactive power equally of parallel connected generators the AVR units are connected parallel in RS-485 bus. Each Unitrol device sends the amount of their reactive power to the RS-485 bus to calculate a common average reactive power set point and compensates the voltage droop and the voltage on the busbar is kept at correct level (ABB 2015).

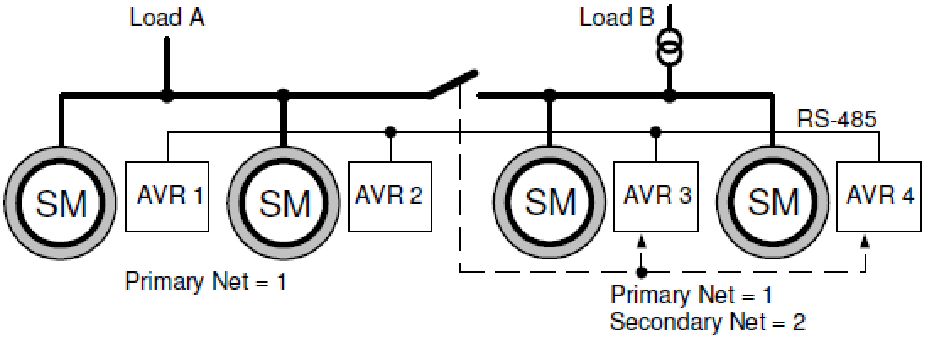


Figure 24. Voltage droop compensation control with four synchronous machines (SM) (ABB 2015).

5.2 Automatic voltage control of a step-up transformer

The purpose of automatic voltage control of a step-up transformer is to make the tap changer commands raise/lower automatic. Automatic voltage control is a function available in RET670. RET670 is provided with manual and automatic control of single and parallel transformer arrangements. It is also possible with automatic control or supervised manual control of OLTC operations, for example through SCADA. Line drop compensation (LDC) and load shedding are other specific voltage control functions that can be used if necessary. Maximum circulating current, maximum load current, over- and undervoltage, forward/reverse power and reverse OLTC action are power system functions that can be monitored. Tap position, OLTC command and response are functions that can be supervised.

The automatic voltage control function is built by the following two IEC61850 logical node function blocks:

- **TR1ATCC** for single transformer control
- **TR8ATCC** for parallel transformer control

Tap changer control and supervision is done by following two IEC61850 function blocks:

- **TCMYLTC** with 6 binary inputs
- **TCLYLTC** with 32 binary inputs

The following function block is required for communication:

- **VCTRRCV** to receive remote goose messages

TCMYLTC and TCLYLTC works as an interface between the automatic voltage control and the transformer tap changer. It gives commands to motor driven load tap changers and receives information about tap position. It also gives information about tap position to the transformer differential protection. TR8ATCC input and output signals are explained in Fig. 25 TCMYLTC input and output signals are explained in Fig. 26.

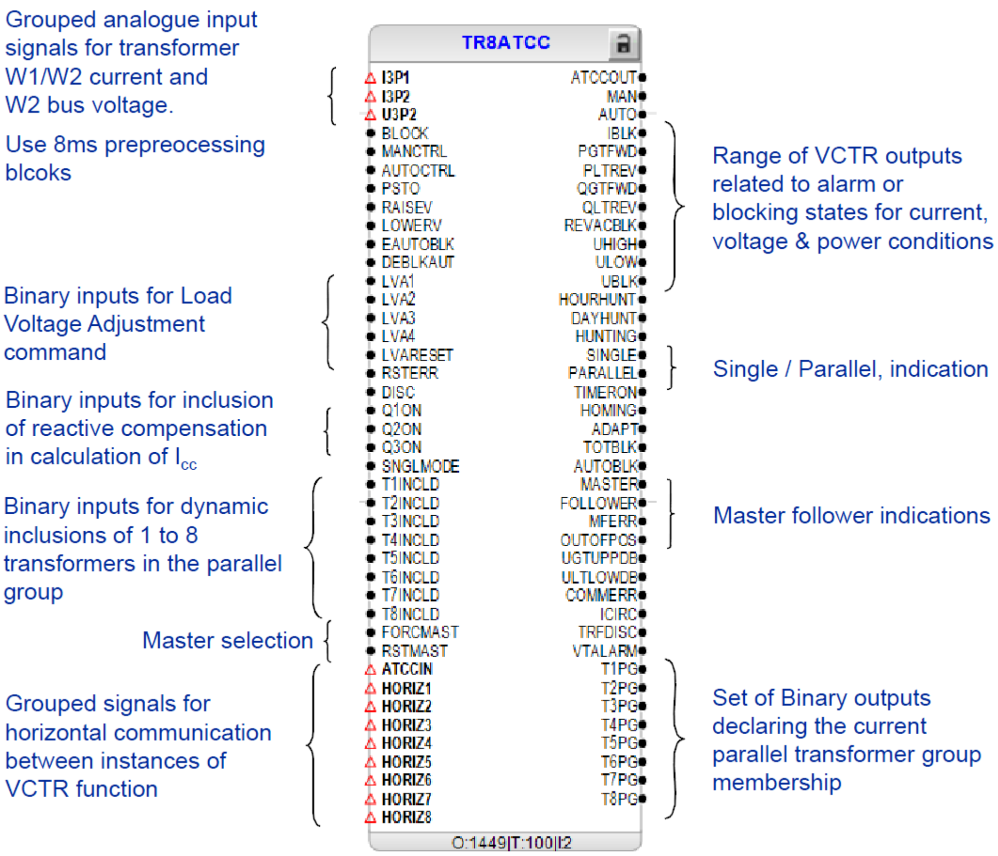


Figure 25. TR8ATCC function block input and outputs (ABB 2013).

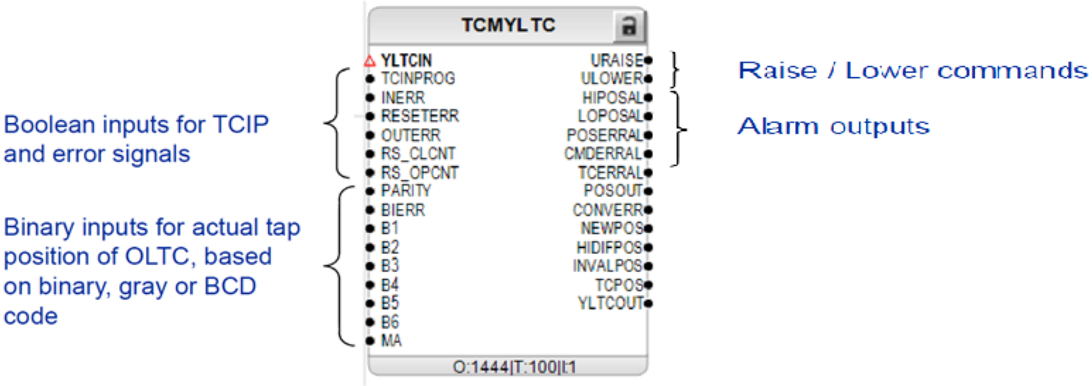


Figure 26. TCMYLTC function block input and outputs (ABB 2013).

Fig. 27 shows an example of how the automatic voltage control is built in ABB software PCM600.

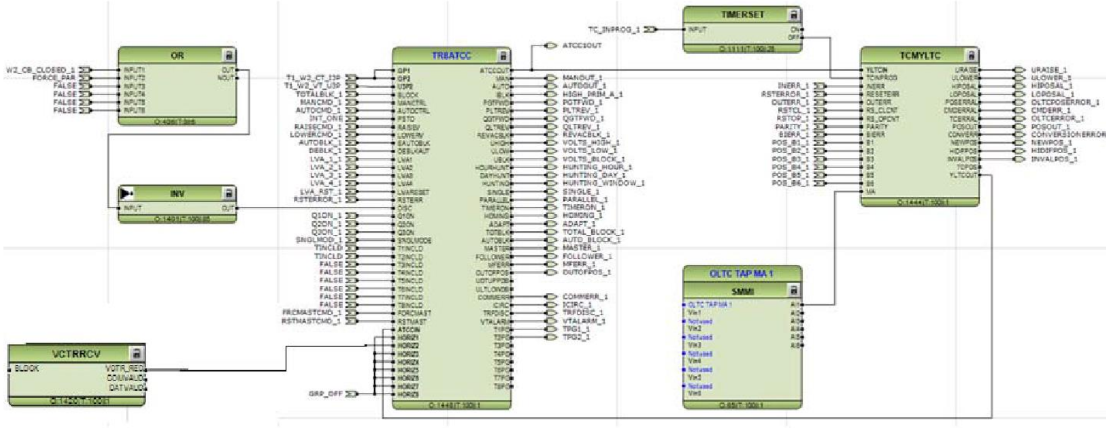


Figure 27. An example of automatic voltage control (ABB 2013).

The main key points of automatic voltage control is:

- Voltage setpoints and dead bands
- Tap change timing
- OLTC raise and lower commands

The principle of automatic voltage control is to measure the busbar voltage level U_b. The measured voltage is compared to a reference value U_{set}.

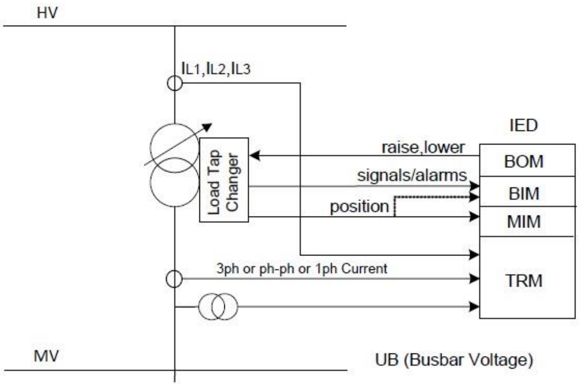


Figure 28. Single transformer with voltage control (ABB 2015).

In the following figure the principle of automatic voltage control is presented. The principle is to keep the power plant MV voltage between U_1-U_2 by setting outer dead band (ΔU) and inner dead band ΔU_{in}

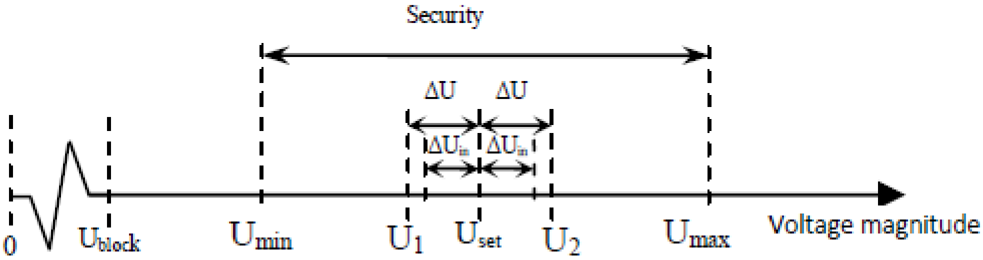


Figure 29. Principle of automatic voltage control with outer dead band; (ΔU) and inner dead band; ΔU_{in} (ABB 2015).

To avoid unnecessary tap switching around the set point an outer dead band (ΔU) is used. ΔU parameter U_{deadband} should be set near to the step-up transformer tap changer voltage. Inside the outer dead band interval no tap changes are operated. If the measured voltage is outside the outer dead band interval longer than a specified time and the voltage level have not come back inside on the inner dead band ΔU_{in} before the specified time has run out, a tap position change command is made. The main purpose of the specified time is to prevent unnecessary tap change operations caused by temporary voltage fluctuations. ΔU_{in} setting $U_{\text{deadbandinner}}$ is recommended to be set smaller than the ΔU value. Each tap step changes voltage level with approximately 0,5 - 1,7 % depending on the step-up transformer. U_{min} and U_{max} are used for security range for voltage levels. If the voltage level is under U_{min} different blocking conditions can be activated. When voltage is over U_{max} fast step down command will be activated which means the tap changer makes one or more fast step changes (Constantin & Iliescu 2012).

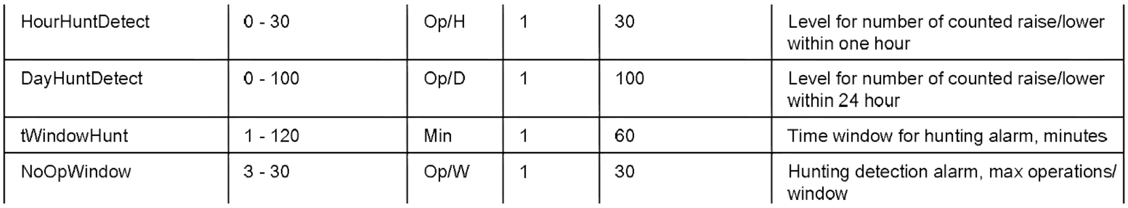
The IED can be operated remotely or from a local place by using IEC 61850 function blocks LOCREM or LOCREMCTRL. Auto or manual control can be chosen by using IEC 61850 function blocks AUTOCTRL or MANCTRL (ABB 2015).

The voltage control IEC 61850 function blocks also include many extra features, for example:

- Simultaneous tap change avoiding
- Standby regulation of parallel transformer tap position even if breaker is open
- Hunting detection
- Monitoring of power flow
- OLTC number of operations and contact life counter

Simultaneous tap changing is avoided by setting parameters so that the transformer with the greatest voltage deviation taps first and then the transformer with the next biggest voltage deviation and so on, according to set time limits. If two transformers have equal voltage deviation pre-setting decides which changes tap first.

Hunting detection is when tap changers operate many times in a short interval. General hunting detection monitors tap changes during the past hour or day. Sliding hunting detection monitors the number of successive commands in opposite directions. The number of operations can be adjusted in settings before an alarm occurs. In Fig. 30 hunting detection settings are shown.



HourHuntDetect	0 - 30	Op/H	1	30	Level for number of counted raise/lower within one hour
DayHuntDetect	0 - 100	Op/D	1	100	Level for number of counted raise/lower within 24 hour
tWindowHunt	1 - 120	Min	1	60	Time window for hunting alarm, minutes
NoOpWindow	3 - 30	Op/W	1	30	Hunting detection alarm, max operations/ window

Figure 30. Hunting detection (ABB 2014).

Blocking is used to protect the tap changer from damage in case of any power system failure. Three different methods are used (Constantin & Iliescu 2012).

- Total block
    - Any tap changer operation is blocked
- Partial block
    - Blocks tap changer operations in one direction for example RAISE or LOWER
    - Available in both manual and automatic control mode
- Automatic block
    - Automatic voltage control disabled
    - Tap changer can still be controlled manually

Blocking is used in cases when, for example, voltage rises or drops dramatically. It is also possible to block automatic tap change control temporary or to reduce the voltage setpoint.

5.3 Voltage control for parallel transformers

Parallel control means control of two or more transformers connected to the same busbar. To operate transformers in parallel increases security and reliability of supply (Gao & Redfern 2010). Parallel operation requires the same phase-angle difference, voltage ratio, percentage impedance, polarity and phase sequence (Guzman, Fischer & Labuschagne 2009). There are different methods for parallel control. With RET670 up to eight transformers can be operated parallel. The following methods for transformer paralleling can be used for RET670.

- Master-follower control
    - All transformers operate on the same tap as the transformer which is selected to be master
- Circulating current control
    - Transformers do not need to have identical tap steps
    - Minimizes the circulating current between transformers

- Reverse reactance control
    - Transformers do not need to have identical tap steps
    - Minimizes open circuit voltage and circulating current between transformers
    - Primary windings need to be connected directly in parallel
    - Each transformer has its own protection system with AVR function
    - Best suited for emergency conditions and for applications in which the load magnitude and load power factor do not vary significantly
- The VAR balance method
    - Minimizes the differences between reactive loads as a fraction of rated power or the load power factors of the transformers operating in parallel
    - Transformers do not have to have identical steps and does not have to have primary windings directly in parallel
- Power factor balance method
    - Minimizes the difference between reactive loads as a fraction of rated power or the load power factor of the transformers operating in parallel
    - Transformers do not have to have identical steps and does not have to have primary windings directly in parallel

Reverse reactance method do not need to have exchange of signals and measured values between transformers or between the transformer and a central control unit because transformers does not need to have identical tap positions and each transformer has its own protection system. But the disadvantage with this method is that the voltage control will be affected by changes in the load power factor. The disadvantage of the master-follower method is that it is mostly limited to applications with similar transformers. The advantage of the circulating current method is that it handles unequal transformers in a smart way. Master-follower relies on communication from master to follower to send commands or tap position between IEDs. The selection of master is defined by the user via input FORCMAST in the configuration. The advantage with master-follower mode is that the followers blindly follows the master and in that way it is impossible for the tap changers to gradually differ and end up in opposite end positions. In the following figure master-follower selection is shown.

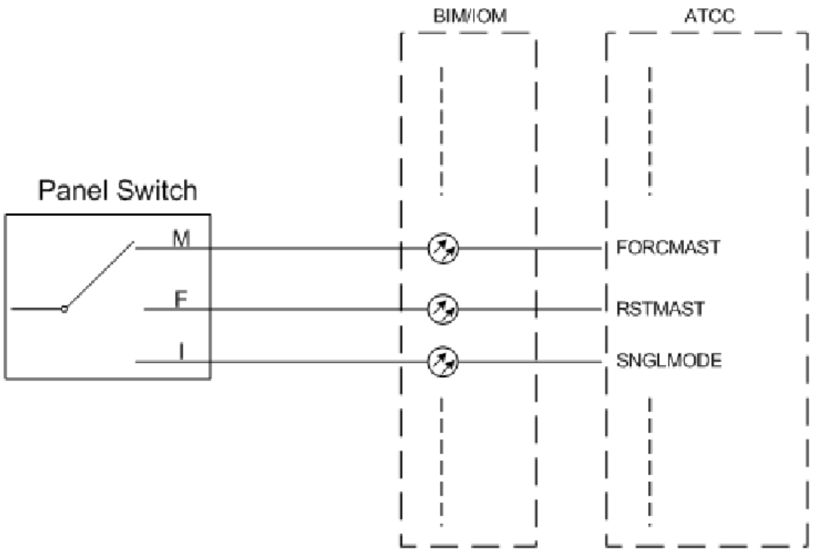


Figure 31. Master-follower selection principle in Protection and Control IED Manager (PCM) (ABB 2013).

It is also possible for the follower to read tap position of the master and adapt to the same position or to an offset position. It is also possible to time delay one or more followers.

The transformer paralleling can be done in two different ways. The first way is that the automatic tap changing control (ATCC) is integrated with protection and control in a single IED for each transformer. Required information for circulating current and master-follower method communication between devices is done by IEC61850-8.1 protocol and exchange of analogy and binary data IEC Goose messages are used. Up to eight transformers can be used in parallel in this way. In Fig. 32 it is shown how two RET670 communicate through IEC61850-8.1. The two RET670 also communicate with three REC670 devices.

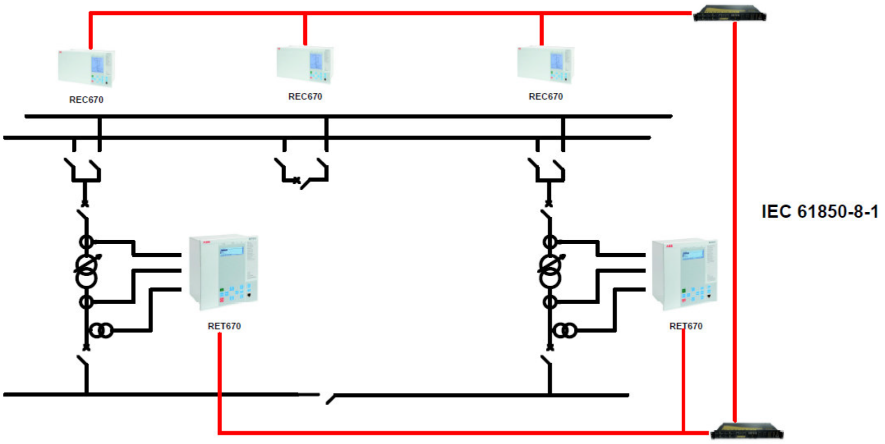


Figure 32. ATCC and transformer protection IEDs separate for each transformer (ABB 2013).

The second way of transformer paralleling control is that only one IED is used and no external communication links are needed. The problem with this alternative is that the current transformer and voltage transformer wiring has to be brought to the same location. A backup IED can also be used, see Fig 33.

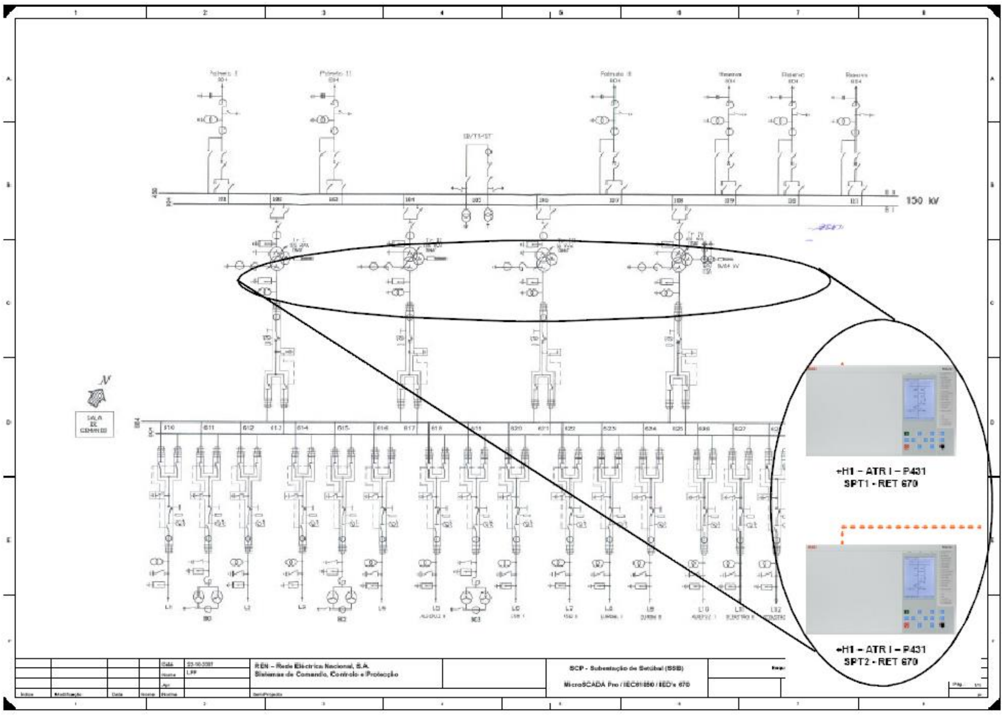


Figure 33. Four transformers control integrated into one single RET670 with a backup device (ABB 2013).

5.4 Key factors

Key factors which need to be studied and taken care of when automatic tap changer control is used:

- Tap changer fault
- Voltage collapse
- Voltage stability problems
- Circulating currents
- Inrush currents
- Turn-to-turn faults

If a load tap changer fails to operate, the voltage will remain at a level which can result in an undervoltage or overvoltage condition for a longer time. In case of misoperation it may cause the system to start an undervoltage or overvoltage condition. Undervoltage and overvoltage conditions lead to reduced performance, reduced service life and possible failure of equipment. In RET670 there are signals called tapChgError (tap change error) and cmdError (command error) which are activated when a tap positions is not changed thus of raise or lower command, for example if there is a mechanical fault and the tap changer is stuck. The tap changer position is measured by tap changer control and supervision (TCLYLTC) IEC 61850 function block. Tap changer position is continuously monitored and when there is a fault an alarm is given.

OLTC will strain to keep the voltage at nominal value. In case of voltage instability the tap changer can cause a voltage collapse with several tap changes. To prevent voltage collapse from happening, tap locking, tap blocking and tap reversing functions are used (Baalbergen, Gibescu & van der Sluis 2011).

Voltage stability problems can be reduced in several ways. There are several methods:

- Must-run generation
    - Use uneconomic generators to change power flow or provide voltage support during emergencies
- Series of capacitors

  - Series of capacitors used to shorten long lines i.e. decreasing the net reactive loss
- Shunt capacitors
  - Used to free spinning reactive reserve in generators
- Static compensators
  - Effective in controlling voltage and preventing voltage collapse but has very exact limitations that have to be recognized
- Operate at higher voltages
  - Decreases reactive demand keeping generators away from reactive power limits
- Secondary voltage regulation
  - Automatic voltage regulation of certain busses which controls coordinately the total reactive power in these areas
- Undervoltage load shedding
  - Most effective in steady-state problems
- Lower power factor generators
  - Using a generator with power factor 0,8 or 0,85
- Use generator reactive overload capability
  - Delay voltage collapse until operators change dispatch or restrain load when reactive overload is modest overload capability must be defined in advance to be most useful

Abilities of transformer protection relays to detect internal faults during inrush current conditions are limited. Common harmonic blocking is often used to detect inrush currents. It has, however, a long trip delay and this can lead to transformer damage. Independent harmonic restraint is a faster way to detect inrush current faults but, it is slower to detect other faults. The negative-sequence differential element has high sensitivity to detect turn-to-turn faults (Guzman, Fischer & Labuschagne 2009).

Unequal no-load voltages appear when the voltage angle or amplitude differ. When $U_1 \neq U_2$ an electromotive force (EMF) appears and causes a circulating current I_{kr} that flows through the windings. The magnitude and angle of the circulating current is determined by short-circuit impedances Z. The circulating current formula (Eq. 6) indicates how the current depends on the difference between no-load voltages U_1 and U_2:

$$I_{kr} = \frac{U_1 - U_2}{Z_{k1} - Z_{k2}} \tag{6}$$

Formation of circulating currents is shown in Fig. 34.

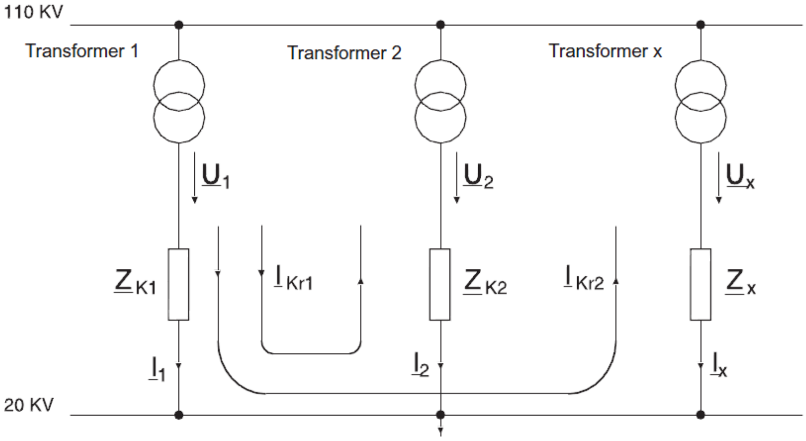


Figure 34. Parallel operation of transformers creates circulating currents (ABB 2015).

By modern relays with time synchronised measurement and custom logic it is possible to minimize circulating currents. By minimizing circulating currents transformer losses and overheating is reduced (Guzma, Fischer & Labuschagne 2009). In RET670 there is also the *CirrCurrBl* (circulating current blocker) function that alarms/blocks tap changer when circulating currents are too high (ABB 2015).

In this chapter, it is shown that RET670 is already designed to handle several problematic situations that can occur. Next chapter will describe how smooth interface between generator AVR and RET670 could be achieved.

6 RET670 AND GENERATOR AVR INTERFACE

The following chapter will describe settings that have to be used for automatic voltage control. The settings will also be simulated in the Wärtsilä power plant simulation model.

6.1 Parameter settings

Wärtsilä power plants can be used for different purposes, for example, as base load and emergency power plants. The network grid conditions usually depend on the country/location. In countries with strong network grids there are less voltage fluctuations and automatic voltage control is easier to handle. Acceptable voltage levels for transmission grids are usually between the following values:

- 110 kV: 106-123 kV
- 220 kV: 200-245 kV
- 400 kV: 370-420 kV

The purpose is that the generator AVR and step-up transformer tap changer takes care of these voltage fluctuations automatically so that equipment does not get damaged. In the following figure, principle of a power plant voltage control set up is shown. Each generator has a Unitrol 1000-15 AVR and each step-up transformer has RET670 differential relay.

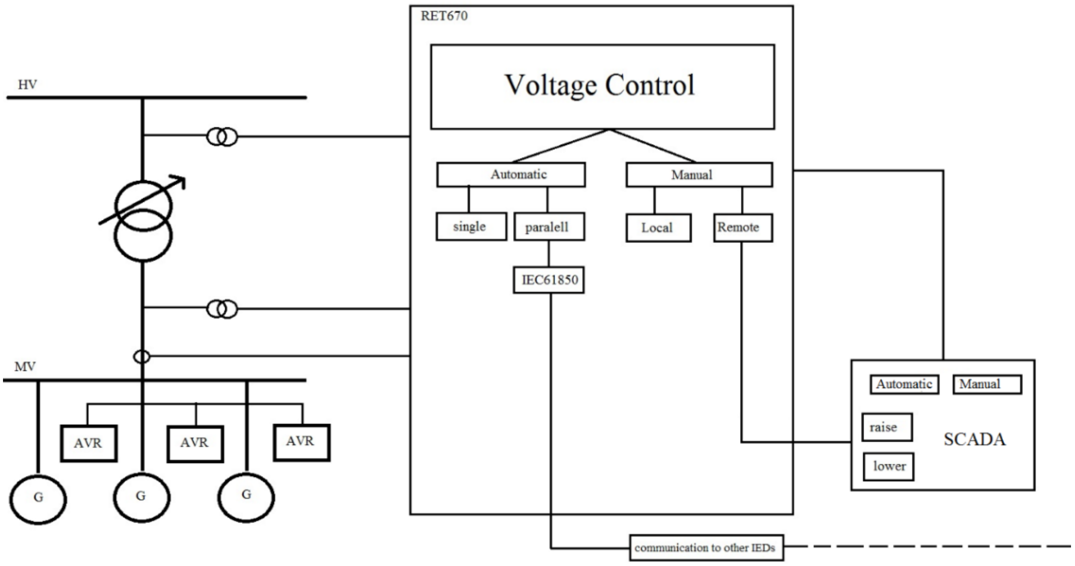
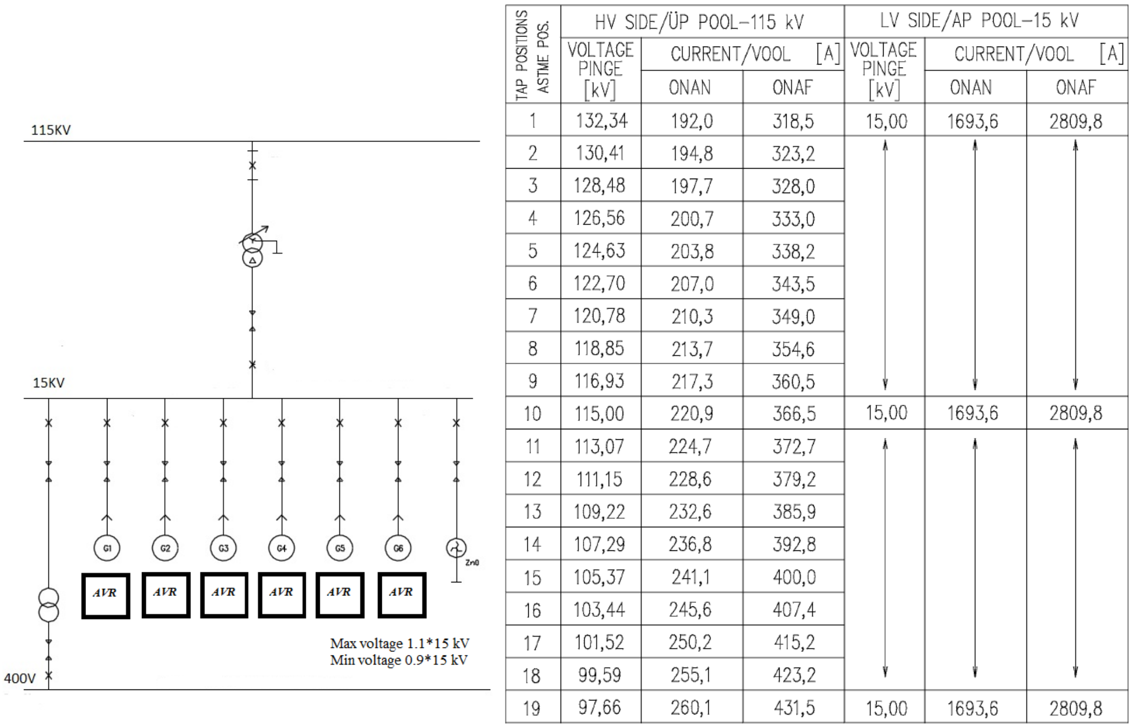


Figure 35. Voltage control set up with generator AVR and RET670.

With RET670 it is possible to measure voltages on both sides of a transformer. In relay settings or via SCADA you can choose automatic or manual control voltage control. If transformers are run parallel it is possible to select master-follower or circulating current mode. In automatic mode the TRIATCC IEC 61850 function block handles the voltage control. In manual mode it is possible to control the voltage locally by the relay or from a remote control centre (RCC), for example SCADA.

Using the step-up transformer OLTC automatic control (RET670) at the same time with generator AVR can result in hunting between two voltage controllers which is not desirable as this will result in unnecessary mechanical operations that wear the tap changer mechanism.

In Fig. 36 generator voltage limits and step-up transformer tap changing ratings are seen. Generator max voltage is 1,1 · 15 kV and minimum voltage is 0,9 · 15 kV which makes the generator voltage range from 13,5 kV to 16,5 kV. Step-up transformers has 19 voltage steps and the voltage range is from 97,66 kV to 132,34 kV.

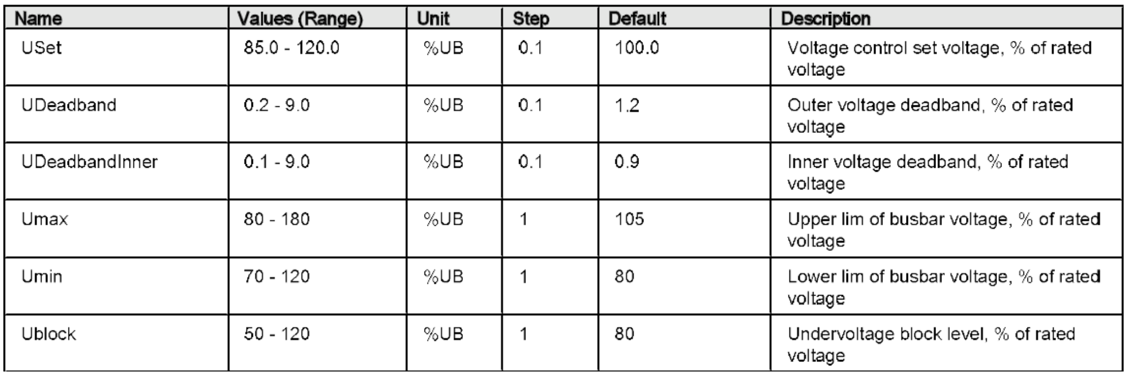


TAP POSITIONS ASTME POS.	HV SIDE/ÜP POOL–115 kV			LV SIDE/AP POOL–15 kV		
	VOLTAGE PINGE [kV]	CURRENT/VOOL [A]		VOLTAGE PINGE [kV]	CURRENT/VOOL [A]	
		ONAN	ONAF		ONAN	ONAF
1	132,34	192,0	318,5	15,00	1693,6	2809,8
2	130,41	194,8	323,2	↕	↕	↕
3	128,48	197,7	328,0			
4	126,56	200,7	333,0			
5	124,63	203,8	338,2			
6	122,70	207,0	343,5			
7	120,78	210,3	349,0			
8	118,85	213,7	354,6			
9	116,93	217,3	360,5			
10	115,00	220,9	366,5	15,00	1693,6	2809,8
11	113,07	224,7	372,7	↕	↕	↕
12	111,15	228,6	379,2			
13	109,22	232,6	385,9			
14	107,29	236,8	392,8			
15	105,37	241,1	400,0			
16	103,44	245,6	407,4			
17	101,52	250,2	415,2			
18	99,59	255,1	423,2			
19	97,66	260,1	431,5	15,00	1693,6	2809,8

Figure 36. Voltage limits for step-up transformer and generator AVR.

Unitrol AVR controls generator voltage and RET670 controls the step-up transformer. In Table 2, automatic voltage control settings of RET670 are shown. U_{Set} sets the voltage reference point which the measured voltage is compared to. U_{Deadband} and $U_{\mathrm{DeadbandInner}}$ sets the limits voltage is allowed to deviate from the U_{Set} value.

Table 2. Automatic voltage control settings of RET670 relay (ABB 2015).



Name	Values (Range)	Unit	Step	Default	Description
USet	85.0 - 120.0	%UB	0.1	100.0	Voltage control set voltage, % of rated voltage
UDeadband	0.2 - 9.0	%UB	0.1	1.2	Outer voltage deadband, % of rated voltage
UDeadbandInner	0.1 - 9.0	%UB	0.1	0.9	Inner voltage deadband, % of rated voltage
Umax	80 - 180	%UB	1	105	Upper lim of busbar voltage, % of rated voltage
Umin	70 - 120	%UB	1	80	Lower lim of busbar voltage, % of rated voltage
Ublock	50 - 120	%UB	1	80	Undervoltage block level, % of rated voltage

The right RET670 automatic voltage settings have to be set depending on the power plant system. In the following figure it is illustrated how transformer dead bands could be set, to smoothly operate with the generator voltage range.

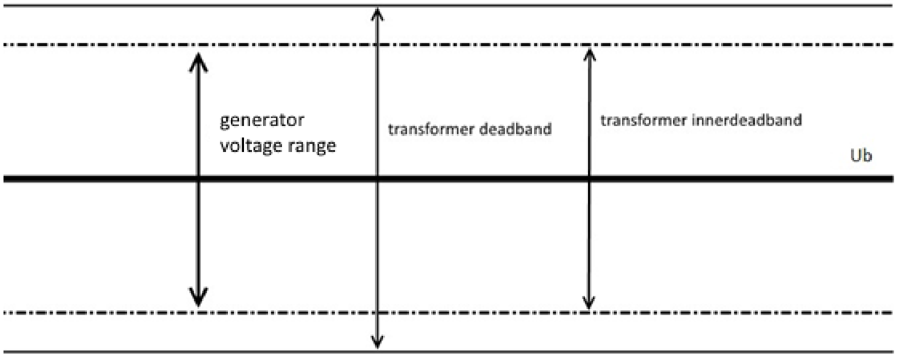


Figure 37. Dead band settings.

The generator AVR will maintain the MV voltage level firstly. When voltage exceeds transformer dead band a tap change command will be made. The protection relays for the generator alarms in 30 s if the voltage is more than ± 5 % of nominal value, for example 15 kV. Step-up transformers voltage range depends on the transformer and it is normally about ±10 % of nominal value, for example 115 kV. Transformer inner dead band and transformer dead band shall be set according to what generator voltage range is going to be used. For example, if the MV-voltage level is 15 kV and we have a transformer tap changer with ± 9 · 1,675 % tapping range. Generator voltage range could be set to 2 · 1,675 = 3,35 % (two tap steps). To avoid hunting transformer dead band could be set 3,35 % + 0,5 % = 3,85 % and -3,35 % - 0,5 % = - 3,85 % and transformer inner dead band to 3,35 % - 0,5 % = 2,85 % and - 3,35 % + 0,5 % = 2,85 %. Fig. 38 shows the calculated dead bands and voltage values.

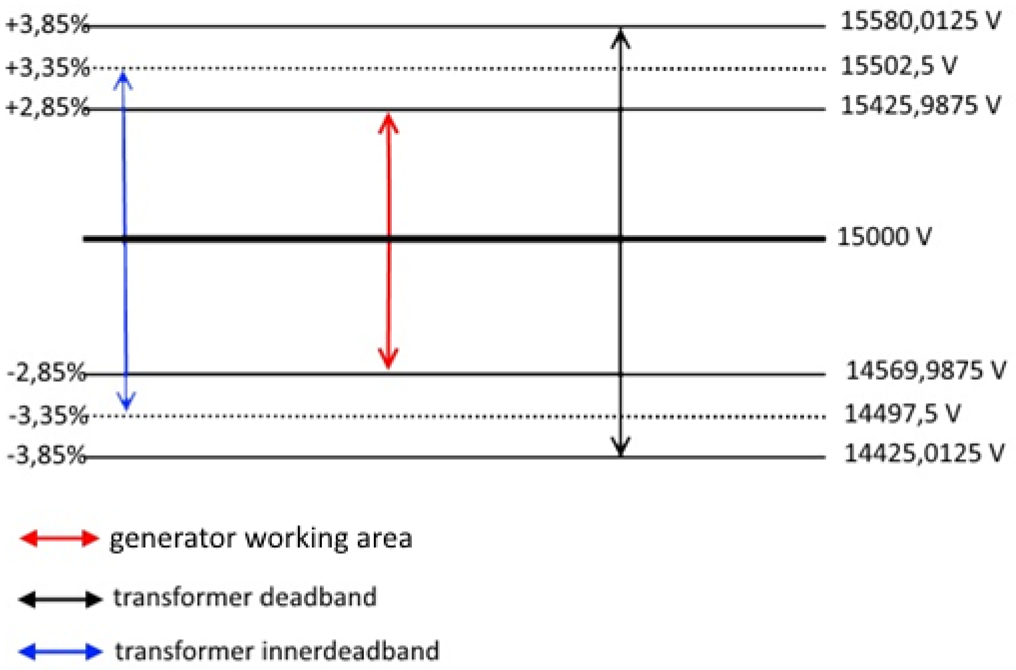


Figure 38. Dead band settings.

The closer the nominal voltage the generator runs, the better it is for the generator, so two tap steps should be enough to avoid hunting. The generator working area can be enlarged to ± 5 %. After ± 5 % protection devices will start to alarm. If wider range is going to be used protection settings have to be readjusted; transformer time delay shall be set so that the OLTC does not notice short voltage fluctuations and so that the generator has time to react. To validate this I have run an OLTC transformer in Wärtsilä Matlab/Simulink power plant model. The target of the simulation model is to run different cases and check what voltage and time limits shall be used.

6.2 Matlab/Simulink simulation

To study generator AVR behaviour with step-up transformer, I have used the Wärtsilä Matlab/Simulink power plant model. The main level of this Simulink model is based on a Wärtsilä 20V32 engine with coupling, generator, AVR, measuring units and electrical system. The Simulink model parameters can be configured through Matlab configuration file. In Fig. 39 main level of power plant simulation model is shown.

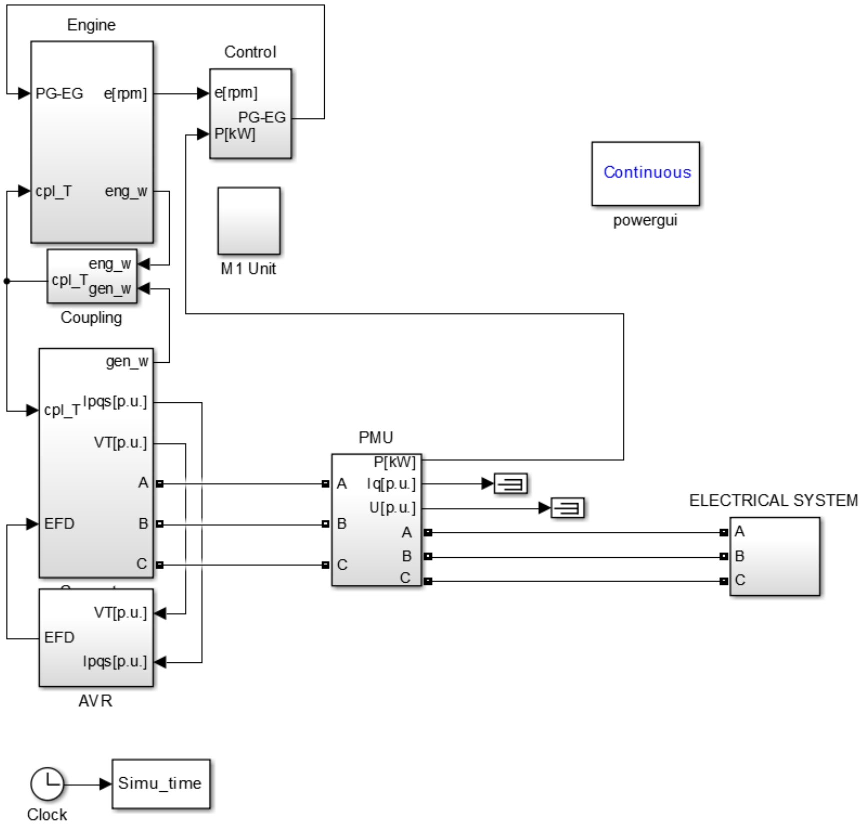
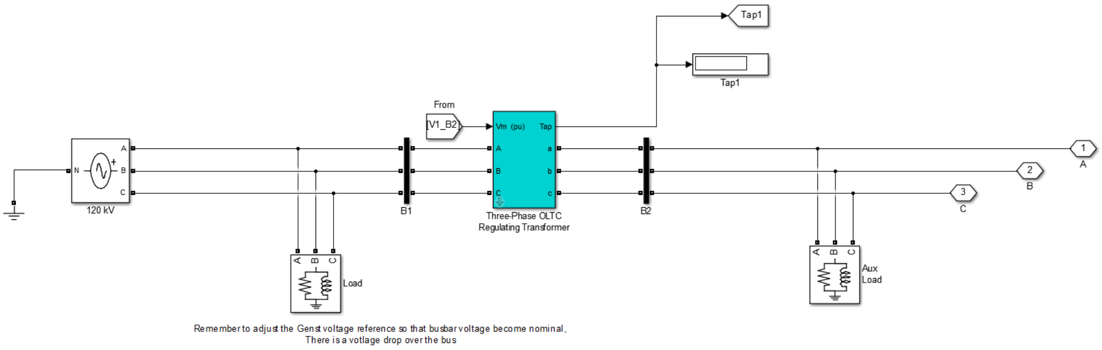


Figure 39. Main level of simulation model with engine, generator, AVR, PMU (Power Monitoring Unit) and grid system.

The power plant model consists of blocks that represent the engine, generator and AVR used in Wärtsilä power plant. In the model I have built an electrical system containing a transformer with OLTC. The engine, generator and AVR blocks are kept unchanged. In control unit and M1 unit you can choose operating mode of the power plant, possible operating modes are:

- Speed / load control
    - Speed droop control mode
    - Isochronous load sharing mode
    - kW control mode
- Voltage control
    - Voltage droop mode
    - Voltage droop compensation control mode
    - Power factor control mode

I have run the model in kW control mode with voltage droop mode. The electrical system I built consists of a three phase OLTC regulating transformer, auxiliary load, load, and programmable voltage source simulating grid voltage. In Fig. 40 you can see a three-phase OLTC regulating transformer, B1 and B2 buses that measures the voltages on both side of the transformer, a programmable voltage source on the left side, load and auxiliary load. The three-phase OLTC measures the voltage from B2 and from the Tap1 indicator the tap position can be read.



Remember to adjust the Genst voltage reference so that busbar voltage become nominal,
There is a votlage drop over the bus

Figure 40. Electrical system with OLTC, grid and loads.

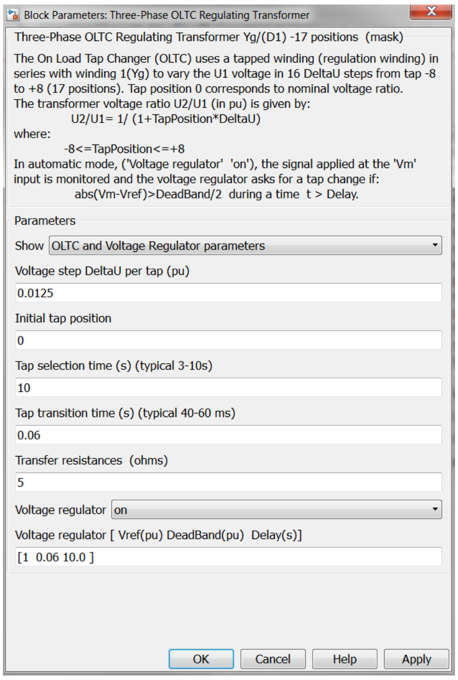
The transformer LV is set to the same voltage level as the generator output. The generator technical characteristics are the following:

Table 3. Generator technical characteristcs.

Rated apparent output [kVA]	11 264
Rated voltage [kV]	11
Rated frequency [Hz]	50
Rated Speed [rpm]	750
Rated power factor	0,8
Rated active power [kW]	9011
Stator resistance	0,00225
Synchronous reactance in *d*-axis [p.u.] (u)	2,137
Transient reactance in *d*-axis [p.u.] (s)	0,305
Subtransient reactance in *d*-axis [p.u.](s)	0,195
Synchronous reactance in *q*-axsis [p.u.] (u)	1,0171
Subtransient reactance in *q*-axsis [p.u.] (s)	0,220
Stator winding leakage reactance	0,166

Generatior inertia [kgm^2]	2350
Engine inertia + Coupling inertia	1130

The generator output voltage is 11 kV. The step-up transformer with OLTC raises the voltage from 11 kV to 120 kV. The OLTC has 17 tap steps from -8 to +8. The initial tap position is 0 and each voltage step is 1,25 % per tap. In the following figures (Figs. 41 & 42) the transformer and OLTC settings are shown.



Block Parameters: Three-Phase OLTC Regulating Transformer

Three-Phase OLTC Regulating Transformer Yg/(D1) -17 positions (mask)

The On Load Tap Changer (OLTC) uses a tapped winding (regulation winding) in series with winding 1(Yg) to vary the U1 voltage in 16 DeltaU steps from tap -8 to +8 (17 positions). Tap position 0 corresponds to nominal voltage ratio.
The transformer voltage ratio U2/U1 (in pu) is given by:
U2/U1= 1/ (1+TapPosition*DeltaU)
where:
-8<=TapPosition<=+8
In automatic mode, ('Voltage regulator' 'on'), the signal applied at the 'Vm' input is monitored and the voltage regulator asks for a tap change if:
abs(Vm-Vref)>DeadBand/2 during a time t > Delay.

Parameters

Show: OLTC and Voltage Regulator parameters

Voltage step DeltaU per tap (pu): 0.0125

Initial tap position: 0

Tap selection time (s) (typical 3-10s): 10

Tap transition time (s) (typical 40-60 ms): 0.06

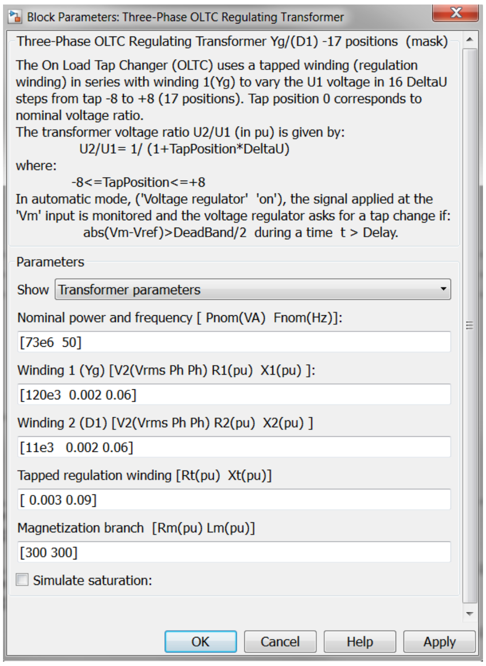
Transfer resistances (ohms): 5

Voltage regulator: on

Voltage regulator [Vref(pu) DeadBand(pu) Delay(s)]: [1 0.06 10.0]

Figure 41. OLTC and voltage regulator parameters.

The following parameters can be adjusted in settings:, the amount of how much the voltage changes per tap step, initial tap position, tap selection time (how long time it will take to change tap), tap transition time, transfer resistances and voltage regulator parameters. U_{reff} is the reference value against which the measured value is compared. DeadBand parameter is the range in which the tap changer does not work. Delay parameter is the time value that decides how long time the measured value can be outside the dead band.



Three-Phase OLTC Regulating Transformer Yg/(D1) -17 positions (mask)

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where:
-8<=TapPosition<=+8
In automatic mode, ('Voltage regulator' 'on'), the signal applied at the 'Vm' input is monitored and the voltage regulator asks for a tap change if:
abs(Vm-Vref)>DeadBand/2 during a time t > Delay.

Parameters

Show: Transformer parameters

Nominal power and frequency [Pnom(VA) Fnom(Hz)]: [73e6 50]

Winding 1 (Yg) [V2(Vrms Ph Ph) R1(pu) X1(pu)]: [120e3 0.002 0.06]

Winding 2 (D1) [V2(Vrms Ph Ph) R2(pu) X2(pu)] [11e3 0.002 0.06]

Tapped regulation winding [Rt(pu) Xt(pu)] [0.003 0.09]

Magnetization branch [Rm(pu) Lm(pu)] [300 300]

☐ Simulate saturation:

Figure 42. Transformer parameters.

The adjustable parameters in the transformer settings are; transformer nominal power and frequency, winding voltage, resistance and reactance, regulation winding resistance and reactance, and magnetization branch.

The voltage regulator works so that it will ask for a tap change if $|U_m - U_{ref}| >$ dead band/2 during a time delay *t*. U_m is the measured voltage, U_{ref} is the reference value. All values are in pu (per unit). The following values were set:

*U*ref	1
time delay	10
dead band	0,06
voltage step	0,0125

So for example if the measured voltage is 1,04 pu $|U_m - U_{ref}| = 0{,}04$ and dead band = 0,06 / 2 = 0,03 the voltage regulator will make a raise command to the tap changer after the time delay has passed. The aim of the simulations is to show that:

- When grid voltage is above 1,03 pu or under 0,97 pu the OLTC shall operate after the given time delay
- If voltage drops suddenly under 0,7 pu the OLTC shall not work

- When grid voltage varies from 0,97 – 1,03 pu the OLTC should not operate

In the first simulation, the grid voltage raises to 1,1 pu from 1,0 pu. The voltage level is over 1,03 pu and the OLTC should operate. The simulation results are shown in graphs, the first graph shows the high voltage in pu value, second graph shows the medium voltage in pu value, and the last graph shows the tap position. On the *x*-axis we have time in seconds.

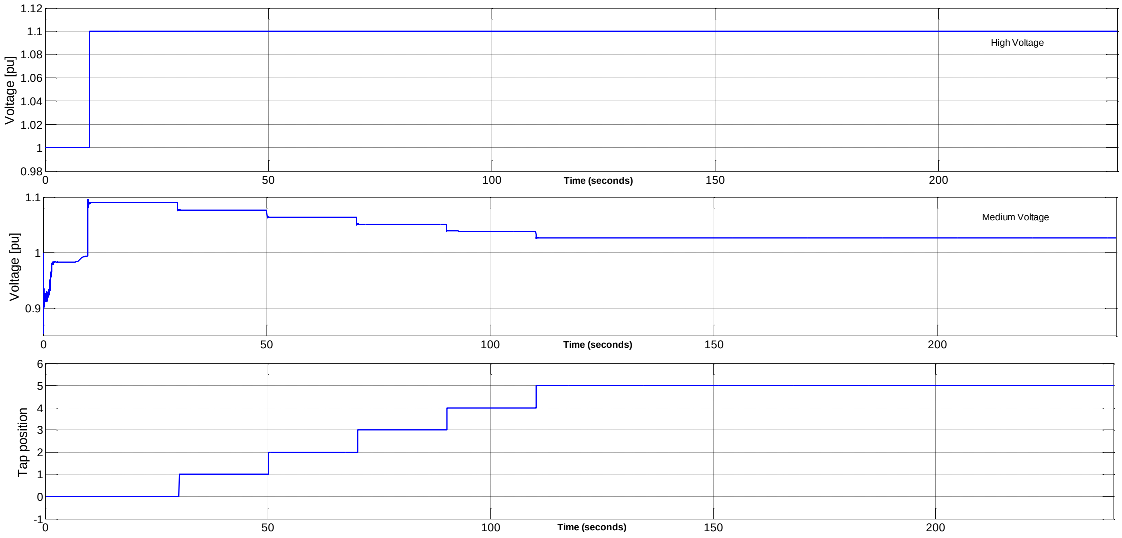

Figure 43. High voltage raises to 1,1 pu tap position changes from 0 to 5 and medium voltage decreases so it comes inside dead band.

From the simulation results we see that the tap changer makes 5 tap steps from the initial position of 0 to 5 until the MV is inside the set dead band value 1,03 pu. The tap changing time is 10 s delay + 10 s selection time = 20 s.

In the second simulation, voltage drops from 1,0 pu to 0,7 pu. The three-phase regulating transformer block does not contain any over- or undervoltage blocking so to simulate blocking I have modified the voltage regulator block. In Fig. 44 is shown how the voltage regulator block is built. In Fig. 45 the results from this simulation are shown.

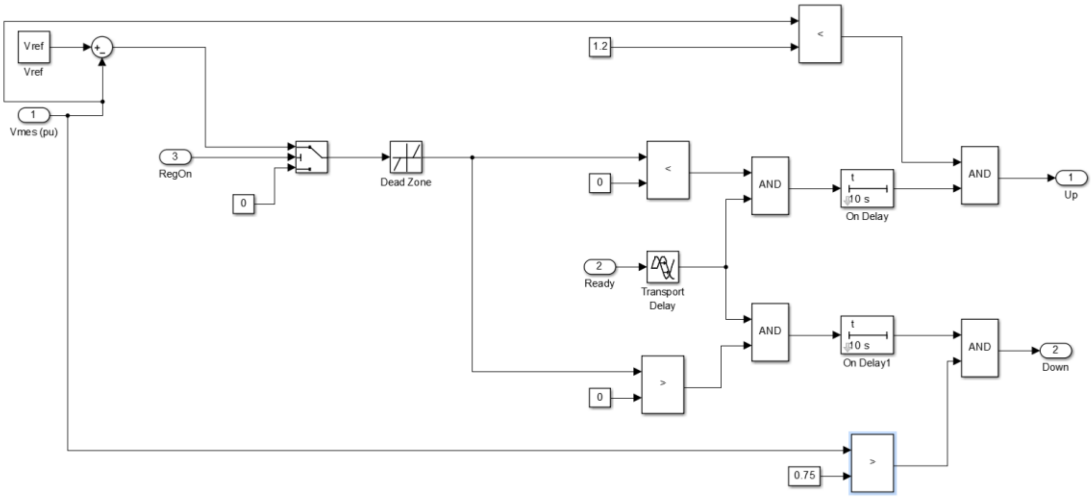

Figure 44. Operation diagram of voltage regulator functions.

The voltage regulator works so that measured voltage *U*mes is subtracted from the set reference value *U*ref. If the subtracted value is not inside the dead zone value, then the tap position moves up or down, depending on if the subtracted value is positive or negative. I added relational operating blocks to simulate blocking conditions so that the tap changer does not operate in overvoltage or undervoltage conditions, in this case when voltage is over 1,2 pu or lower than 0,75 pu.

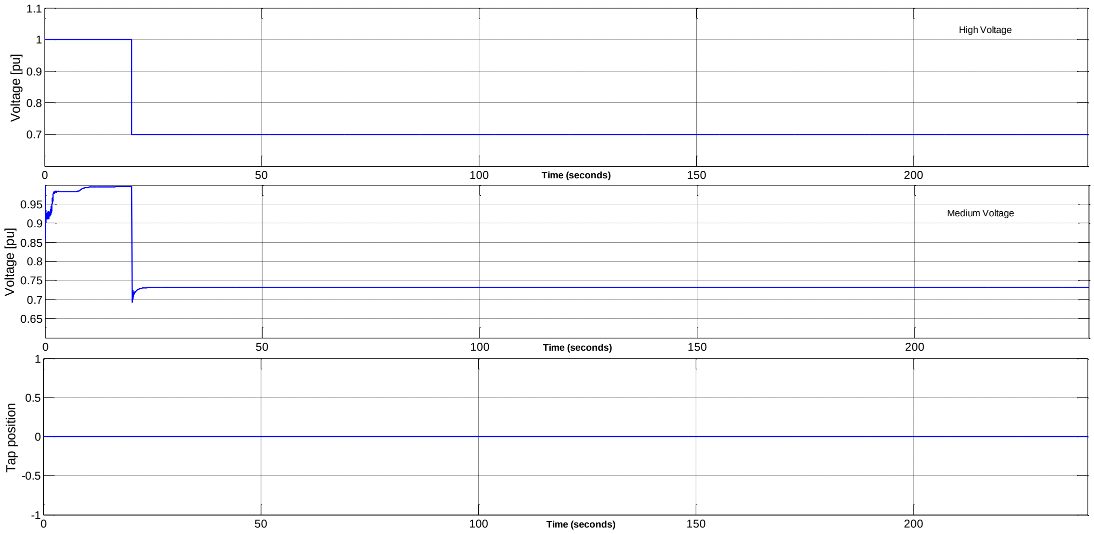

Figure 45. High voltage drops to 0,7 pu OLTC does not operate.

From the simulation results we see that the high voltage drops to 0,7 pu. Because the undervoltage limit is set to 0,75 pu, the OLTC does not operate.

In the following case voltage is between 1,03 pu and 0,97 pu. The values are inside the dead band so the OLTC does not operate. The results are shown in Fig. 46.

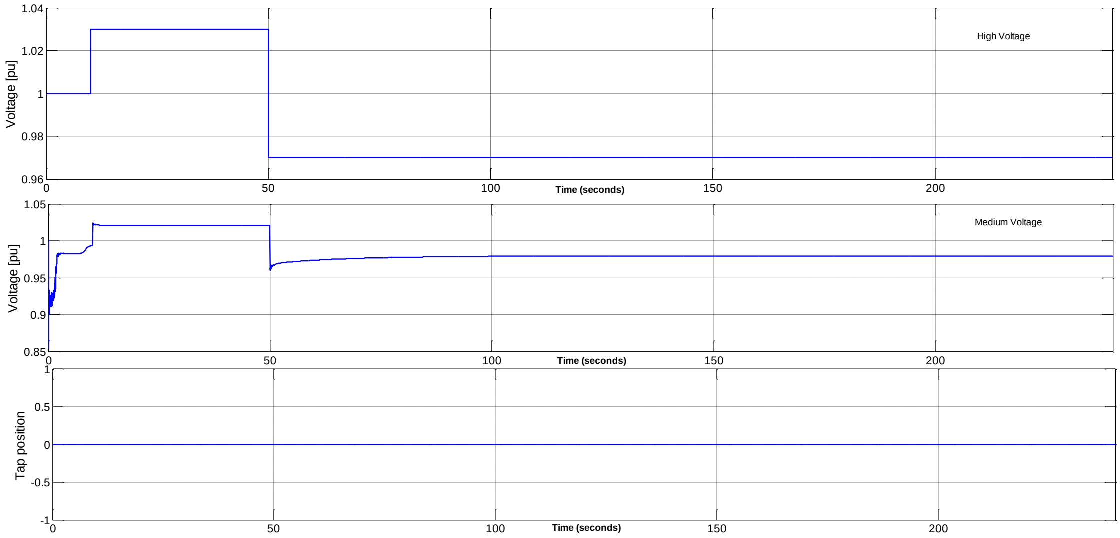

Figure 46. OLTC raises to 1,03 and drops to 0,97, no OLTC operation.

The following simulations show cases with different initial tap positions. In following figure the voltage drops to 0,95 pu from 1,0 pu and initial tap position is 4.

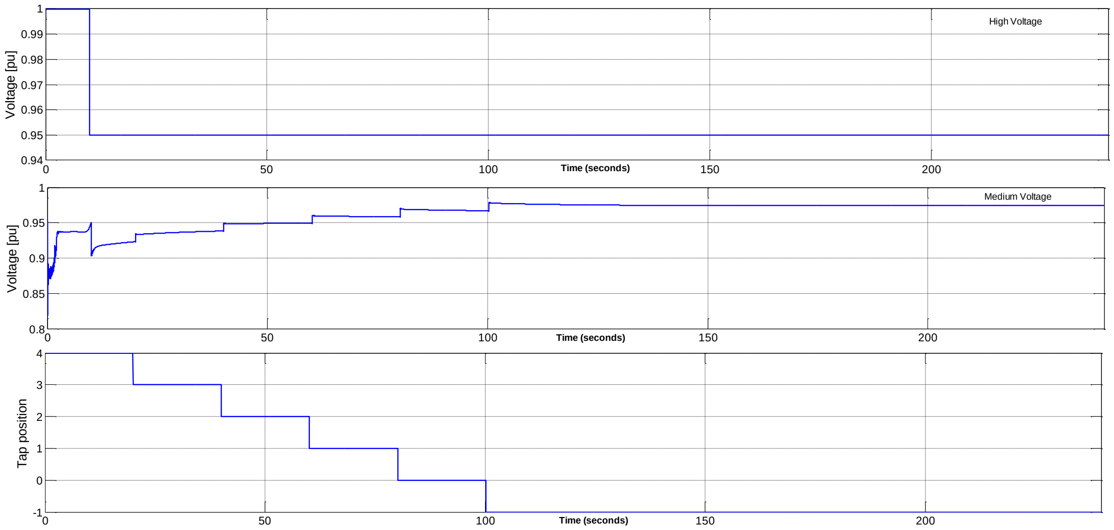

Figure 47. High voltage drops to 0,95 and initial tap position is 4.

From the simulation results we see that the OLTC makes five steps from tap position 4 to -1 and the medium voltage rises to 0,97 pu.

In the next simulation the initial tap position is set to 8 and the voltage level falls to 0,95 pu from 1,0 pu, see Fig. 48.

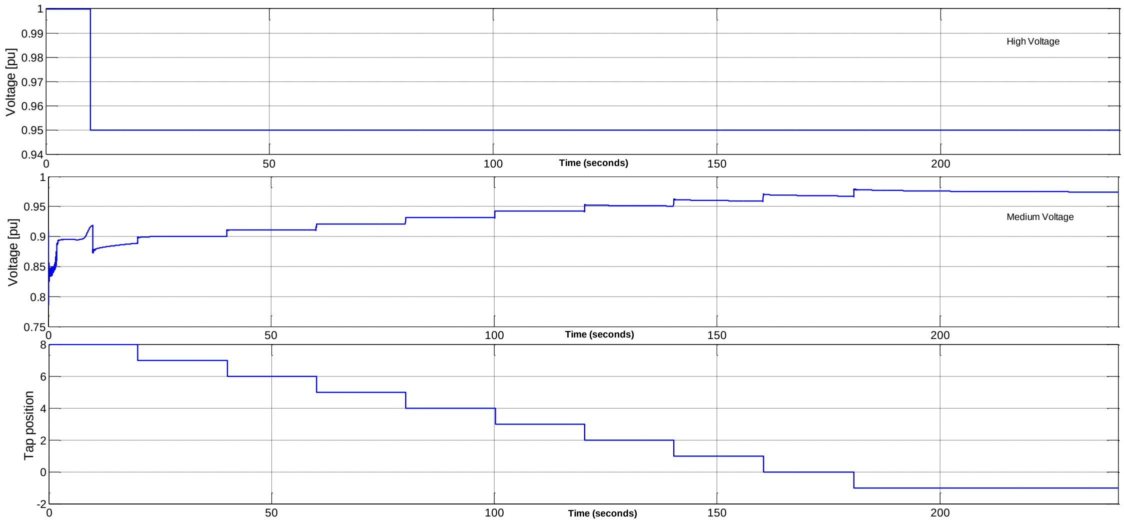

Figure 48. High voltage drops to 0,95, initial tap position is 8.

From Fig. 48 we see that MV increase until it comes inside the dead band. The tap position moves down 8 steps from 8 to 0. From the simulation we see that in Fig. 47 only 5 tap position changes were made compared to eight in Fig. 48.

Simulation results show that it is important to choose the correct initial tap position and by correct dead bands and right time delays it is possible to avoid hunting and unnecessary tap operations. The initial tap position has to be decided according to the usual grid voltage level, so that the OLTC operations can be minimized. The dead band and time delays have to be decided according to how fast the OLTC shall operate. For example in grids with stable voltage level, the dead band and time delays could be set narrower. In grids with larger voltage fluctuations, dead bands and time delays could be set larger. In the simulation model the generator AVR runs in voltage droop mode. The generator AVR does not interfere with the OLTC. For further works it could be investigated if we need the generator AVR to control voltage level. The following figure illustrates the operating scheme of automatic voltage control based on the results. This operating scheme is a guideline of how the automatic voltage could work. The operating scheme tells when the OLTC shall operate automatically. This operating scheme can be used when designing upcoming projects were automatic voltage control is an option.

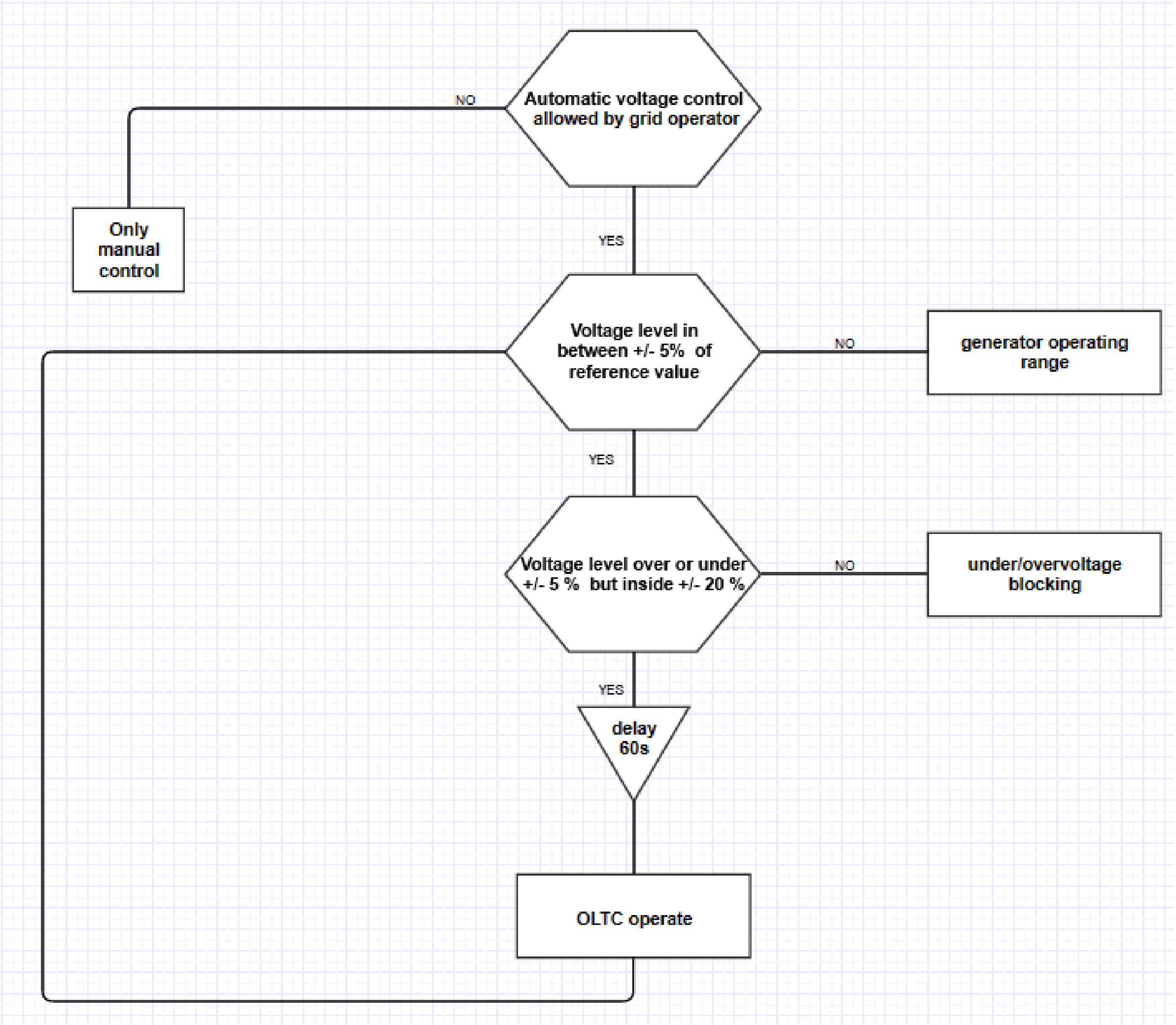

Figure 49. Operating scheme of automatic voltage control.

7 RECOMMENDATIONS

This chapter will give recommendations for the projects where there is a requirement for automatic voltage control. After studying product manuals and having meetings with product experts it was clear that RET670 could be used as an automatic voltage controller by setting right dead bands and time delays. Correct dead bands and time delays need to be chosen based on the power plant application and operation methods.

My recommendation is that there should be a real case pilot project where the automatic control is used. In the pilot project the settings and limits should be set in close cooperation with ABB well in advance. It is very important to collect the requirements of the plant operational needs and the allowable tolerance well in advance before starting the design to make sure that the controller and its functions are correctly selected and designed. Before keeping the automatic controller in use it is very important to have a through testing and commissioning with several operational scenarios to make sure that it works correctly. In case of misoperation it should be possible to change to manual mode.

The simulation model shows good results. The simulation model electrical system is quite simple and could be built more advanced with for example feeders, several generators and transformers and relay function blocks to compare it to a real case scenario. The more complex system you build the more time it takes to simulate it. So to get more time value several simulation cases should be run on a fast network computer. To model different relays for example RET670 would be interesting for future works.

During my thesis work some development ideas came into mind. Communication between Unitrol 1000-15 and RET670 devices is not currently possible. If communication would be possible between these two devices it could be so that Unitrol 1000-15 asks RET670 relay for a tap change. Another idea that came in to mind is that it could be nice to set several dead bands with RET670. Now it is only possible to set one dead band. What also could be investigated is if we need the generator AVR to control voltage level.

8 CONCLUSION

The aim of the thesis was to use RET670 relay instead of separate AVR. The second aim was to achieve automatic voltage control. During my thesis the RET670 was taken to use for both transformer protection and tap changing but the tap changing was still done manually.

There are many things to consider by taking automatic voltage control into use in power plants. The first thing to check is if it is allowed by the grid operator. The second is to study the grid fluctuations. In grids with usually little fluctuations the automatic voltage control should operate with no problems and correct parameters like voltage dead bands and time delays are easier to set. By setting dead bands and time delays you have to consider how much the generator operating range should be and how fast the OLTC shall operate so unnecessary tap changes is avoided. If grid voltage is steady quite small generator operating range could be used. In grids with larger fluctuations it can be smarter to use a broader voltage range to save OLTC from wearing.

In this thesis it is proven that the RET670 relay can take care of most problems, for example tap changer malfunction, hunting, circulating currents etc. RET670 is also capable of handling several transformers run in parallel.

The simulation results show that the generator and step-up transformer can cooperate but more simulations or real case testing has to be done. At the moment there is not any ongoing project to test automatic voltage control. The automatic control should be considered in upcoming projects.

9 SUMMARY

The goal of this thesis was to achieve automatic voltage control in a power plant. To achieve automatic voltage control two active controllers has to cooperate smoothly. Firstly this thesis describes about how Wärtsilä Power plant electrical system is built. To understand how voltage is controlled in a power plant, the thesis contains theory about the generator and the step-up transformer. After the generator and step-up transformer theory, protection system chapter describes how the generator and transformer are protected and what default relay settings are used. Chapter 5 tells about the automatic voltage regulation with the generator and step-up transformer. Chapter 6 is about how different parameters should be set so the generator AVR and Step-up transformer OLTC can smoothly cooperate. Finally the results are tested with Matlab/Simulink power plant simulation.

This thesis gives you a great understanding about the electrical system of a power plant and how the voltage level is controlled. The result of this thesis shows that automatic control in a power plant is possible by choosing right parameter values. By choosing correct dead band values and time delays the generator AVR and step-up transformer can smoothly operate together and automatic voltage control of a power plant is achieved. The results of this thesis are theoretical and should be verified with practical tests before on site applications.

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APPENDIX

Appendix 1. Generator standards

IEC60034	Rotating electrical machines
ISO 8528	Internal combustion engine driven alternating current generating sets
ISO R773	Rectangular or square parallel keys and their corresponding keyways
ISO R774	Taper keys with or without gib head and their corresponding keyways
ISO R775	Cylindrical and 1/10 conical shaft ends
ISO 2768	General tolerances
ISO 1940	Mechanical vibration-balance quality for rotors in a constant (rigid) state

Appendix 2. IEC standards compared to ANSI standards (Csanyigroup 2010).

Description	ANSI	IEC 60617	Description	ANSI	IEC 60617
Overspeed relay	12	$\omega >$	Inverse time earth fault overcurrent relay	51G	I⏚$>$
Underspeed relay	14	$\omega <$	Definite time earth fault overcurrent relay	51N	I⏚$>$
Distance relay	21	$Z <$	Voltage restrained/controlled overcurrent relay	51V	$U\nearrow I >$
Overtemperature relay	26	$\theta >$	Power factor relay	55	$\cos\varphi >$
Undervoltage relay	27	$U<$	Overvoltage relay	59	$U>$
Directional overpower relay	32	→ $P >$	Neutral point displacement relay	59N	$U_{rsd} >$
Underpower relay	37	$P <$	Earth-fault relay	64	I⏚$>$
Undercurrent relay	37	$I <$	Directional overcurrent relay	67	→ $I >$
Negative sequence relay	46	$I_2 >$	Directional earth fault relay	67N	→ I⏚$>$
Negative sequence voltage relay	47	$U_2 >$	Phase angle relay	78	$\varphi >$
Thermal relay	49		Autoreclose relay	79	$0 \rightarrow 1$
Instantaneous overcurrent relay	50	$I >>$	Underfrequency relay	81U	$f <$
Inverse time overcurrent relay	51	$I >$	Overfrequency relay	81O	$f >$
			Differential relay	87	$I_d>$

Appendix 3. Functions for generator protection

- REG670

[51]	AC inverse time overcurrent relay
[50]	Instanteous overcurrent relay
[46]	Reverse-phase or phase-balance current relay
[51V]	Voltage dependent overcurrent
[67N]	Directional earth fault
[51N]	Non-directional earth fault
[50N]	Non-directional earth fault
[59]	Overvoltage
[27]	Undervoltage
[59N]	Ground fault overvoltage relay
[81H]	Overfrequency
[81L]	Underfrequency
[32]	Directional power
[40]	Loss of field relay
[24]	Over excitation
[87G]	Differential generator
[78]	Pole slip
[49]	Thermal overload
[87CT]	Differential current transformer
[60FL]	Voltage transformer fault
[50BF]	Breaker failure relay

- RET615

[51]	Time overcurrent relay
[50]	Instanteous overcurrent relay
[87G]	Differential protection generator
[50BF]	Breaker failure relay

Appendix 4. Step-up transformer protection

- REC670

[51]	AC inverse time overcurrent relay
[67]	AC directional overcurrent relay
[50]	Instanteous overcurrent relay

- RET670

[87T]	Differential protective relay for transformer
[64]	Ground detector relay

- REF615

[50]	Instanteous overcurrent relay
[51]	AC Inverse time overcurrent relay
[51N]	AC Inverse time overcurrent relay for network
[50N]	Instanteous overcurrent relay for network
[87CT]	Differential protective relay for current transformer
[50BF]	Instanteous overcurrent relay for breaker failure

- Buchholz relay

[97QT]	Bucholz relay for oil temperature
[49T]	Transformer thermal relay
[26QT]	Apparatus thermal device of oil temperature
[99QT]	Oil level indicator