Application Fields and Control Principles of Variable Shunt Reactors with Tap-Changer

Investigation of Possible Control Strategies of Variable Shunt Reactors through Simulation of a Power System under Different Operating Conditions

Master of Science Thesis

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Department of Energy and Environment
Division of Electric Power Engineering
CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sweden, 2011

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Cover:
Picture of a 120-200 MVAr, 420 kV ABB Variable Shunt Reactor.

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Abstract

The market interest in Variable Shunt Reactors (VSR) is steadily increasing and from a manufacturer's perspective, tender requests for VSRs become more frequent. Although a few VSRs have been in service for several years and such application is not new, it is within the last years that utilities and network planners have become more interested in this option. With increasing market interest in the application of VSRs, the control strategy of VSRs has become an important issue. Since ABB is the leading company in design and manufacturing of large High Voltage VSRs, the investigation of VSR control strategy is of great interest and importance for ABB. The purpose of this project is to investigate the control strategy of tap-change Variable Shunt Reactors (VSR) to control the voltage level during different load conditions. As an approach, operation of a VSR under various network conditions has been simulated and changes in different parameters of the network have been observed. The work starts with investigating the voltage behaviour after running load flow simulation and studies in DIgSILENT, and continues with extracting a control strategy of the VSR through modelling and simulation using MATLAB. One of the very challenging parts of the work is to design a proper and accurate model for VSR with tap-change control system, since there is no available model for such a VSR in MATLAB. For this reason, all the required data from Statnett (Norway's Transmission Grid Owner and Operator) and also Test Report Sheets of ABB Transformers AB, Ludvika have been collected. In order to have an intelligent, wise, and accurate tap changing process, various practical issues are taken into account and several simulations have been done. Finally, a robust and reliable control signal has been introduced in this thesis.

Keywords: Variable Shunt Reactor, Reactive Power Balance, Voltage Stability, Voltage Control, Tap changer, DIgSILENT, MATLAB Simulation, Load Flow.

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Table of Contents

1. Introduction

The voltage level along an AC transmission line is influenced by two main factors; the capacitive charging and the loading of the line. The capacitive charging, which is the source of reactive power generation (Q_C), depends on the line geometry and the line voltage level; and arises because of the capacitance between its conductors and the earth. On the other hand, when the line is loaded, both the load and the line consume reactive power (Q_L) as inductive electrical elements. In an AC transmission system, it is important to keep the balance between generated and consumed reactive power since it is the reactive power balance which decides the voltage stability of the line.

In order to achieve the reactive power balance, the line should be loaded at its natural load (SIL) where the generation and consumption of reactive power along the line are equal. When the load varies in the system, the consumption of reactive power changes, and consequently the voltage fluctuates along the line. If the generated reactive power is more than the consumed reactive power, the voltage increases, whereas the voltage decreases if the consumption is more than generation of reactive power.

Shunt Reactors are widely used in transmission and distribution networks. They absorb (consume) reactive power by connecting them to the transmission line. Since they decrease the voltage level, they are typically used during light load conditions.

A Variable Shunt Reactor (VSR) is a Shunt Reactor where the inductance can be varied in steps. The reactive power consumption can increase up to twice its initial value over the whole regulating range. Generally, when there is a slow variation of the load, the VSR works as an efficient reactive power compensator in order to fine tune the voltage in the system. VSRs provide dynamic reactive power compensation with the regulation range around 100% (e.g. 50-100 MVAr) and ratings up to 250 MVAr, 500 kV.

Although a few VSRs have been in service for several years and the application of VSRs is not new, it is within the last years that utilities and network planners have become more interested in this option. With increasing market interest in application of Variable Shunt Reactors, the control strategy of VSR has become an important issue. Since ABB is the leading company in the design and manufacturing of large High Voltage VSRs, the investigation of VSR control strategy is of great interest and importance for ABB.

1.1. Aim

The purpose of this project is to investigate the control strategy of tap-change Variable Shunt Reactors (VSR) to control the voltage level under different load conditions. As an approach, operation of a VSR under various network conditions has been simulated and the change in different parameters of the network has been observed. Finally, a robust and reliable control signal has been introduced in this thesis.

1.2. Thesis Outline

Below is an outline in order to guide the reader through the thesis report and make it easy to comprehend.

Chapter 2, 3: Background

Chapter 4 – 7: Theory

The theory behind and a summary of the literature study performed within this thesis.

Chapter 8: Method, Experimental Results and Discussion

Chapter eight, deals with the numerical part of this thesis. Here the method and simulations performed within this thesis are described.

Chapter 9: Conclusion

A brief summary of the work and obtained results is discussed here.

Chapter 10: Future Work

2. Introduction on Reactive Power

Generally in an electric circuit, the rate of energy flow in a specific point of the circuit is called power. In Alternating Current (AC) circuits, there are energy storage elements such as capacitance and inductance which can periodically reverse the direction of energy flow. Active Power (P) is known as the part of power that averaged over the whole cycle of the AC waveform results in a net transfer of energy in one direction. On the other hand, another part of power related to the stored energy, which returns to the source in each cycle is defined as reactive power (Q). As shown in Figure 2-1, complex power (S) is the total power in the circuit and consists of active and reactive power as real and imaginary components respectively [1].

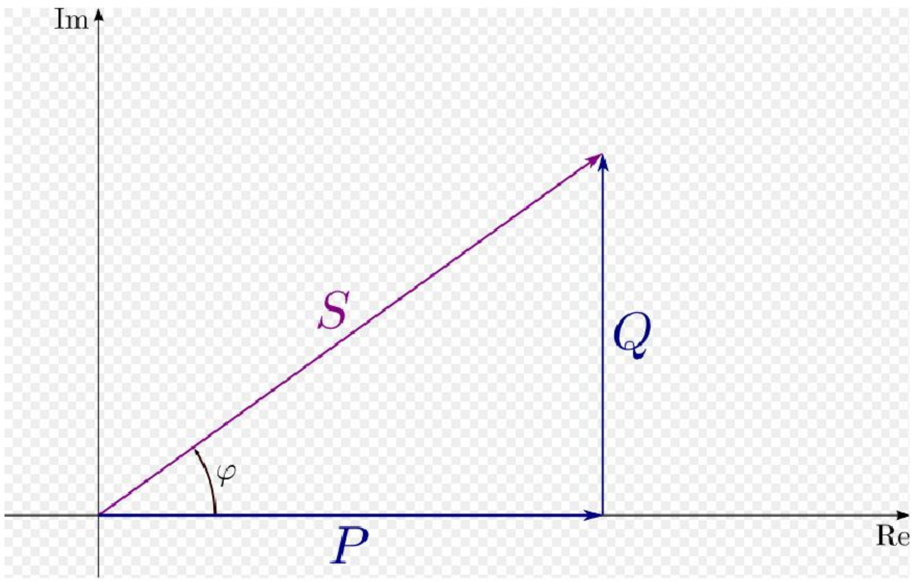


Figure 2-1: Active power (P) and reactive power (Q) as real and imaginary components of complex power (S)

Apparent power is known as the absolute value of complex power (|S|). The general expression for the (complex) apparent power is:

2-1 $$\bar{S} = \bar{V}\,\bar{I}^* = P + jQ$$

Figure 2-2 illustrates voltage and current vectors when current is lagging and leading voltage. Since current is conjugated in equation 2-1, considering counter clockwise direction as positive, the negative φ in Figure 2-2 corresponds to positive Q in Figure 2-1, and vice versa.

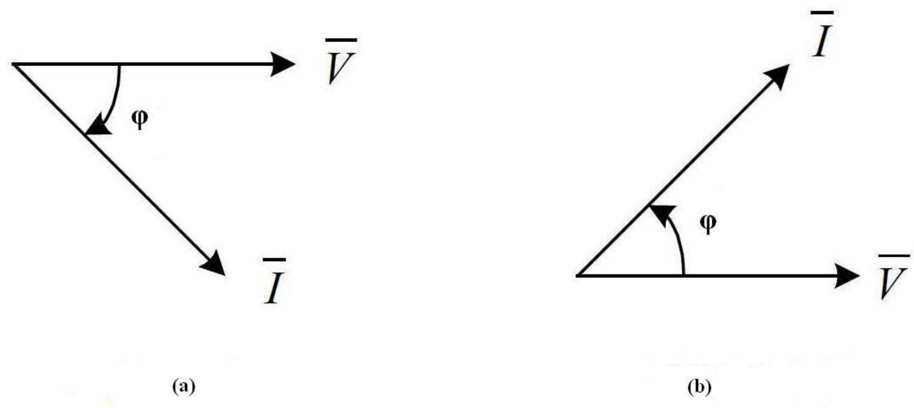


Figure 2-2: Voltage and current vectors when: **(a)** current is lagging voltage, and **(b)** current is leading voltage

According to Figure 2-1, the following equations are applicable:

2-2 $$P = S\cos\varphi = VI\cos\varphi$$

2-3 $$Q = S\sin\varphi = VI\sin\varphi$$

Power factor (pf) is defined as the ratio between active power and apparent power which represents the efficiency of a power distribution system by showing how much of apparent power (S) is active power (P); i.e. how much of total power is transferred. Hence,

2-4 $$pf = {}^{P}\!/_{S} = \cos\varphi$$

In summary, reactive power flow is unavoidable in an AC transmission system in order to support the transfer of active power over the network. As mentioned, the periodic reversal of energy flow direction in AC circuits results from the temporary energy storage in inductive and capacitive elements. The part of energy that can be used is active power; which is in fact, the portion of power flow remaining after being averaged over the complete AC waveform. On the other hand, reactive power is the portion of power flow that is temporarily stored in the form of magnetic or electric fields and is returned to the source.

Inductive elements which store energy in the form of magnetic field could generally be categorized as reactors consisting of a large coil. As the voltage is applied to the coil, the magnetic field builds up, and it takes a period of time for the current to reach its final value. This causes the current to lag the voltage, and hence these devices are said to absorb reactive power (positive Q for an inductive load).

Capacitive elements which store energy in the form of electric field are generally categorized as capacitors. As a current is driven through a capacitor, it takes a period of time for the charge to build up and make the full voltage difference. Since the voltage across a capacitor in AC network is always changing, the capacitor opposes this change which causes the voltage to lag behind the current; i.e. the current leads the voltage, and hence these devices are said to generate reactive power (negative Q for a capacitive load).

The stored energy in capacitive or inductive elements of the network increases the reactive power flow. Reactive power flow strongly influences the voltage level in the network. To allow a power system to be operated within acceptable limits, voltage level and reactive power flow must be carefully controlled and supervised.

3. Introduction on Voltage Stability

According to definitions given by IEEE [1], voltage stability refers to the ability of a power system to maintain steady voltages at all buses in the system after being subjected to a disturbance from a given initial operating condition. By definition, voltage collapse is the process by which the sequence of events accompanying voltage instability leads to abnormally low voltages in a significant part of the power system and consequently leads to a system blackout.

As a result, the voltage problems can be divided to two main categories namely, undervoltage problem and overvoltage problem. There are two types of overvoltage; one is transient overvoltage or voltage spike (voltage surges) which has short duration and high magnitude, and the other one is long-term overvoltage. Both under and overvoltage have some negative effects [2].

Some negative effects of under-voltage condition are:

- Lamps start to dim because they are constant impedance loads
- Dimming or shrinking television or computer images
- Flashing of digital clocks and electronic equipments
- Data loss, processing errors
- Poor quality or loss of radio and television reception
- Overheating of electrical motors

On the other hand, overvoltage can cause:

- Insulation breakdown
- Over-fluxing
- Saturation, and
- Harmonics

Voltage stability is divided to large-disturbance and small-disturbance voltage stability. Large-disturbance voltage stability refers to the system's ability to maintain steady voltages following large disturbances such as system faults, loss of generation, or circuit contingencies. Small-disturbance voltage stability refers to the system's ability to maintain steady voltages when subjected to small disturbances such as incremental changes in system load.

At the same time, there are also short-term and long-term voltage stabilities. Short-term voltage stability includes dynamics of fast acting load components such as induction motors, electronically controlled loads, and HVDC converters. However, long-term voltage stability is related to slower acting equipment such as tap-changing transformers, thermostatically controlled loads, and generator current limiters.

Voltage instability is the inability of the power system to meet demand for reactive power and as mentioned before, it could result in voltage collapse. The contributing factors resulting voltage instability are as follows:

- Generator Q/V control limit
- Load characteristics
- Characteristics of reactive power compensation devices (Shunt Reactors, Shunt Capacitors, and generally FACTS devices)
- Action of On Load Tap Changer (OLTC)

4. Voltage Variation in Transmission Network

In order to analyse the voltage changes on the busbars of a transmission network, first the equivalent Π-Model of a Transmission Line is introduced. Then the effect of load variations on voltage level has been studied.

4.1. Equivalent Π-Model of a Transmission Line

There are some parameters which should be considered when modelling an overhead line. First, every overhead line has a certain Resistance (R), depends on the material chosen for conductor. Second, it also has an Inductance (L) as it forms a loop with the return conductor (e.g. the earth). Third, in case of high voltage lines there is also some leakage of current (G) along the insulator strings as they are not ideal insulators; they can be polluted or cracked, and their surface conductivity will change due to climatic conditions; the high electric field at the conductor surface could also cause partial discharges and may lead to considerable active losses. Finally, each phase has a Capacitance to earth and other phases (C). Figure 4-1 shows the equivalent Π-Model of a transmission line. In certain cases it is possible to make simplifications and neglect one or more components; for example R and G will be neglected in case of having a lossless line [3].

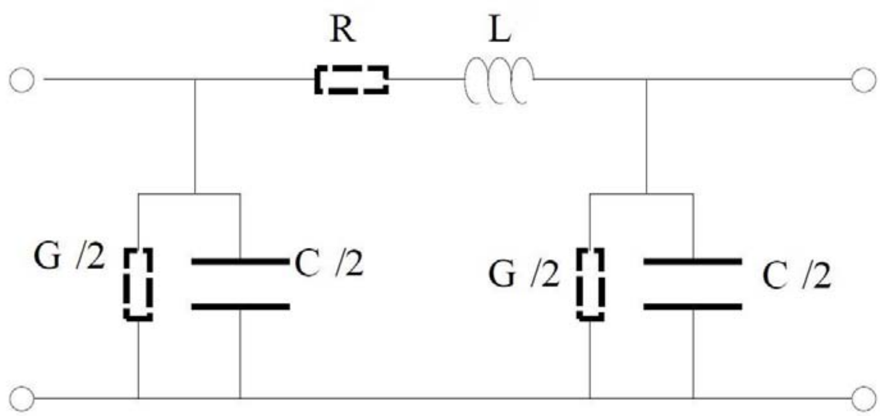


Figure 4-1: Equivalent Π-Model of a transmission line

The following formulas apply to this model.

4-1 $$\omega = 2\pi f$$

4-2 $$X_L = \omega L$$

4-3 $$X_C = \frac{1}{\omega C}$$

4-4 $$b = \frac{1}{X_C} = \omega C$$

4-5 $$\overline{Z} = R + jX_L$$

4-6 $$\overline{Y} = G + jb$$

4-7 $$\boldsymbol{Z_V} = \sqrt{\frac{\overline{Z}}{\overline{Y}}} = \sqrt{\frac{R+j\omega L}{G+j\omega C}}$$

Where, f is the power frequency, X_L and X_C are Inductive and Capacitive Reactance respectively, Z is Impedance, b is Susceptance, G is Conductance, Y is Admittance, and Z_V is defined as the surge impedance or the wave impedance of the line.

It should be mentioned that Figure 4-1 shows a lumped parameters model which is only applicable for short transmission lines (less than around 200 km). If the line length is longer than 200 km, this simple model becomes increasingly unreliable and the distributed parameters model has to be used in that case. In other words, longer lines can be modelled connecting line sections in cascade. In general, the longer the line or the higher the frequency, the more line sections are required for the same accuracy. Increasing the number of line sections to infinity will turn the lumped parameter model into the distributed parameters model.

4.2. Important Load Conditions

To explain the effect of different load conditions on voltage level, the phasor diagram method has been used; because it is easier to understand this effect by studying phasor diagrams. Figure 4-2 shows a two-bus system modelling a lossless transmission line, i.e. R=G=0. Note that for a lossless line the wave impedance is purely resistive. The following equations are applicable.

4-8 $$Z_V = \sqrt{\frac{L}{C}}$$

4-9 $$\overline{V_s} = V_s \angle\delta = V_s \cos\delta + j\, V_s \sin\delta$$

4-10 $$\overline{V_r} = V_r \angle 0 = V_r$$

4-11 $$\overline{I} = \frac{\overline{V_s} - \overline{V_r}}{jX_L}$$

4-12 $$\overline{V_s} = \overline{V_r} + jX_L\overline{I}$$

Where, V_r and V_s are corresponding voltages at the receiving and sending busbars.

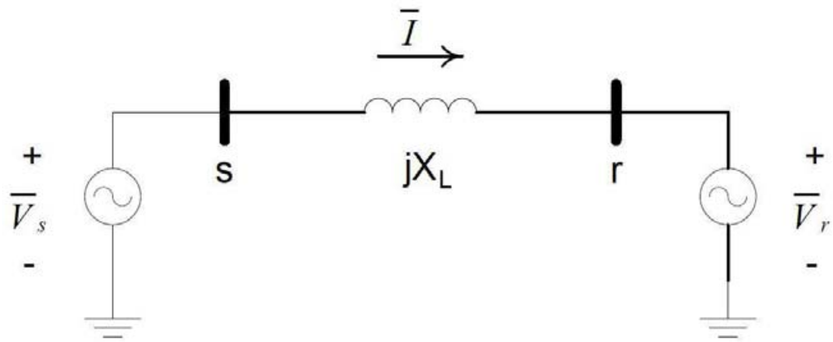


Figure 4-2: A two-bus system representing a lossless transmission line

Three main load conditions are as follows:

- No-load situation
- Surge Impedance Loading (SIL)
- Heavily loaded condition

4.2.1. The No-load Situation

Considering a Π-Model of a long lossless transmission line at no-load situation, the current (I) is leading the voltage by 90 degrees as the source of current is only the line capacitance (charging current). Figure 4-3 shows the phasor diagram of a long lossless transmission line at no-load situation according to equation 4-12. As seen, the voltage magnitude at the receiving point (V_r) is greater than that of sending point (V_s). In fact, the effect of pure capacitive current leads the voltage drop across the line inductance (L) to be in phase with the sending voltage (V_s).

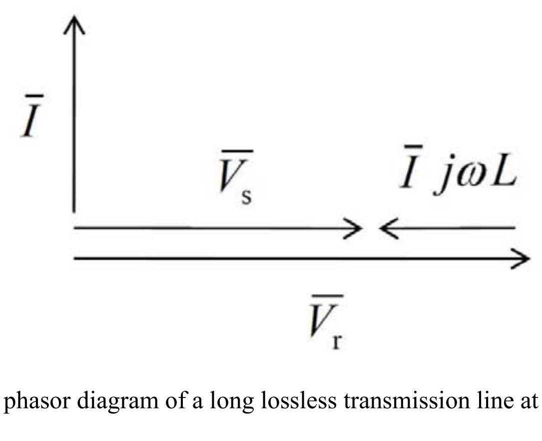


Figure 4-3: The phasor diagram of a long lossless transmission line at no-load condition

The fact that long transmission lines under no-load conditions increase their voltage is called the Ferranti phenomenon. To explain, since the capacitive effect of the line is mainly depend on voltage, in case of no-load or lightly loaded lines, the behaviour of the line capacitance is dominant and the current flowing is primarily due to charging of the capacitance. Hence the current is leading the voltage [3].

4.2.2. Surge Impedance Loading (SIL)

When the load at the receiving end has an impedance, which is equal to the wave impedance (Z_V), it is called Surge Impedance Loading (SIL) or natural load. At SIL, the reactive power generated by the line capacitance (C) is consumed by the line inductance (L). Figure 4-4 illustrates the distributed parameters model of a long transmission line at Surge Impedance Loading [3].

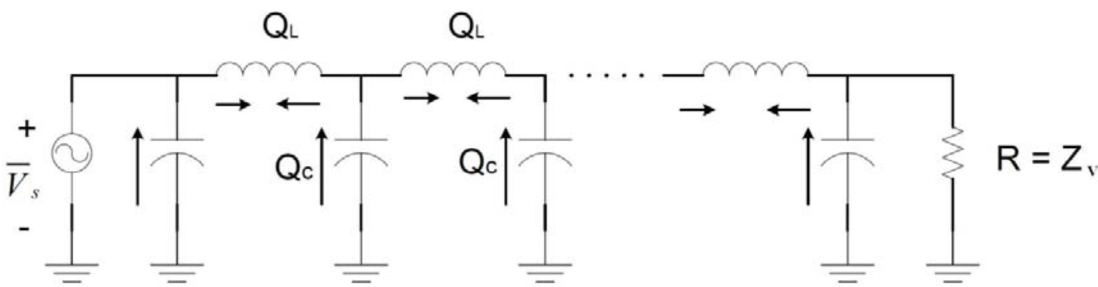


Figure 4-4: Distributed parameters model of the line at SIL

It can be shown that at SIL, there is a constant phase difference between voltage and current at any point of the line; in other words, the phase shift of voltage and current along the line is the same. As mentioned before, in case of a lossless line the wave impedance is a resistance (Equation 4-8); hence the voltage and current will be in phase at any point of the line. Considering small portions of the line as differential inductance (dL), the small voltage drops over these differential inductances would be perpendicular to the voltage since the current is in phase with voltage. Figure 4-5 shows how the voltage angle changes in each point of the line but the voltage magnitude is approximately constant.

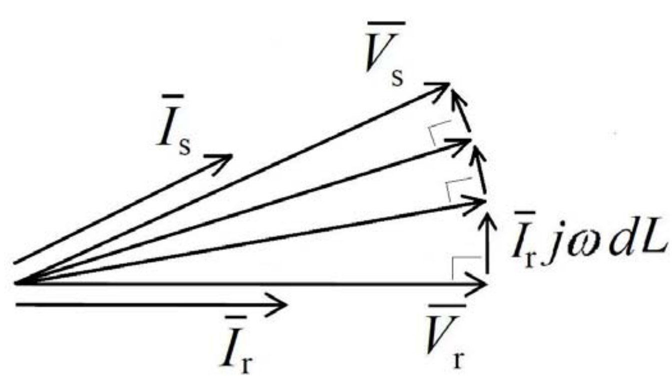


Figure 4-5: The phasor diagram of a long lossless transmission line at SIL

As a result, at SIL the voltage at the receiving end is equal to the voltage magnitude at the sending end and is equal to the voltage of all other points at the line (Figure 4-6). This is called flat voltage profile.

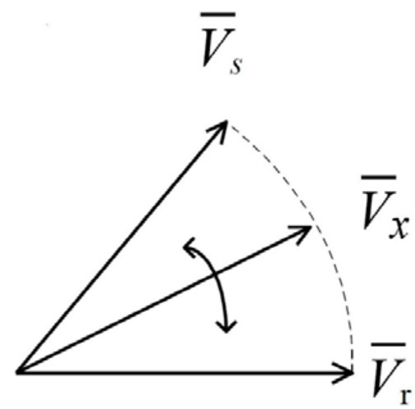


Figure 4-6: Voltage phasors at different points of a line at SIL

4.2.3. Heavily Loaded Conditions

By increasing the load, the reactive consumption increases due to the load current whereas the reactive generation is constant as it is depending on the voltage. Heavily loaded lines and especially long lines are large consumers of reactive power; hence the inductive effect of the line is dominant, which makes the current to lag the voltage. As shown in Figure 4-7, according to equation 4-12, the voltage at the receiving end is lower than that of sending end.

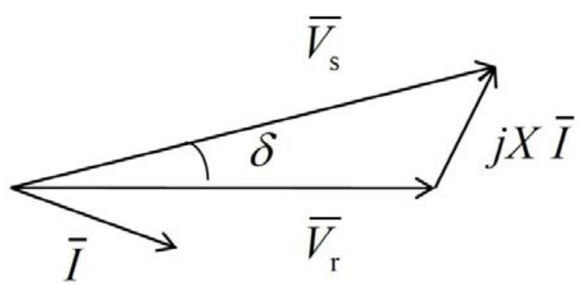


Figure 4-7: The phasor diagram of a long lossless transmission line at heavy load condition

Figure 4-8 summarises voltage profiles of an uncompensated line corresponding to different load conditions [4].

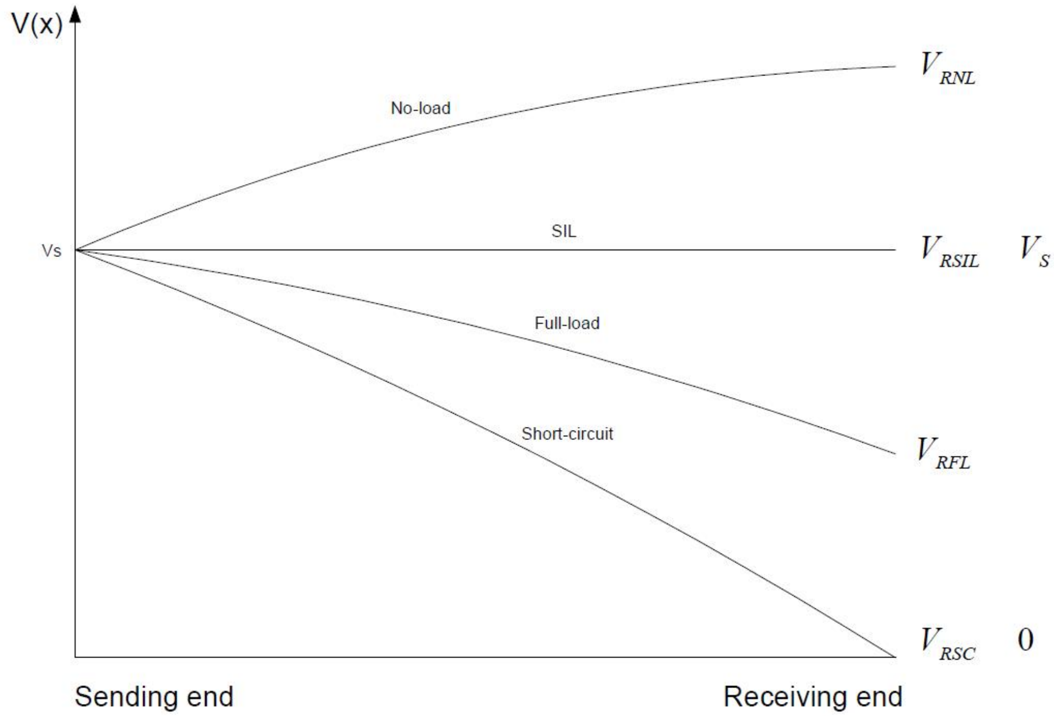


Figure 4-8: Voltage profiles of an uncompensated line

5. Reactive Power Compensation

5.1. General Reactive Power Theory

As described before, the voltage along an AC transmission line is influenced by two main factors; the capacitive charging and the loading of the line. The capacitive charging, which is the source of reactive power generation (Q_C), depends on the line geometry and the line voltage; and is because of the capacitance between its conductors and the earth. For example, a long distance 400 kV, air insulated transmission line has a reactive generation around 0.7 MVAr/km. Whereas the corresponding generation for a 400 kV cable is almost 20 times as large or about 12 MVAr/km. The capacitive generation is also influenced by the voltage level. An 800 kV line has a capacitive generation per km line of about four times as high as a 400 kV line. Thus the capacitive generation is approximately proportional to the square of the transmission voltage [7].

On the other hand, when the line is loaded, both the load and the line consume reactive power (Q_L) as inductive electrical elements. In an AC transmission system, it is important to keep the balance between generated and consumed reactive power since this is the reactive power balance which decides about the voltage stability of the line; no matter it is an overhead line or a cable. The difference between cables and overhead lines is that cables generate more reactive power per unit of length with the same voltage level. The corresponding shunt capacitance for a 345kV cable is almost 20 times that of an overhead line with the same voltage level [4].

It should be noted that normally an overhead line is loaded around its SIL whereas an AC cable is never loaded to its natural load. The reason is that cables normally reach thermal limitations before SIL which make it impossible to load them to their natural loads. The technical consequence of this is that there is always more reactive power generated in a cable than what is consumed and it therefore needs inductive compensation for cables at much shorter lengths than overhead lines [6].

In order to achieve the reactive power balance, the line should be loaded at its natural load (SIL) where the generation and consumption of reactive power are equal. If the generated reactive power is more than the consumed reactive power, the voltage increases whereas the voltage decreases if the consumption is more than generation of reactive power.

5.2. Voltage Regulating Devices

As mentioned before, when the load varies in the system, the consumption of reactive power changes, and consequently the voltage fluctuates on the line. In order to control and correct the voltage fluctuations, there are several voltage regulating devices that are used in the power system; which are briefly described as follows [5]:

- **Synchronous Generators:** Synchronous generators are not only used for generating active power; they can also be used for both generation and consumption of reactive power. When they are in over-excitation mode, they deliver reactive power to the power system; while they absorb reactive power from the grid when working in underexcitation mode. Thus a synchronous generator could be considered as a device to regulate the voltage.

- **Regulating Power Transformers:** It is possible to change a power transformer's voltage ratio by using tap-changer which consequently affects the voltage level and also the reactive power balance.

- **Shunt Capacitors:** Capacitors generate reactive power. By connecting capacitors to a transmission line, they deliver reactive power and increase the voltage level; so they have typically been used during heavy load conditions. Depending on the voltage of the line, the capacitors can be connected directly or via a transformer to the line.

- **Shunt Reactors:** In contrast with capacitors, reactors absorb (consume) reactive power by connecting them to a transmission line. They are typically used during light load conditions since they decrease the voltage level. The shunt reactor can be directly connected to the line or through the tertiary winding of a three winding transformer.

- **Static Var Compensators:** In case of applications that need very fast compensation (generation or consumption) of reactive power, Static Var Compensators (SVC) have been used. For example, when a fault happens on the network, an immediate compensation of reactive power is needed in order to keep the voltage stability in the electrical power system. To control the reactive power continuously and dynamically, SVCs are equipped with electrical components like capacitors and reactors which are switched in and out very fast with the help of semi conductive electronic devices. Since these electronic devices cannot usually be connected directly to the high voltage power line, it is necessary to also install an intermediate power transformer.

6. Shunt Reactors

6.1. Introduction on Shunt Reactors

Viewed externally in the substation yard, a large high voltage Reactor does not differ much from a transformer. The easiest way to distinguish a Reactor from a transformer is to observe its terminals and bushings on top of the device. To explain more, contrary to a 3-phase transformer which has three primary and three secondary voltage terminals, a 3-phase Shunt Reactor has only three voltage connections. Figure 6-1 illustrates a 3-phase Shunt Reactor [7].

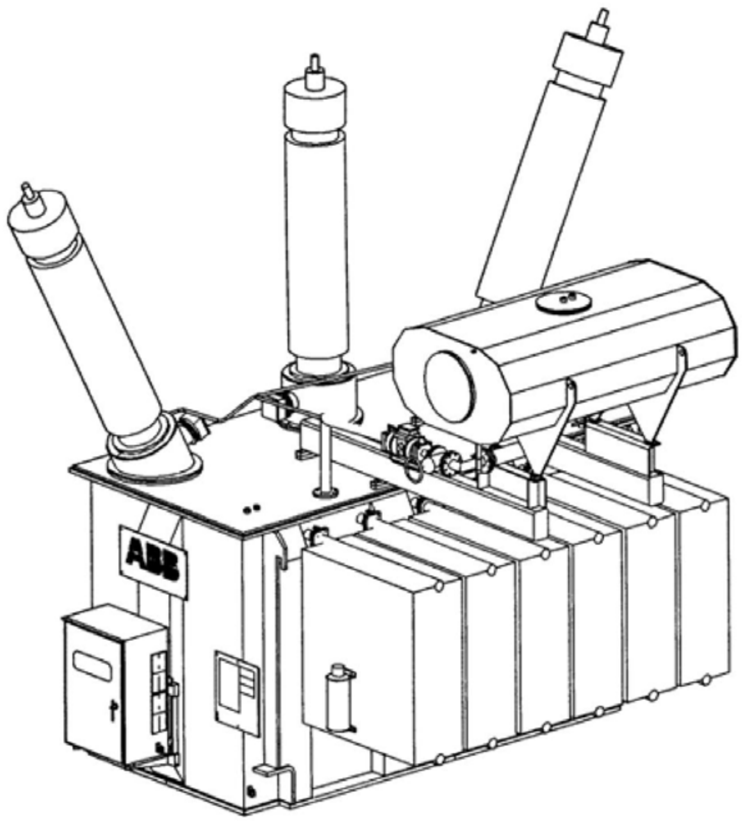


Figure 6-1: Schematic of a 3-phase Shunt Reactor

The shunt reactor is the most cost efficient equipment for maintaining voltage stability on the transmission lines. It does this by compensating for the capacitive charging of the high voltage AC-lines and cables, which are the primary generators of reactive power. The reactor can be seen as the voltage control device which is often connected directly to the high voltage lines. Figure 6-2 shows how the generated capacitive reactive power of the line is consumed by the reactors [8].

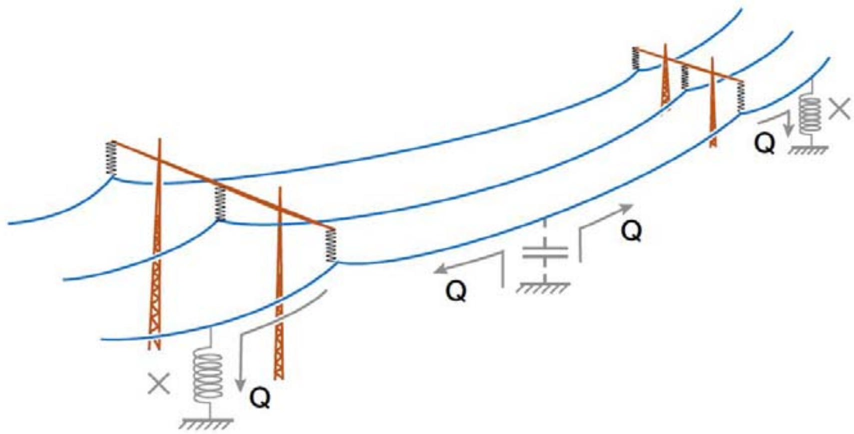


Figure 6-2: Generated reactive power by the line is consumed by the reactor's inductance

There are two main applications for Shunt Reactors. First, Shunt Reactors can be used for stability reasons especially on long transmission lines and cables (EHV and HV lines/cables); which in this case, Shunt Reactors are required to be permanently in service. Second, for the purpose of voltage control, where they can only switched in during light loaded conditions and are used in the underlying system and near to load centres [4].

Although Reactors reduce over voltages during light load conditions, they can also reduce the line loadability if they are not removed under full-load condition.

As seen in Figure 6-3, the Switched Reactor is connected to the busbar for voltage regulation while the Non-switched Reactor is connected to the line for stability reason. However, the Switched Reactor could be also connected directly to the line.

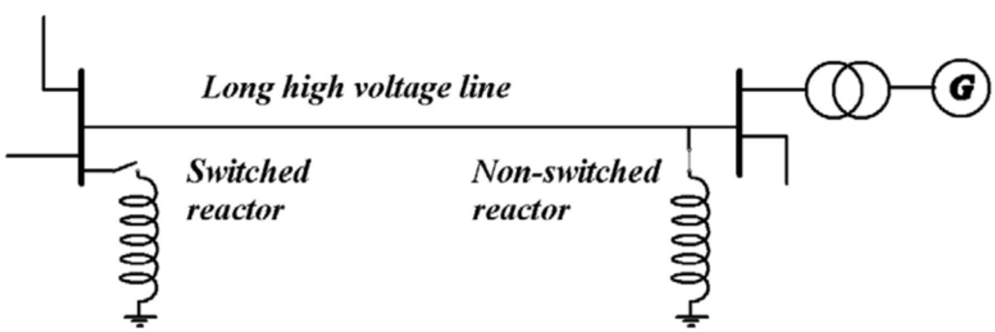


Figure 6-3: General application of Switched and Non-switched Fixed Reactors

Shunt Reactors are commonly installed at both ends of EHV lines, and sized to prevent the line voltage from exceeding a designed value when energized from one end. The reason that they are installed at both ends of the line is that there is usually some uncertainty regarding which end of a line may be energized (or de-energized) first. Figure 6-4 shows the equivalent Π-Model of a transmission line with Switched Shunt Reactors connected at both ends [4].

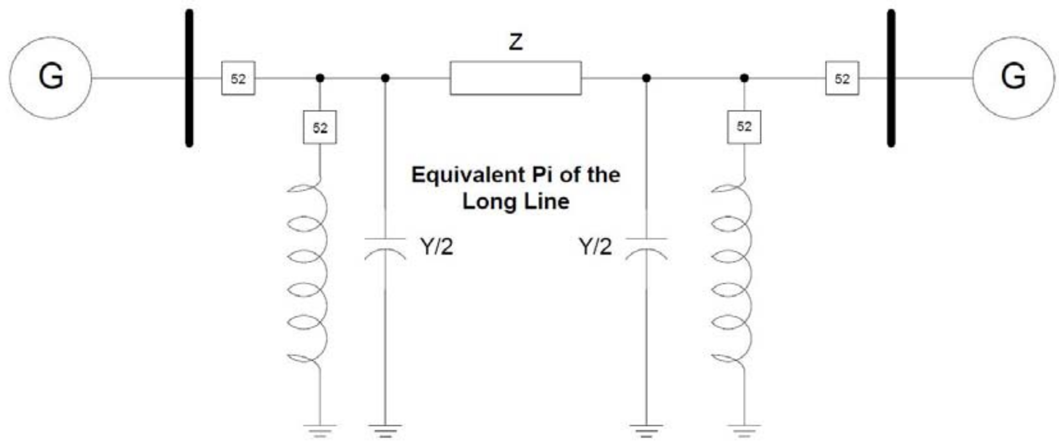


Figure 6-4: Single line diagram of the Switched Shunt Reactors connected at both ends of the line

The shunt reactor could be permanently connected or switched via a circuit breaker (Fixed Shunt Reactor). To improve the adjustment of reactive power consumption, the reactor can also be variable (Variable Shunt Reactor).

6.2. *Fixed Shunt Reactor*

Fixed Shunt Reactors have been traditionally used in transmission and distribution systems for many years. The reason that it is called Fixed Shunt Reactor is that its rated reactive power consumption is approximately constant; in other words, it has a fixed reactance (X_R). The inductive reactive power which is consumed by Reactor can be calculated as follows:

6-1 $$Q_{IR} = \frac{V^2}{X_R} = X_R \times I^2 = \sqrt{3}\, V \times I$$

6-2 $$X_R = L_R \omega$$

Where:

- **Q_{IR}** is the 3-phase inductive reactive power consumed by the Shunt Reactor in VAr
- **V** is the phase-to-phase voltage at the point the reactor is connected to the network in Volts
- **X_R** is the total inductive reactance of the Shunt Reactor in Ohms
- **L_R** is the equivalent inductance of the Shunt Reactor in Henry, and
- **I** is the flowing current into the Reactor's branch in Amperes

As seen in equation 6-1, the consumed reactive power (Q_{IR}) is only a function of the line voltage (V) and is not affected by the load current of the line. The Reactor is characterized by the following [9]:

- Rated power (Q_{IR})
- Rated system voltage (V)
- Power frequency (f)
- Number of phases
- Insulation level
- Temperature rise
- Sound Level
- Linearity characteristic

In order to design a Shunt Reactor, the required rated power (Q_{IR}) and the rated system voltage (V) are specified; so according to equation 6-1, all that should be done is to implement a certain reactance (X_R) to have the desired reactive power consumption.

There are two general types of Shunt Reactors. First one is dry-type Reactor of an air-core or core-less design. Second one is oil-immersed Shunt Reactor.

Dry-type Shunt Reactors are limited to voltages up to 34.5kV and are often installed on the tertiary of a transformer (Figure 6-5) or are used in SVC installations.

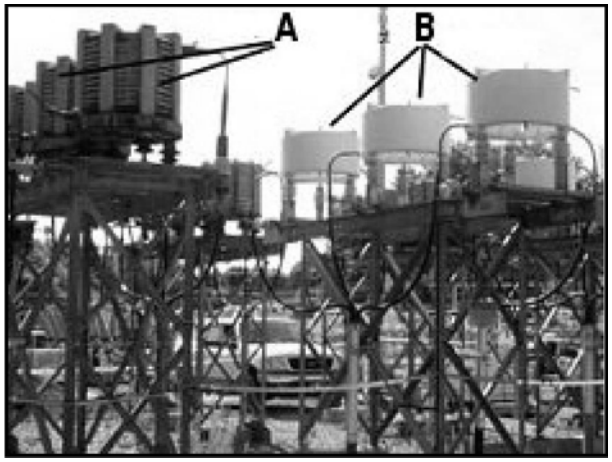


Figure 6-5: An old design air-core Shunt Reactor (A) and a modern air-core Shunt Reactor (B), connected to the tertiary winding of a large transmission network transformer

Figure 6-6 illustrates a three-phase core-less Shunt Reactor (dry-type) which is installed in a distribution substation. As seen, there is no iron at all in the core-less concept.

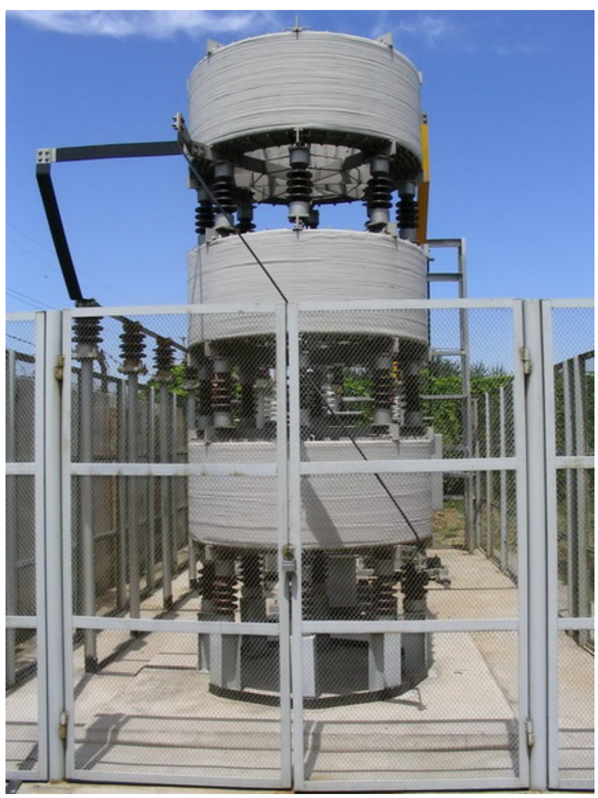


Figure 6-6: A 3-phase core-less or air-core Shunt Reactor

On the other hand, oil-immersed Shunt Reactors are used for higher voltage levels (higher than 40kV) and are the most compact and cost efficient Reactors. Regarding the core design, two different ways has been used in building oil-immersed Shunt Reactors. First one is referred to as core-type or gapped core, and the second one is called shell-type design.

The gapped core Reactor has a subdivided limb of steel core with air gaps; the limbs are located inside the winding. Figure 6-7 shows a cylindrical segment of the radially laminated core steel sheets which are then moulded in epoxy resin to make a solid piece. Each core module is a core steel block with its stiff ceramic spacers. Core modules are then accurately stacked on top of each other and cemented to make a solid core limb column (Figure 6-8-a).

As mentioned before, it is desired to implement a certain reactance (X_R) in the reactor in order to consume the required level of reactive power. Since it is needed to take a relatively large current in Shunt Reactors to have considerable reactive power consumption, the equivalent reactance in Shunt Reactors should be small compare to a power transformer magnetizing impedance. Therefore the magnetic permeability of the core (μ) should be reduced in Reactors. A good way to reduce the magnetic permeability and the resulting reactance (X_R) is to create air-gap in the core. One way is to create one big air-gap and adjust the gap length in order to achieve a certain level of reactance. However, having one big gap results in large losses.

As can be seen in Figure 6-8-a, instead of having one big gap, number of smaller gaps are implemented in order to minimize the losses. On the other hand, the magnetic field in the core limb creates pulsating force whenever it passes through different materials in the core. Since these forces are proportional to square of current (I^2), the frequency of these pulsating forces would be twice the system frequency (i.e. 100Hz). These forces could be equal to tens of tons. In case of having several number of air-gaps, the pulsating forces across all air gaps create vibrations, and the reactor limbs and the whole core must be very stiff to withstand them. Consequently the noise produced by the reactor will be reduced as well.

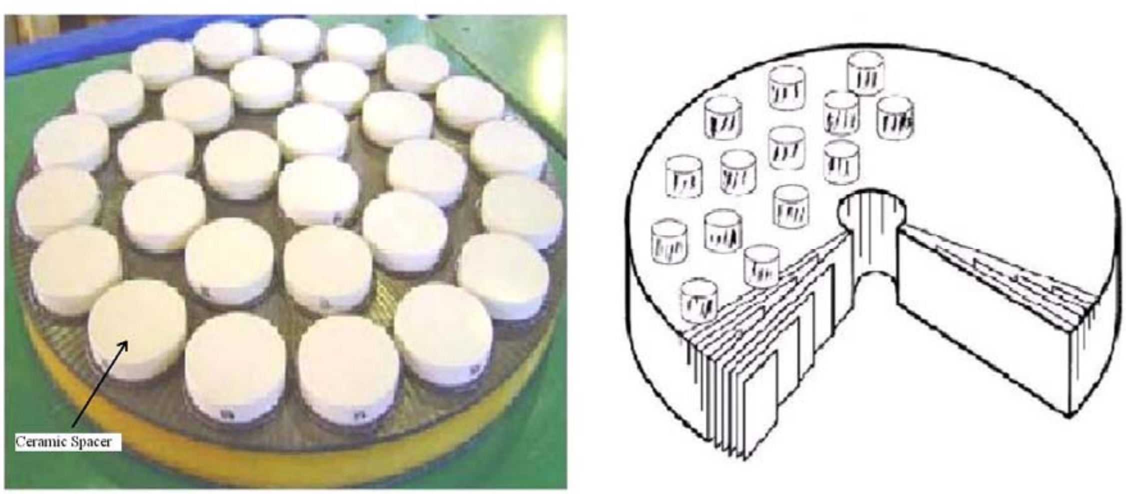


Figure 6-7: A cylindrical segment (a core module) of the radially laminated core steel sheets arranged in a wedge shaped pattern

Figure 6-8-b illustrates the winding arrangement of one phase of a gapped core Shunt Reactor. As seen, the core limb is located inside the winding. The reason that the High Voltage conductor is connected at the middle height of the winding is to have the maximum insulation clearance with the rest of Reactor's conductive parts. Finally the whole structure including all 3 phase limbs will be located in the enclosure (tank) filled with oil.

Figure 6-8-c shows structure of a five limb three-phase Shunt Reactor. Most three-phase reactors are designed with five limbs. The unwound side limbs (two outer limbs without gaps and winding) make it possible for the reactor to have the zero sequence impedance equal to the positive sequence impedance and also have more mechanical strength against vibrations [7]. Such design results in a larger and heavier core but prevents the magnetic flux from flowing through the tank walls during switch on, and reduces the subsequent dynamic forces [10].

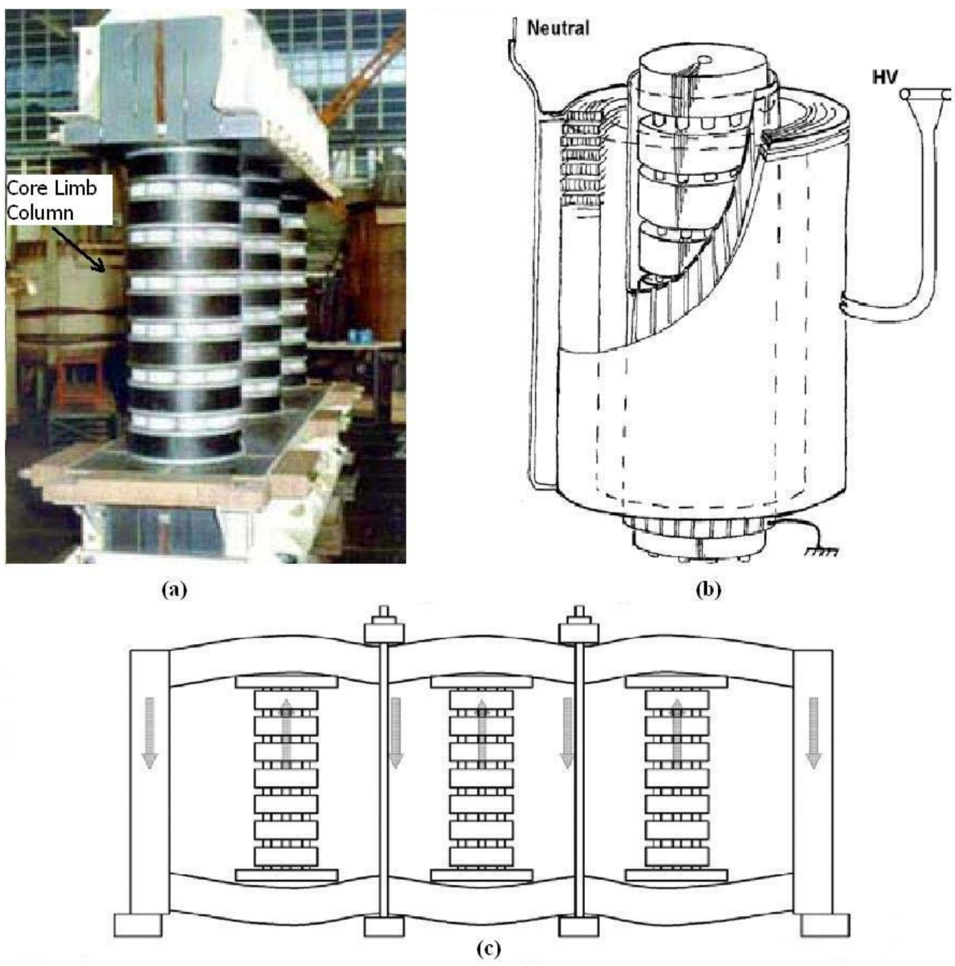


Figure 6-8: a) A 3-phase gapped core Shunt Reactor under construction **b)** Showing the windings around the core limb **c)** Schematic of a five limb 3-phase Shunt Reactor's cores and limbs

Shell-type reactors have been designed as a coil enclosed in a laminated steel core adjacent to the oil-tank walls. As seen in Figure 6-9, the winding is usually composed of two coils connected at the HV terminal located at the winding mid-length. The neutral is made from both ends close to grounded magnetic shield circuit. The magnetic flux lines pass mainly inside the oil filled winding window, and return via the laminated steel core.

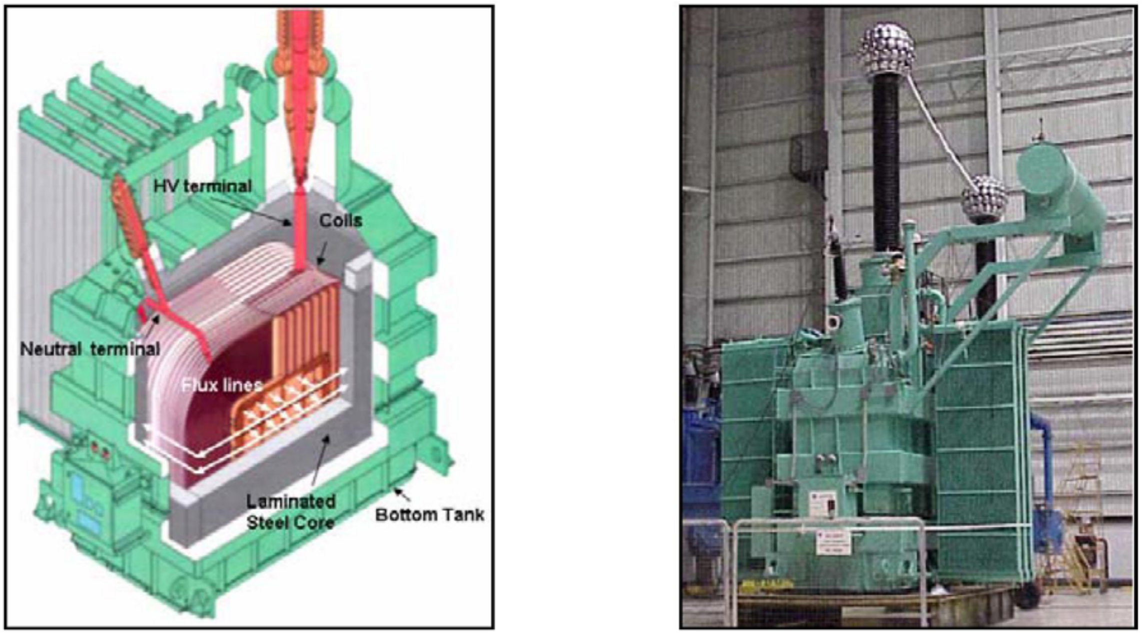


Figure 6-9: Cross section of a single phase shell-type Shunt Reactor (left), and a view of 400kV, 50MVA single phase shell-type Shunt Reactor (right)

Figure 6-10 Shows construction principle of both core-type and shell-type design.

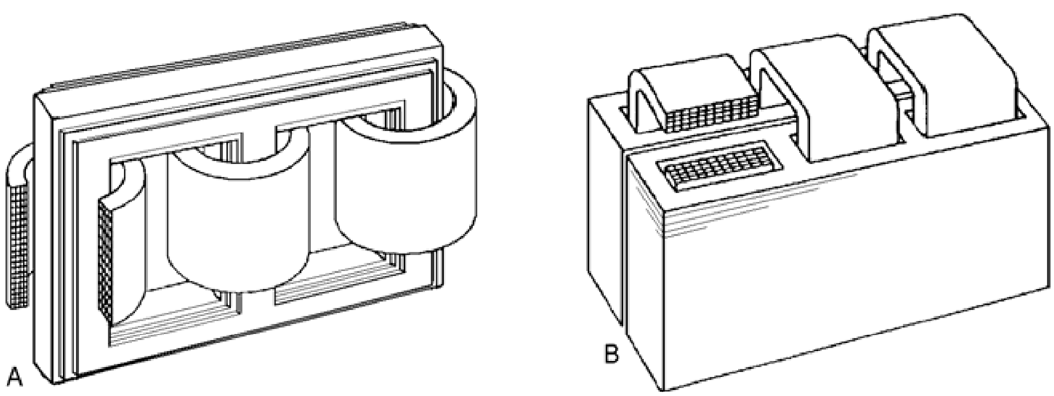


Figure 6-10: A) 3-phase core-type design, **B)** 3-phase shell-type design

Due to higher energy density and lower losses especially at higher voltage levels, the gapped core design has become more advantageous than the coreless one. Typically, total Shunt Reactor losses are in order of 0.2% of its rated reactive power. The following formulas are used for active loss evaluation of Shunt Reactors [4]:

6-3 $$P_{Total} \approx 0.002\, Q_{IR}$$

6-4 $$P_{Cu} = 0.75\, P_{Total} \approx 0.0015\, Q_{IR}$$

6-5 $$P_{Fe} = 0.25\, P_{Total} \approx 0.0005\, Q_{IR}$$

Where:

- P_{Total} is the total Shunt Reactor losses in Watts
- P_{Cu} is the total Shunt Reactor copper losses in Watts
- P_{Fe} is the other Shunt Reactor losses (mostly iron losses) in Watts

In order to properly simulate Shunt Reactors, the aforementioned data are important.

In practice, both single phase and 3-phase Shunt Reactors are used. Figure 6-11 illustrates both designs.

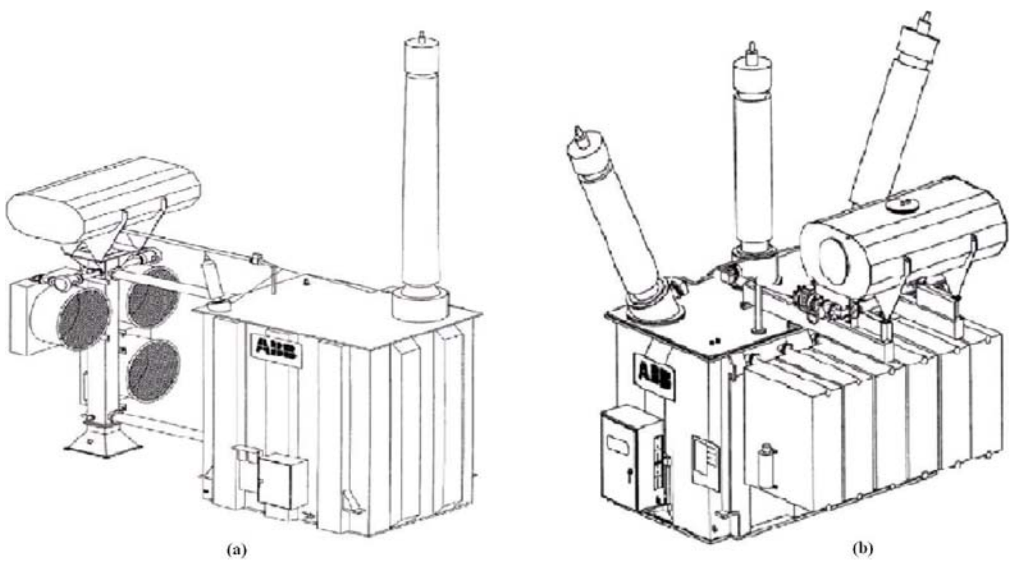


Figure 6-11: a) single phase Shunt Reactor **b)** 3-phase Shunt Reactor

As seen in Figure 6-12, all oil-immersed three phase shunt reactors are star connected.

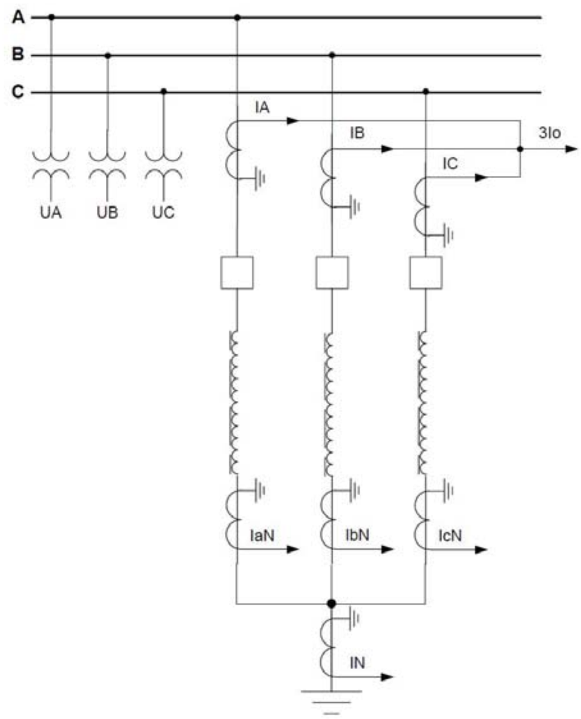


Figure 6-12: A 3-phase Shunt Reactor connected to the transmission line

Basically, the choice between single or 3-phase shunt reactors is exactly the same as transformers. It should be a balance between cost savings and risk costs when large 3-phase reactors are used instead of three single phase units.

One 3-phase Shunt Reactor has cost advantages compare to three single phase units. To explain, the price of a 3-phase reactor is lower than three single phase units. In addition, the total power loss is also lower in a 3-phase unit. Moreover, the size of substation decreases and additional savings can be made in civil works and related substation equipment.

On the other hand, when using three single phase shunt reactors, it is economically reasonable to keep a fourth single phase unit as spare. However utilities seldom keep a spare 3-phase Reactor due to cost reasons; for this reason, the reliability of 3-phase Shunt Reactors is very important. A well-designed and well-manufactured Shunt Reactor should have the same or better reliability as a transformer and should also have low levels of sound and vibrations. It should be noted that the reliability of a 3-phase Shunt Reactor should be the same as a single phase one.

6.3. *Variable Shunt Reactor (VSR)*

6.3.1. *Introduction on VSR*

As described, the Shunt Reactor is a consumer of reactive power. In some applications there is a need to consume the inductive reactive power in steps. In such a case, several shunt reactor units are needed to connect and disconnect frequently which requires more circuit breakers and foot prints at substation. Instead of having several units, one unit that covers the entire power range could be an economical solution.

A Variable Shunt Reactor (VSR) is a reactor where the inductance can be varied in steps. The reactive power consumption can increase up to twice its initial value over the whole regulating range. The regulation speed is determined by the operation time of the tap changers used; and it is in the order of seconds. VSRs are based on the same concept as a Fixed Shunt Reactor. However, the design requires special attention and the VSR is considered as a separate product type [11].

Generally, when there is a slow variation of the load, the VSR works as an efficient reactive power compensator in order to fine tune the voltage in the system. VSRs provide dynamic reactive power compensation with the regulation range around 100% (e.g. 50-100 MVAr) and ratings up to 250 MVAr, 500 kV. ABB is the world's leader in design and constructing VSRs and so far 16 VSRs have been sold to the US, Norway, Denmark, Sweden, Ghana and Burkina-Faso. Currently, the world's largest VSR in service has the rating 400 kV, 120-200 MVAr.

6.3.2. *Applications of VSR*

Compared to shunt reactors with a fixed rating, Variable Shunt Reactors provide several benefits to the operators. Customer values and applications of VSRs are as follows [8]:

- To reduce voltage spikes in the network resulting from switching in and out the Fixed Shunt Reactors; especially in networks with low short circuit power. Generally, switching Fixed Shunt Reactors in and out is a non-optimal compensation which leads to voltage steps and also wearing out the breakers. It is possible to avoid switching actions by using a VSR and regulate it to its minimum power tap position. VSRs reduce voltage jumps during switching operation.

- In substations with SVC equipment and rotating phase compensators, the VSR has the capability to be coordinated with the SVC/phase compensators in order to maximize the dynamic capacity of the network during failure.

- For wind park generation applications, a VSR may be used by the operator of the wind park to control reactive power fluctuations. An important difference between wind parks and conventional large generation is the fluctuating and unpredictable active power exchanges of the wind park to the main grid; these active power fluctuations cause in turn reactive power losses which are a serious concern regarding network operational security. Using Fixed Shunt Reactors require too many switching actions and the need for advanced control possibilities of SVC may not be needed.

- It is possible to reduce number of circuit breakers by having one VSR instead of two or more parallel fixed reactors. This will consequently cause reduction on maintenance work on breakers and space requirements.

- VSRs are suitable to be used for seasonal load variations. At low loading condition the full MVAr rating is needed to maintain a stable voltage. As the load increases in the intermediate season the VSR acts to fine tune the voltage to the required level.

- Daily load variation is another possible application of VSRs. The loading varies as a consequence of Economic Load Dispatch (ELD) and Optimal Power Flow (OPF) in the power system. For this reason there is a need for a more flexible compensation of the reactive power.

- VSRs can also be used for voltage regulation at high voltage AC cables. AC cables generate much more reactive power per unit of length than overhead lines (almost 20 times more) and because of thermal constraints in the cables it is normally not possible to load them at SIL. Therefore there is a need for reactive power compensation to stabilize the voltage. At variable stationary loads, better fine-tuning of the voltage and consequently a better control of the network can be achieved using a VSR.

- VSRs are flexible to adapt with revisions in the network. The future load and generation pattern is not specified and the demand for reactive power compensation may change. To meet the new demand there is a possibility to regulate the VSR.

- It is possible to adjust the reactive power consumption of a VSR during maintenance or a failure situation on another reactor.

6.3.3. Design of VSR

As mentioned before, the main function of VSR is to regulate the consumption of reactive power. This task is accomplished by connecting/disconnecting electrical turns in the reactor. According to equations 6-1 and 6-2, the reactive power consumption of the VSR (Q_{IR}) is proportional to the square of voltage and inversely proportional to the equivalent inductance of the Reactor (L_R). Considering a constant voltage level, more inductance leads to less current flowing in VSR branch and less reactive power consumption. Following equations show how the reactive power consumed by the reactor is related to the number of electrical turns of the inductive component [8].

6-6 $$\boldsymbol{Q_{IR} \sim \frac{V^2}{L_R}}$$

6-7 $$\boldsymbol{L_R = \frac{\mu N^2 A}{l}}$$

Where:

- **μ** is the magnetic permeability of the core material
- l is the physical length of the coil (inductive component)
- **A** is the cross-sectional area of the coil
- **N** is the number of electrical turns

Equation 6-7 shows the inductance of the reactor (L_R) is proportional to the square of the number of electrical turns (N).

6-8 $$L_R \sim N^2$$

As a result, the power consumption of the reactor is controlled by the following equation:

6-9 $$Q_{IR} \sim \left(\frac{V}{N}\right)^2$$

At maximum reactive power rating the minimum numbers of electrical turns are connected and at minimum reactive power rating the maximum numbers of electrical turns are connected. Thus the minimum reactive power rating is limited by the physical length of the regulating winding and consequently the size of the VSR. This change in number of turns is done by using a tap changer. The same type of tap changer which is already utilized for decades in power transformer applications has been used for VSR. Therefore, it is possible to fine tune the power system voltage level by using VSR.

In order to regulate the power in the Variable Shunt Reactor, a separate regulating winding is used. This winding is located outside the main winding around the core limb. The high voltage (HV) inlet to the main winding could either be located as a yoke entrance or as a centre entrance to the winding. High Voltage centre entrance design is commonly used. Figure 6-13 shows the design principle of the active part of a Variable Shunt Reactor [8].

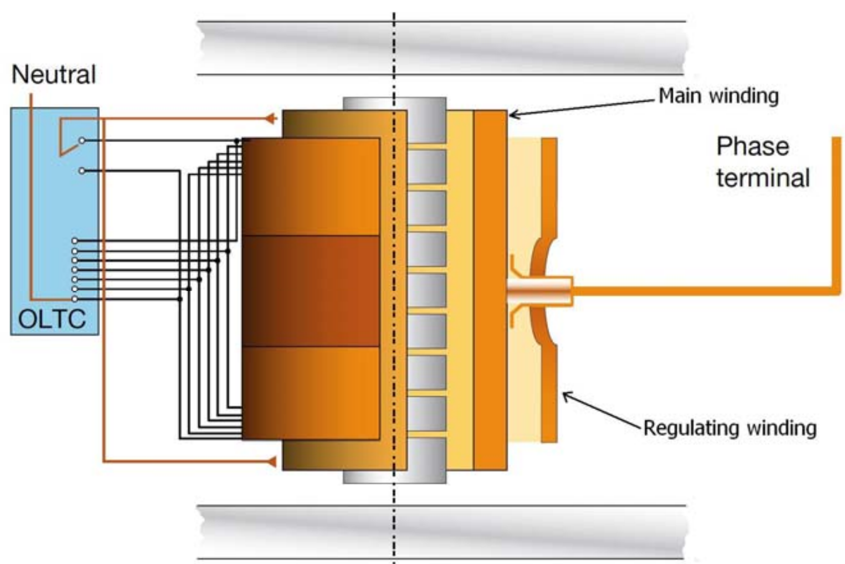


Figure 6-13: The design principle of the VSR's active part

As seen in Figure 6-13, the taps from the regulating winding are connected to the tap changer. Depending on regulating range, voltage level and loss evaluation, the regulating type can be linear, coarse/fine or plus/minus.

The ABB VSR design is a result of extensive development work in combination with well proven and known technology used in power transformers and Fixed Reactors. Figure 6-14 shows a 420kV, 120-200MVAr ABB Variable Shunt Reactor.

Figure 6-14: The 420kV, 120-200MVAr ABB Variable Shunt Reactor

A 242kV, 50-100MVAr ABB Variable Shunt Reactor is also shown in Figure 6-15. This VSR is designed and manufactured in order to deliver to USA. As seen, the cooling system and the expansion tank are separated from the reactor in this design.

Figure 6-15: Front-side view and back-side view of a 242kV, 50-100MVAr ABB Variable Shunt Reactor

In reality, because of high mechanical forces VSRs are complex devices and in many cases provide higher engineering and production challenges than transformers. The field reliability of the VSR is often stressed by utilities and is dependent on the design and manufacturing capabilities of the manufacturers. The quality of design, production and testing of a VSR unit is therefore of highest importance [11].

6.3.4. Regulation of VSR

Variable shunt reactors are available at voltages up to around 400 kV and three phase ratings up to around 250 MVAr. The maximum regulation range is a function of voltage and is normally around a factor 2 at 400 kV. Another limitation is the electrical behaviour of the regulating winding at transient voltage stresses. The regulating winding in a VSR is electrically much longer than a regulating winding used in transformer applications. The feasible regulation range depends on the voltage rating of the reactor as shown in Figure 6-16. The maximum regulating range increases at lower voltage levels. As seen, at 150 kV the corresponding regulation range is around 2.5 [8].

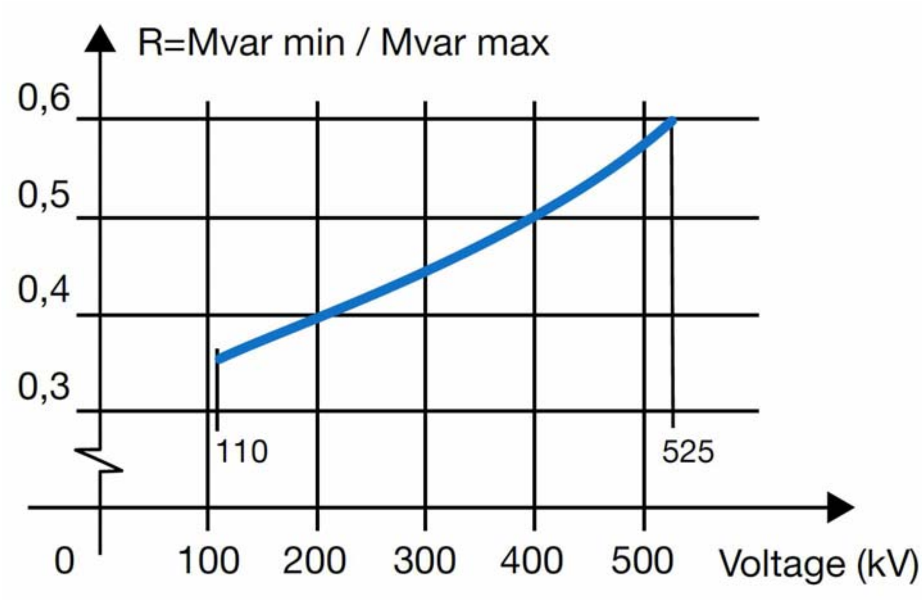


Figure 6-16: The feasible regulating range of the VSR depending on the voltage rating

As mentioned before, there are three possible regulating types available for Variable Shunt Reactors as for power transformers; namely:

a. Linear regulation,
b. Coarse/fine regulation and
c. Plus/minus regulation

Figure 6-17 illustrates the three winding arrangements corresponding to these three regulation types. In this figure, winding 1 is the main winding and windings 2 and 3 are regulating windings. As VSR has a long electrical length of the regulation in comparison with a power transformer, the linear regulation is rarely used in the VSR applications; because it directly affects the size of the VSR. The choice of coarse/fine or plus/minus regulation depends mainly on the loss evaluation given by the customer. At the extreme minus tap position the maximum power rating and the highest current is achieved. The extreme minus tap position for winding arrangement b) means that only the main winding is connected which is advantageous in order to minimize the losses. However, for the winding arrangement c) in order to achieve the extreme minus tap position, the complete regulating winding in the reverse direction is connected which leads to develop more losses in this case. On the other hand the c) solution has lower manufacturing costs than the b) solution. Therefore, at high loss evaluations and voltages equal or less than 400 kV, a yoke entry with a coarse/fine regulation is normally used. However, at low loss evaluations, plus/minus regulation is an alternative; at voltages higher than 400 kV a centre entry solution with a plus/minus regulation should be chosen. It is important that the customer in the technical inquiry informs about how the losses economically will be evaluated. For this reason it is also important to know at which tap position the customer is going to evaluate the losses [5].

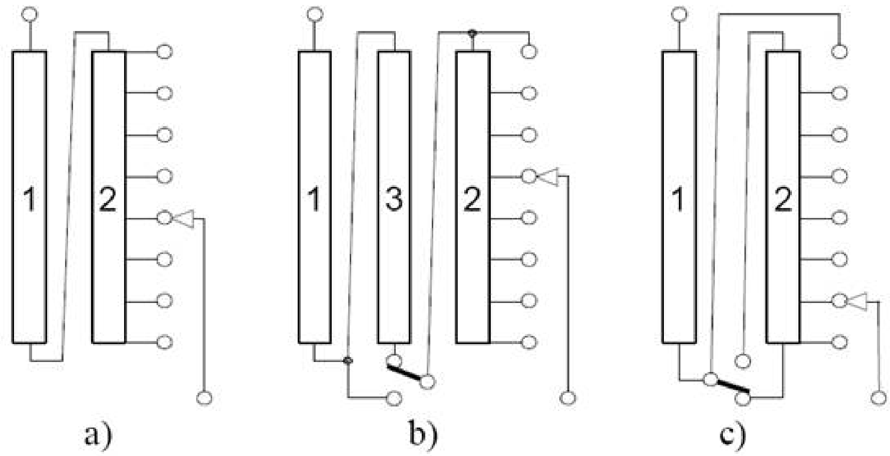


Figure 6-17: Three different regulating types of VSR, **a)** Linear, **b)** Coarse/fine, and **c)** Plus/minus regulation

As mentioned, the tap changers used for VSR are the same type as them used for transformers. Nevertheless, the design and selection of the tap changer has an impact on the Variable Shunt Reactor application and must be carefully considered in the design. Especially due to the long electrical length of the regulation, the leakage flux inductance in the regulating circuit could reduce the available valid step power and step voltage for the tap changer [8].

Number of steps required for a specified regulating range is decided by the maximum allowed step voltage of the tap changer. It means in most cases, more regulating steps will be used than what is actually required by the user of the VSR. A good recommendation when writing the technical specification is to ask the manufacturer to minimise the number of steps with respect to the chosen tap changer [5].

7. Protection of Shunt Reactors

Generally, a same strategy is used for protection of both Fixed and Variable Shunt Reactors. Although multifunctional numerical protection relays are widely used for both power transformers and Shunt Reactors protection, still the typical traditional protection schemes with few protection functions are applied in some cases.

7.1. Traditional Protection Scheme

There are two common traditional protection arrangements. The first one uses Restricted Earth Fault (REF) protection (87N) as the Reactor unit protection. Figure 7-1 illustrates this protection scheme [4].

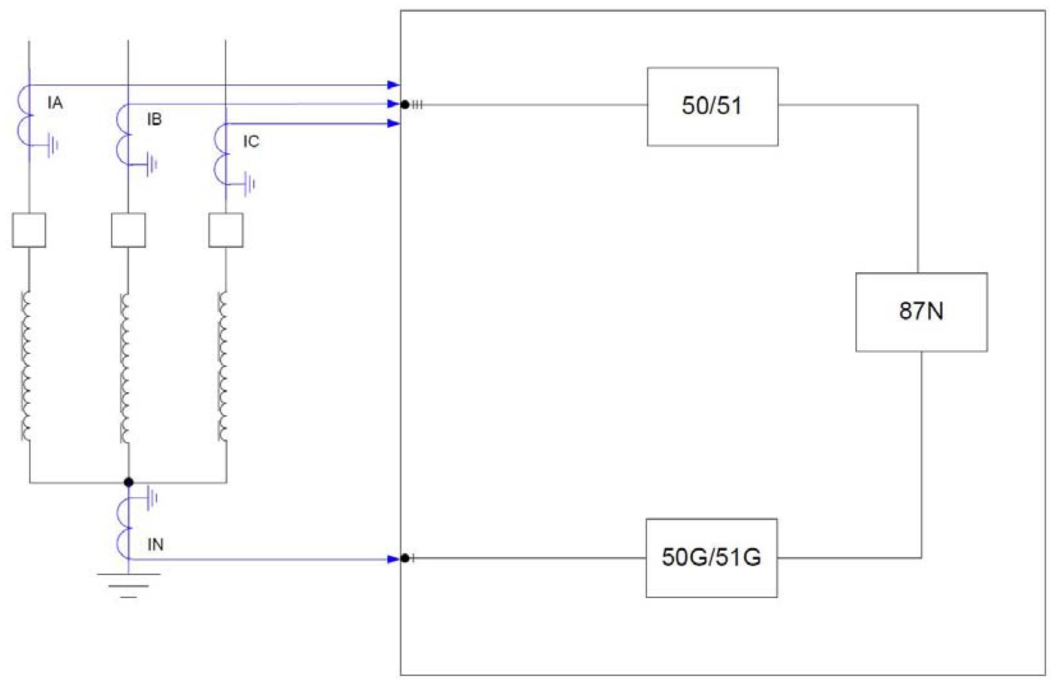


Figure 7-1: Typical Shunt Reactor protection scheme using Restricted Earth Fault function (87N)

REF protection (87N) shall instantaneously trip for all internal phase to ground faults. For detecting internal phase-to-phase faults Over-Current protection is used (50/51). Ground Over-Current protection (50G/51G) is utilized as the backup protection for ground faults. Ground Over-Current protection is also used as main protection for circuit breaker pole disagreement condition.

The second traditional protection scheme for Shunt Reactors is shown in Figure 7-2. As seen, it utilises Differential protection (87) as the unit protection for Reactor which shall trip instantaneously for all internal phase-to-phase and phase to ground faults. Over-Current protection (50/51) is used as backup protection for internal phase-to-phase faults; while Residual Over-Current protection (50N/51N) is used as backup protection for ground faults and as main protection for circuit breaker pole disagreement condition.

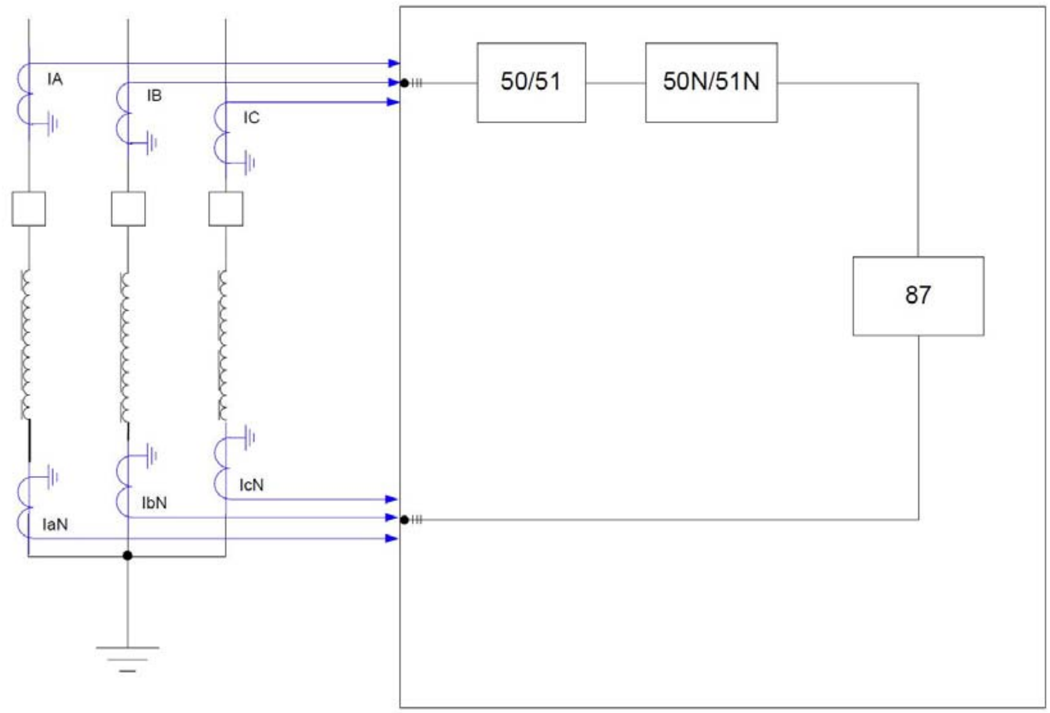


Figure 7-2: Typical Shunt Reactor protection scheme using Differential protection function (87)

7.2. Advanced Protection Scheme

New multifunctional numerical relays offer much more functionality and flexibility compare to traditional protection schemes. Figure 7-3 shows an advanced complete protection and control scheme for a HV Shunt Reactor using a multifunctional numerical protection relay which deploys Discrete Fourier Transform (DFT) filtering technique [4].

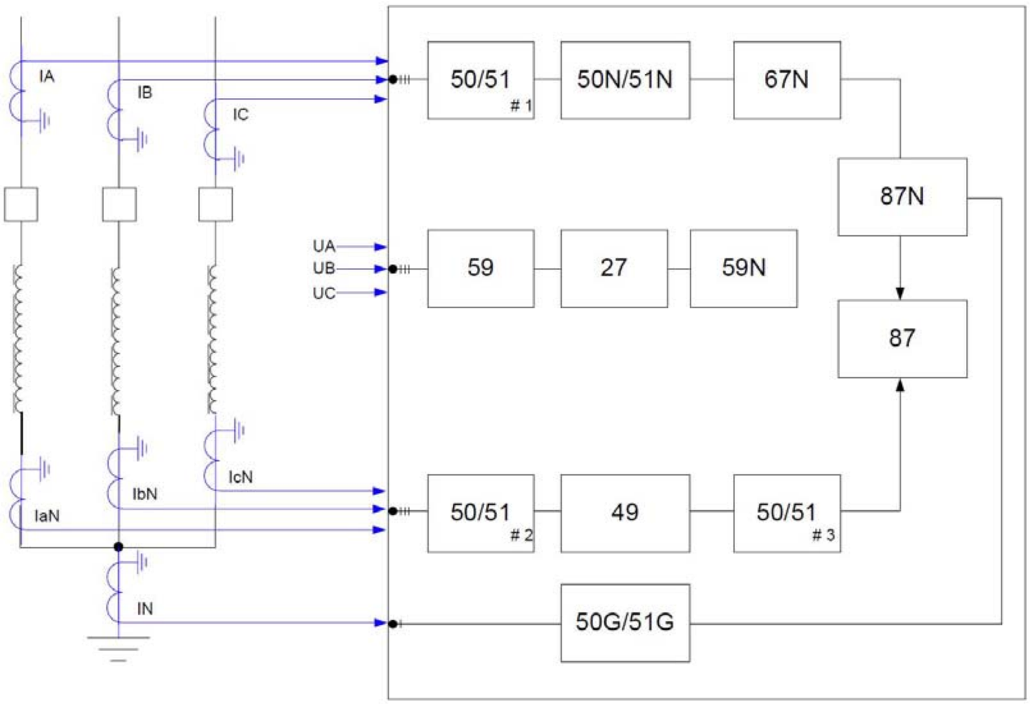


Figure 7-3: Example of a complete HV Shunt Reactor protection and control scheme with multifunctional numerical relay

As seen, in addition to current measurements, the phase voltages are also used by the relay for control purposes (Under/Over voltage 27&59).

Table 7-1 gives a summary of each function and proposes some typical setting values [12]. It should be noted that the typical settings specified with * mark, are only suggested for HV Shunt Reactor with its own circuit breaker.

Table 7-1: List of functions for complete HV Shunt Reactor protection and control scheme

Function	Comment	Typical setting shown in percents of the shunt reactor rating
87=low impedance differential protection	Check suitability for shunt reactor application with relay manufacturer.	Set restraint differential level to 10-15% with 2nd harmonic restrain set at 10%. Set unrestraint differential level 200%.
87N=low impedance, restricted ground fault protection	Check suitability for shunt reactor application with relay manufacturer.	Set differential level to 10%. Set operate angle for directional criteria to ±65 deg. Relay shall include adaptive 2nd harmonic restrain feature.
#1-50/51=HV overcurrent protection	Backup protection, sensitive for internal faults close to the reactor bushings.	Set low set to 130% with time delay in between 0.6s and 1s. Set high set to 250% with time delay of 0.1s. *
#2-50/51=HV overcurrent protection	Backup protection, sensitive for internal fault close to the reactor star point.	Set low set to 130% with time delay in between 0.6s and 1s. Set high set to 200% with time delay of 0.1s. *
#3-50/51=HV overcurrent protection	Used as circuit breaker failure protection and indication that reactor is energized for the cooling control logic.	Set low set to 30% with appropriate time delay as CBF protection. Set high set to 50% in order to indicate that shunt reactor is energized. *
49=thermal overload protection	Shall be used with great care. Shunt reactor overload can only be caused by overvoltage in a power system. That is the exact time when reactors are required to be energized. Thus it might come in conflict with shunt reactor voltage/reactive power control functionality in the power system.	Specific manufacturing data are required in order to properly set this function. Possible to use winding/oil contact thermometer instead.
50G/51G=ground fault protection in reactor neutral point	Backup protection, sensitive for internal fault close to the reactor star point. Used for turn-to-turn fault detection logic.	Specific system data are required in order to properly set this function.
50N/51N=ground fault overcurrent protection in reactor HV side	Backup protection, sensitive for internal faults close to the reactor bushings.	Set low set to 20% with time delay in between 0.6s and 1s or even longer. Use 2nd harmonic blocking. Set high set to 175% with time delay of 0.1s. *
59N=unbalance overvoltage	Used for turn-to-turn fault detection logic.	Specific system data are required in order to properly set this function.
67=directional ground fault protection	Used for turn-to-turn fault detection logic.	Specific system data are required in order to properly set this function.
27&59=under/over voltage	Used for automatic shunt reactor control. Often more than one stage required.	Specific system data are required in order to properly set these functions.

8. Control of Shunt Reactors

8.1. Control of Fixed Shunt Reactors

Generally, Fixed Shunt Reactors are designed and located in a way to be connected to the network most of the time. However, lately it is often required by the electrical utilities to perform automatic switching in/out operations on Switchable Fixed Shunt Reactors by monitoring the busbar voltage level. Figure 8-1 illustrates a typical Switchable Fixed Shunt Reactor control scheme [13].

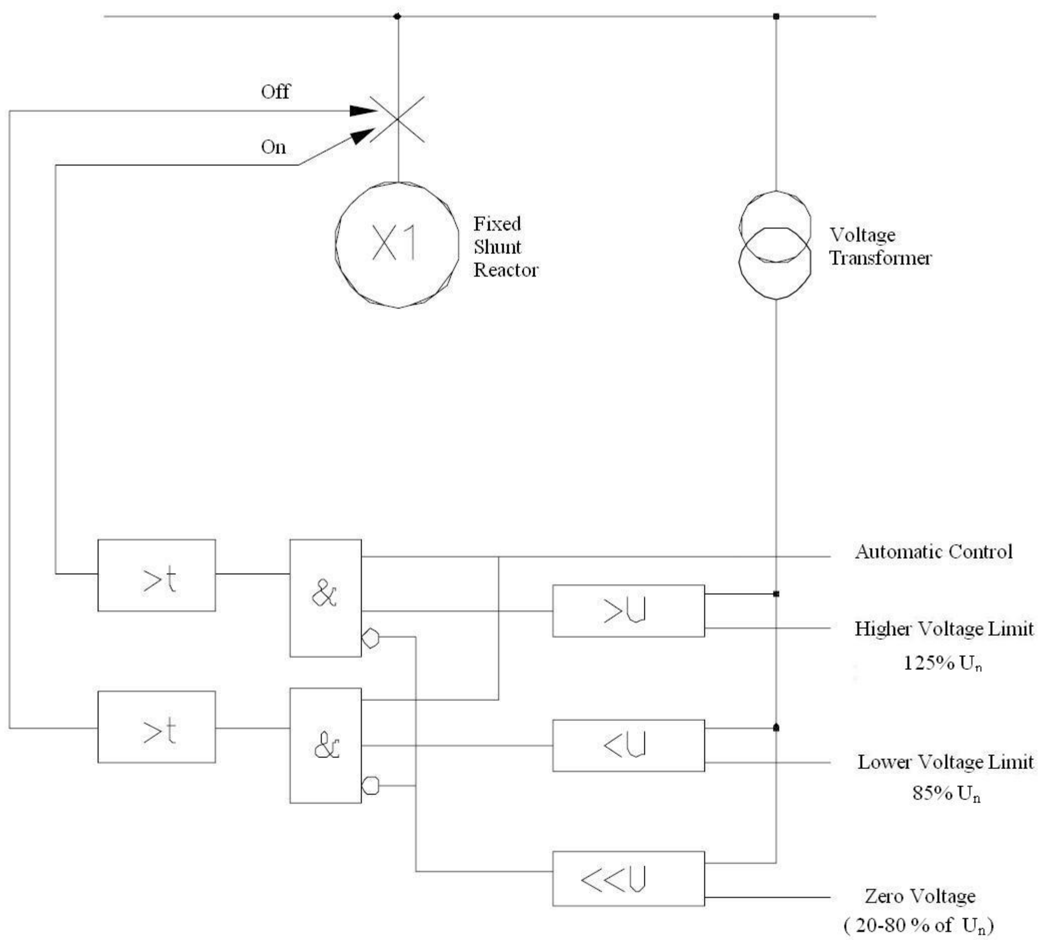


Figure 8-1: Typical On/Off switching control of a Fixed Shunt Reactor

As seen in Figure 8-1, the normal operating range is 85% to 125% of busbar nominal voltage. For voltages higher than 125% of the nominal voltage, the switch-in (On) command is issued. Likewise, for voltages lower than 85% of the nominal voltage, the switch-out (Off) command is issued. This control system is interlocked with a zero voltage detection which is considered as voltages very lower than 20-80% of the nominal voltage; in this case, the busbar will be assumed dead and the control function will be blocked. As shown, this switching function is delayed in order to ensure that the voltage change in network is stable. The aforementioned functionality is quite easy to integrate into multifunctional numerical relays.

Moreover, the shunt reactors are generally designed for natural cooling with the radiators mounted directly on the tank. However, sometimes it is required to have some control action on the cooling circuit depending on the status of the shunt reactor circuit breaker. The control action can be initiated by either the circuit breaker auxiliary contact or the operation of an Over-Current relay which is set to 50% of the reactor rated current. By using Over-Current relay, more secure control action is achieved when Shunt Reactor is energized regardless of the circuit breaker auxiliary contact status [4].

8.2. *Control strategy of Variable Shunt Reactors (VSR)*

8.2.1. Brief Discussion on Choosing Proper Simulating Software

In order to investigate the control strategy of Variable Shunt Reactors (VSR) with tap-changer, the best way is to take the advantages of modelling and simulation through computer software; because in reality, it is impossible to connect VSR to the network and compare the results of several different experiments. In fact, it would be time-consuming and costly along with lots of practical issues and problems in each experiment.

There are some powerful power system simulation software such as DIgSILENT Power Factory, PSS/E, Power World, EMTDC, and MATLAB SimPowerSystem Blockset. Every software has its own strength points and limitations. It is decided to start the work in DIgSILENT Power Factory since it is a powerful tool for load flow studies. However, there is no possibility in DIgSILENT to investigate a new control strategy. On the other hand, it is possible in MATLAB to access all the information and control the whole simulation process precisely; it is good for data gathering, manipulating different parameters of the system and analyzing the results in order to extract an appropriate control strategy. As a result, the work starts with putting the VSR in a realistic network model in DIgSILENT and investigating the voltage behaviour after running load flow simulation and studies and also running some possible load scenarios. Afterwards, the work continues with extracting a control strategy of the VSR through modelling and simulation using MATLAB SimPowerSystem/ Phasor Mode.

8.2.2. Investigation of Voltage Behaviour in DIgSILENT

Since one of these VSRs is currently connected to the grid in Norway transmission network, a part of this network is modelled in DIgSILENT. All data and parameters used for modelling are based on realistic data gathered from Statnett (Norway's Transmission Grid Owner and Operator). Appendix A shows the simulated model in DIgSILENT.

There are four substations available in this area namely Aurlanda 1, Aurlanda 2, Sima, and Dagali; among them Aurlanda 1 (900MVA), Aurlanda 2 (150MVA), Sima (1300MVA) have generation units while Dagali is an intermediate substation supplying 1350MW load out of this area. Figure 8-2 shows the interconnection between these substations and also available loads and generation units in this area. The rest of interconnected norway's transmission network is considered as an infinite busbar.

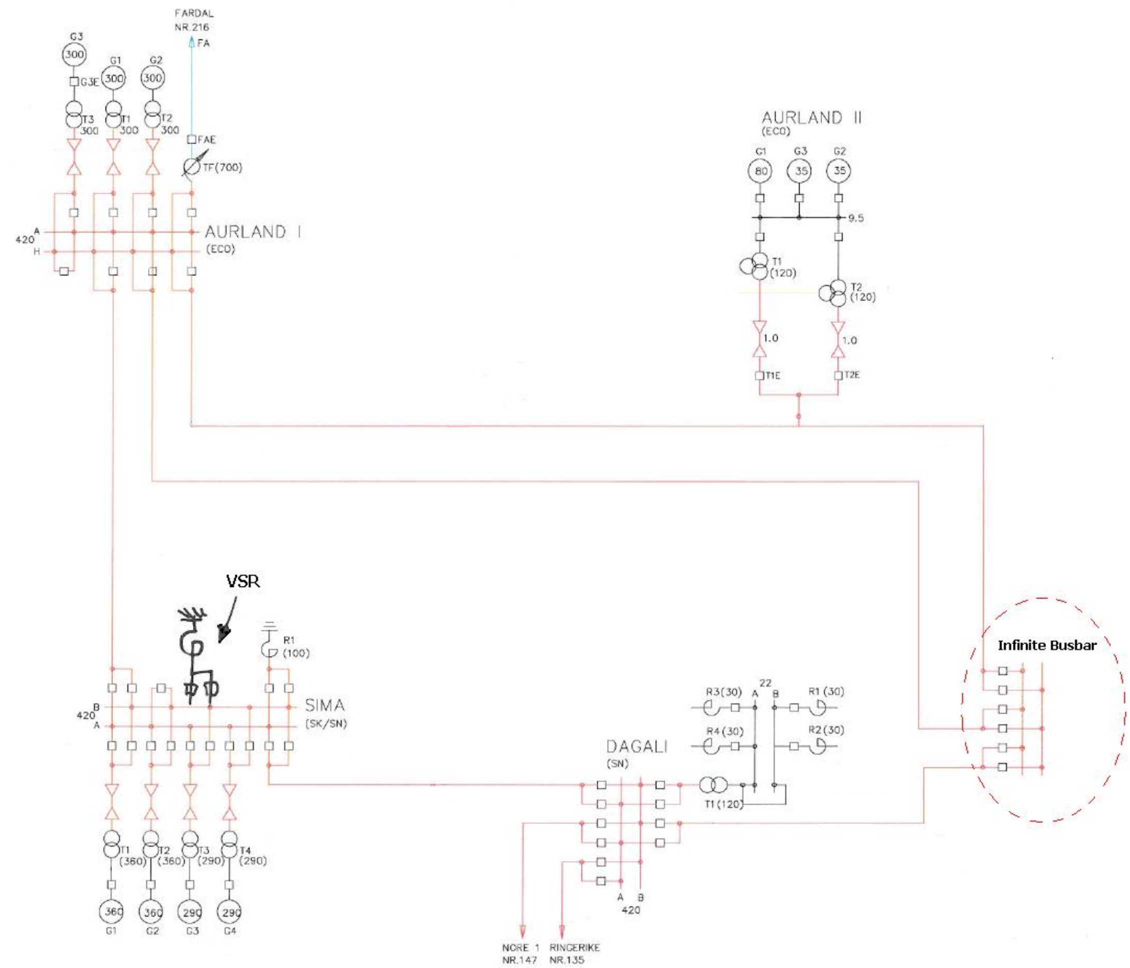


Figure 8-2: The single line diagram showing part of Norway's transmission network

Figure 8-3 shows Sima substation which is part of the simulated network in DIgSILENT. A 420kV, 120-200MVAr Variable Shunt Reactor is connected to this substation. Unfortunately there is no realistic model for a VSR available in DIgSILENT. For this reason, due to simulate the connected VSR at Sima substation, one 120MVAr fixed shunt reactor together with a 0-80MVAr switchable shunt reactor are used (Figure 8-3) and a 5 seconds operating time is set for each tap to simulate a realistic tap-changing process.

In order to investigate the voltage behaviour at Sima substation, a load scenario has been simulated in DIgSILENT. The scenario is that, initially the network is operating under normal operating condition; i.e. the voltage level at all busbars is within the dead-band and all generators are operating within their limits and the transmission line capacities are not exceeded. After 50 seconds due to under-frequency protection trip in NORE 1 and RINGERIKE, 30% of load is shed in each area. Consequently the frequency gets stable again, however after 170 seconds the load restoration coincides with some extra demand in these two areas which results in total 55% load increase in each area. The simulation is run for 300 seconds.

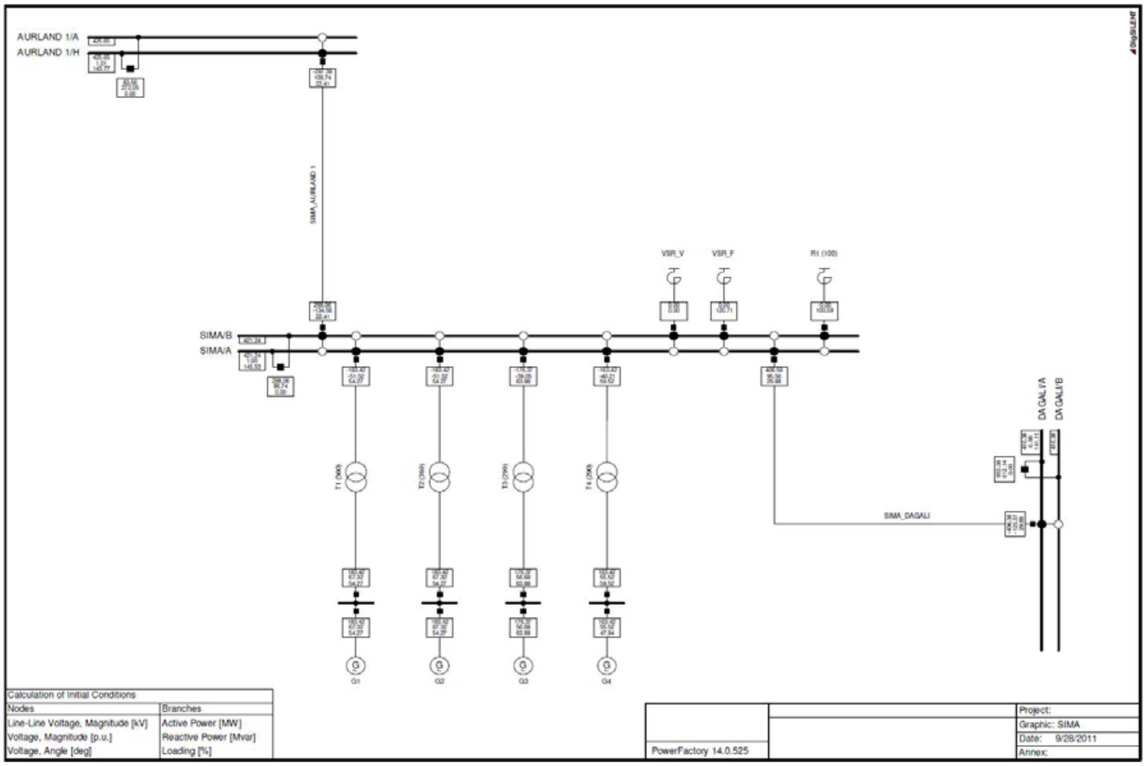


Figure 8-3: The single line diagram model of Sima substation simulated in DIgSILENT

Figure 8-4 illustrates the voltage behaviour at Sima substation during the load scenario. As seen, initially the voltage is close to 1 per unit; after 50 second because of load shedding the voltage goes high immediately and consequently the VSR starts to step down the voltage when it exceeds the voltage dead-band. The tap changing process stops when the voltage goes back within the dead-band. However after few seconds (170 seconds from the beginning) the voltage drops down suddenly due to 55% load increase. At this time, the tap-changer starts to operate in opposite direction to decrease the reactive power consumption of VSR and increase the voltage level again. Similarly it stops when the voltage goes within the dead-band.

Figure 8-5 shows the voltage steps in larger scale, while the VSR is tapping to step down the voltage. The sample step which is specified with a circle in this figure is magnified in Figure 8-6.

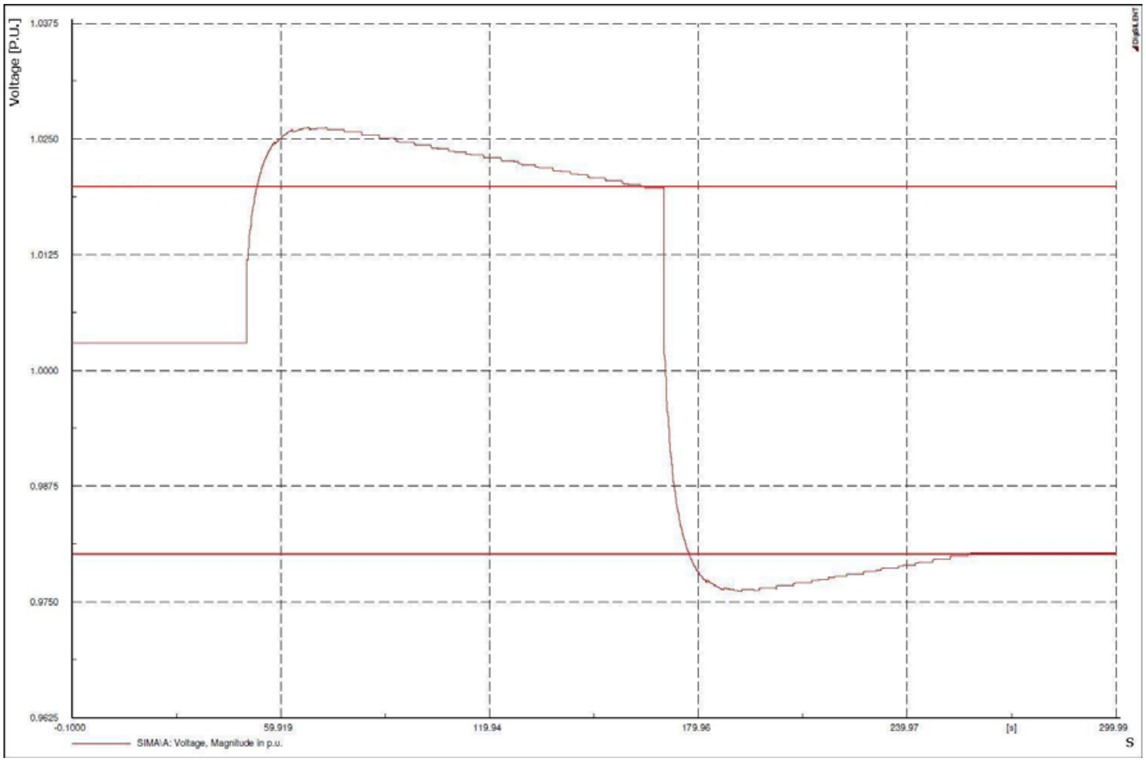


Figure 8-4: The voltage behaviour at Sima substation during simulated load scenario in DIgSILENT

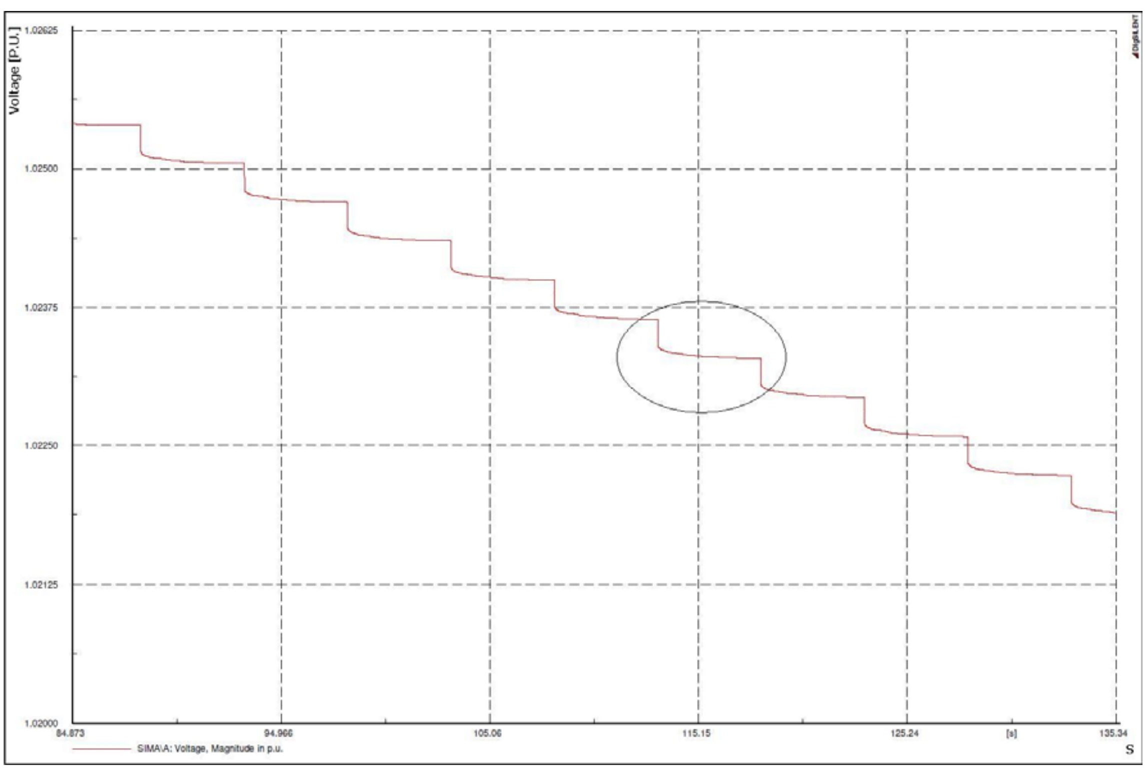


Figure 8-5: The voltage behaviour at Sima substation during simulated load scenario in larger scale

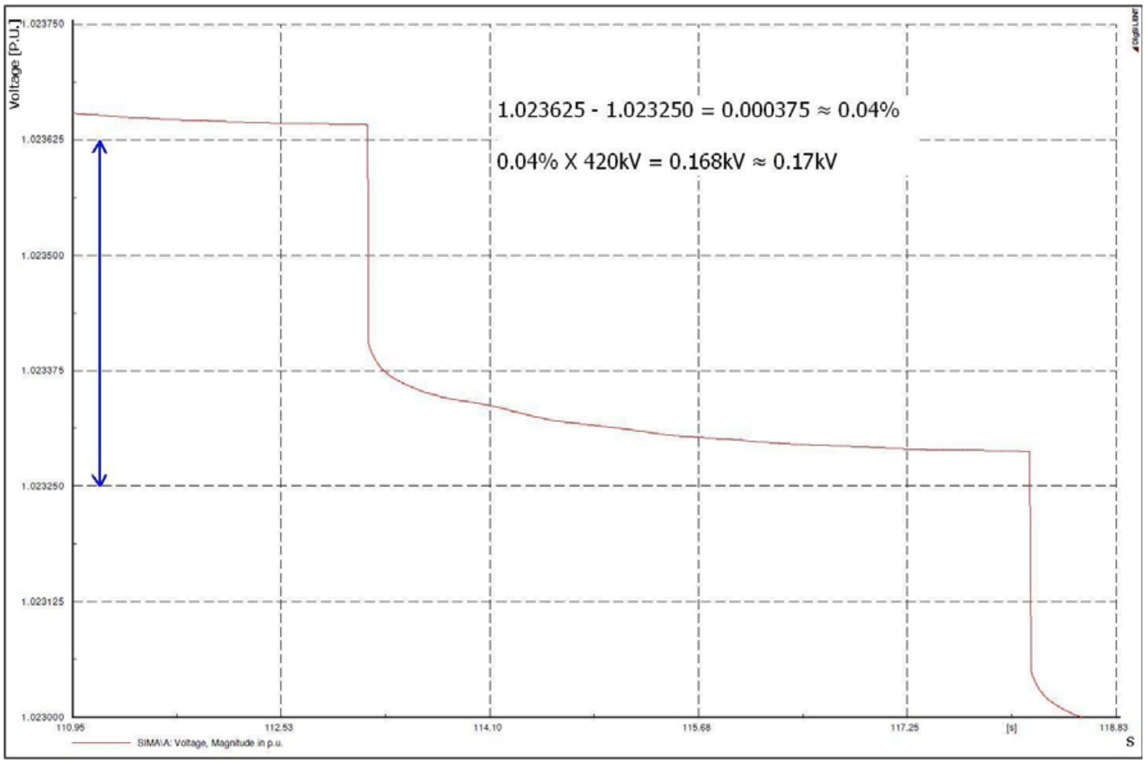


Figure 8-6: A close look at one voltage step and estimation of voltage step size

As seen in Figure 8-6, this single voltage step size is approximately 0.04% of the reference voltage which is a small voltage variation equal to about 0.17kV.

To conclude, by using a VSR in the network, a very fine and smooth voltage regulation is achieved and there is no voltage spike as expected. However as seen in Figure 8-6, the voltage step sizes are so small which in practice could be a source of problem to control this process. As a result, an impression of how small these voltage steps could be in practice is obtained by the simulations in DIgSILENT. Following, the work continues in MATLAB to investigate possible control strategy of tap-change Variable Shunt Reactors.

8.2.3. Modelling the VSR in MATLAB

In order to simplify simulation and shorten computing time, all the calculations and modelling has been done in single-phase mode and the phasor-mode simulation has been used. It should be noted that the voltage control is a slow process with a response time in the order of seconds. Therefore there is no problem to use phasor-mode based simulation and modelling.

One of the very challenging parts of the work is to design a proper and accurate model for VSR with tap-change control system, since there is no available model for this type of reactor in MATLAB. For this reason, it is necessary to collect required data from Statnett (Norway's Transmission Grid Owner and Operator) and also ABB Transformers AB, Ludvika Test Report Sheets.

The VSR which is intended to be modelled is a 420kV, 120-200MVAr Variable Shunt Reactor which is the world's largest VSR at this time. Figure 8-7 shows this ABB Variable Shunt Reactor.

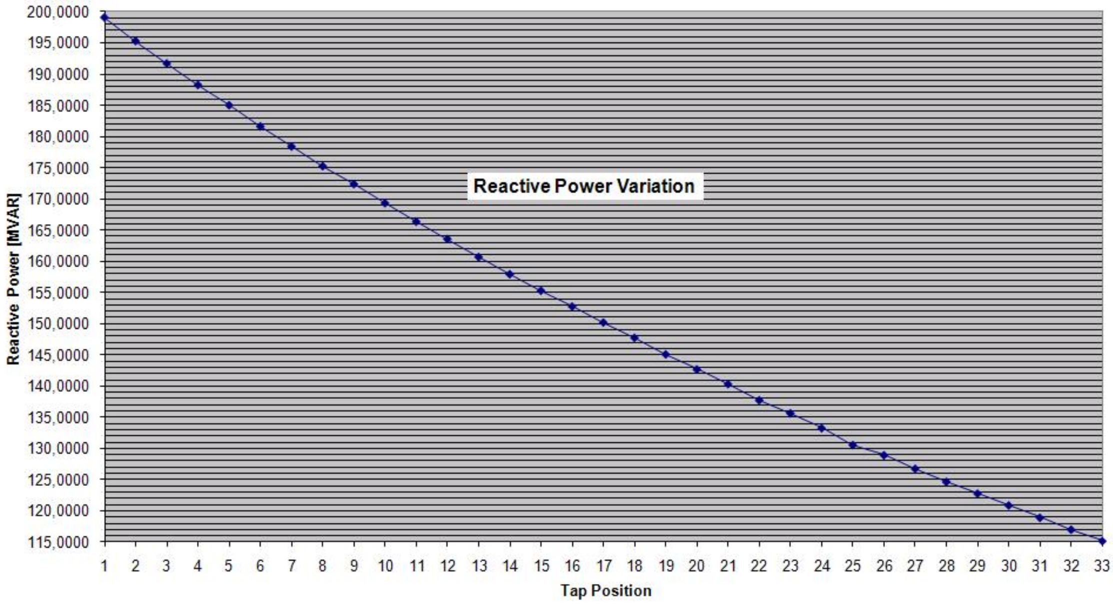
Figure 8-7: The 420kV, 120-200MVAr ABB Variable Shunt Reactor

This VSR has 33 different reactance steps which correspond to different reactive power consumption levels. Each tap position corresponds with a certain reactance [X] and resistance [R]. As the tap steps increase, the corresponding impedances [X,R] decrease, and because of the fixed 420 kV line voltage, the current [A] will increase and consequently the reactive power will increase (the losses will also increase). It should be mentioned that for this particular reactor, the Tap-changing order is in opposite direction, i.e. it starts from tap position 33 (Lowest amount of reactive power consumption) and ends up with tap position 1 (highest amount of reactive power consumption). Table 8-1 shows how these different parameters change with tap position [14].

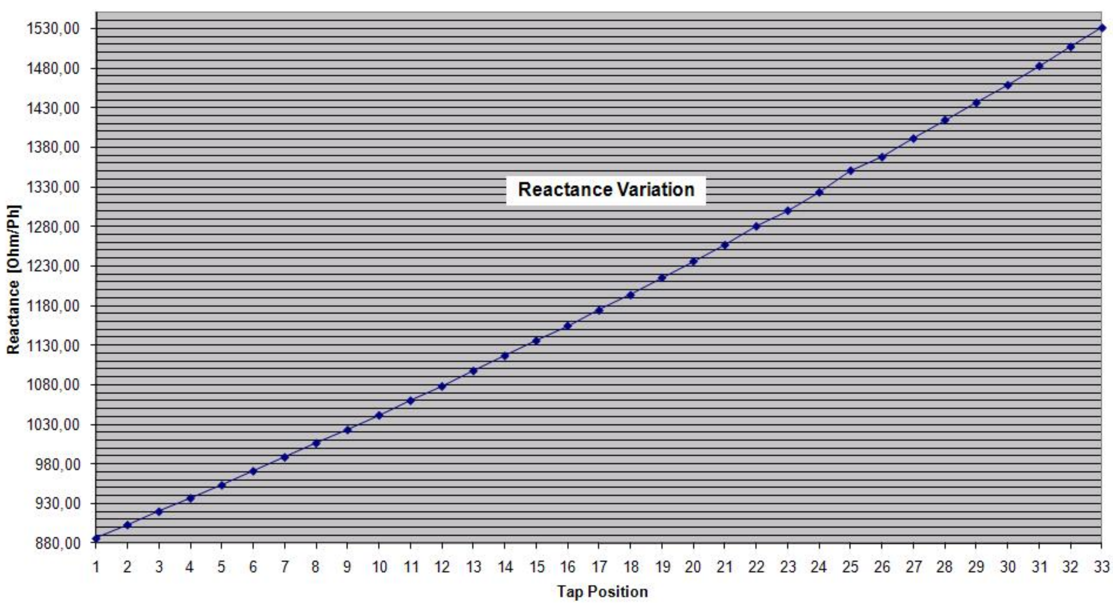
Table 8-1: Different parameters variation corresponding with tap position

Tap Position	X [ohm/ph]	R_{Cu} [ohm/ph]	Voltage [V/ph]	Reactive Power [MVAR]	Current [A]
1	886,20	1,28	242 487,11	199,0517	273,63
2	903,30	1,27	242 487,11	195,2836	268,45
3	920,20	1,26	242 487,11	191,6971	263,52
4	937,10	1,24	242 487,11	188,2400	258,76
5	953,50	1,23	242 487,11	185,0023	254,31
6	971,30	1,21	242 487,11	181,6120	249,65
7	988,80	1,20	242 487,11	178,3978	245,23
8	1 006,60	1,19	242 487,11	175,2432	240,90
9	1 023,30	1,17	242 487,11	172,3832	236,97
10	1 041,80	1,16	242 487,11	169,3221	232,76
11	1 060,30	1,14	242 487,11	166,3678	228,70
12	1 078,30	1,13	242 487,11	163,5907	224,88
13	1 097,70	1,11	242 487,11	160,6995	220,90
14	1 116,80	1,10	242 487,11	157,9511	217,13
15	1 135,80	1,09	242 487,11	155,3089	213,49
16	1 154,70	1,07	242 487,11	152,7668	210,00
17	1 174,30	1,05	242 487,11	150,2170	206,49
18	1 193,70	1,07	242 487,11	147,7757	203,14
19	1 215,50	1,09	242 487,11	145,1253	199,50
20	1 236,10	1,10	242 487,11	142,7068	196,17
21	1 256,80	1,12	242 487,11	140,3564	192,94
22	1 280,40	1,13	242 487,11	137,7693	189,38
23	1 300,20	1,14	242 487,11	135,6713	186,50
24	1 323,40	1,16	242 487,11	133,2929	183,23
25	1 350,80	1,17	242 487,11	130,5892	179,51
26	1 367,80	1,19	242 487,11	128,9661	177,28
27	1 391,30	1,20	242 487,11	126,7878	174,29
28	1 414,50	1,21	242 487,11	124,7083	171,43
29	1 436,30	1,23	242 487,11	122,8155	168,83
30	1 458,60	1,24	242 487,11	120,9378	166,25
31	1 482,90	1,26	242 487,11	118,9560	163,52
32	1 507,00	1,27	242 487,11	117,0537	160,91
33	1 531,00	1,28	242 487,11	115,2187	158,38

Figure 8-8 shows how the reactive power and reactance of VSR are changing with tap-changing operation. As seen, the reactive power increases with decreasing the tap position number (tapping up), while the equivalent reactance (X) decreases at the same time. Interestingly, both trends are almost linear which makes the modelling process much easier.



(a)



(b)

Figure 8-8: a) Reactive power variation of VSR by changing tap position **b)** Reactance variation by changing tap position

In order to avoid switching effects in simulation, the VSR model in MATLAB is designed as 33 parallel inductive branches which add up together step by step. In other words, each branch has its own switch and with each Raise command, the corresponding switch of next lower tap position will be closed while all the previous switches are still close. In case of Lower command, the procedure is vice versa. Figure 8-9 shows these parallel inductive branches and their corresponding switches.

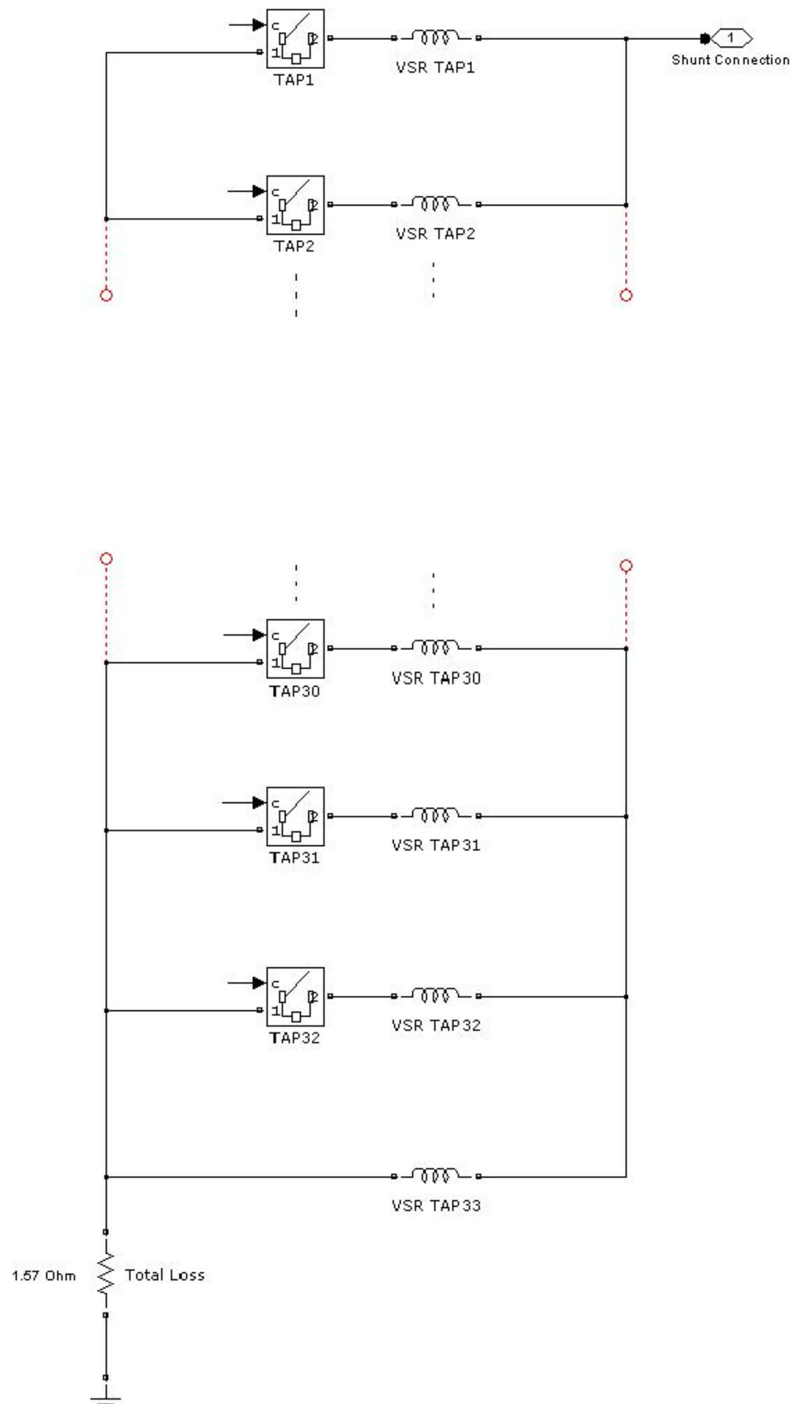


Figure 8-9: VSR parallel inductive branches and corresponding switches

As seen in Figure 8-9, the VSR branch 33 corresponds to tap position 33 and is always connected in order to maintain the continuity of reactive power consumption and preventing transient switching effects. As mentioned before, with each Raise command, the relative switch of next lower branch number will be closed. For example, when the VSR is on tap position 30, the equivalent inductance is equal to the parallel summation of four previous branches i.e. branches 33, 32, 31, and 30. Issuing one another Raise command will lead to parallel addition of branch number 29 to these four parallel branches. Hence, the inductances of all branches in this model are calculated in a way that in each tap position the equivalent inductance of parallel branches is the same as the corresponding inductance (reactance) of that specific tap position according to Table 8-1 and Table 8-2. Table 8-2 indicates the inductance of each individual branch based on the equivalent inductance and reactance of each tap position [14].

In this model, a 1.57 ohms resistance is also considered in grounding path which with good approximation simulates total losses in reactor (see Figure 8-9). As it is described in section 6.2, Fixed Shunt Reactors, this approximation is because the total active losses are small and negligible compare to reactive power consumption (see Table 8-2).

As explained before, with each Raise/Lower command, the On/Off control of these switches must be done in a proper way. To explain more, according to the voltage level at the busbar where the voltage is intended to be controlled, three different conditions are likely to happen;

- The voltage at the busbar is higher than the voltage regulating range (here, 1p.u. ±2%)
- The voltage at the busbar is lower than the voltage regulating range (here, 1p.u. ±2%)
- The voltage at the busbar is within the voltage regulating range (here, 1p.u. ±2%)

Correspondingly, the appropriate actions that should be taken are as follows:

- Raise command
- Lower command
- No action

In fact, each Raise command would decrease the voltage by increasing reactive power consumption; and Lower command would increase the voltage by decreasing reactive power consumption. Figure 8-10, shows the logic for issuing Raise/Lower command. As seen, it is implemented by comparing the measured busbar voltage with the reference voltage in a desired range (±2%) and finally a bitwise (1 or 0) Raise/Lower command is issued. Since in both Lower command case and No action case, the issued Raise/Lower command is 0, another signal is needed to avoid unwanted Lower commands. As shown in Figure 8-10, the STOP command will be 0 if the measured voltage is not within the desired voltage range, otherwise it becomes 1 and all the switch positions will be frozen in a same situation as they are, i.e. the tapping up/down process will be stopped.

Table 8-2: Inductance of each individual branch (L_{br}) based on the equivalent inductance of each tap position (L_{eq})

Tap Position	Reactive Power [MVAR]	Total Loss [KW]	Loss/Q [%]	X [ohm/ph]	Voltage [V/ph]	Q STEPS [MVAR]	L_{br} [H]	L_{eq} [H]
1	199,0517	384,48	0,19	886,20	242 487,11	3,768142	149,0389	2,8214
2	195,2836	365,94	0,19	903,30	242 487,11	3,586473	156,5884	2,8758
3	191,6971	348,79	0,18	920,20	242 487,11	3,457115	162,4477	2,9296
4	188,2400	332,46	0,18	937,10	242 487,11	3,237671	173,4582	2,9834
5	185,0023	317,76	0,17	953,50	242 487,11	3,390326	165,6480	3,0357
6	181,6120	302,61	0,17	971,30	242 487,11	3,214193	174,7253	3,0923
7	178,3978	288,69	0,16	988,80	242 487,11	3,154645	178,0235	3,1480
8	175,2432	275,18	0,16	1 006,60	242 487,11	2,859911	196,3702	3,2047
9	172,3832	263,18	0,15	1 023,30	242 487,11	3,061121	183,4627	3,2579
10	169,3221	250,75	0,15	1 041,80	242 487,11	2,954302	190,0962	3,3168
11	166,3678	239,31	0,14	1 060,30	242 487,11	2,777157	202,2218	3,3757
12	163,5907	228,36	0,14	1 078,30	242 487,11	2,891179	194,2467	3,4330
13	160,6995	217,62	0,14	1 097,70	242 487,11	2,748343	204,3421	3,4947
14	157,9511	207,57	0,13	1 116,80	242 487,11	2,642245	212,5474	3,5556
15	155,3089	198,14	0,13	1 135,80	242 487,11	2,542070	220,9232	3,6160
16	152,7668	189,15	0,12	1 154,70	242 487,11	2,549791	220,2542	3,6762
17	150,2170	179,87	0,12	1 174,30	242 487,11	2,441326	230,0407	3,7386
18	147,7757	177,01	0,12	1 193,70	242 487,11	2,650357	211,8974	3,8004
19	145,1253	173,01	0,12	1 215,50	242 487,11	2,418559	232,2060	3,8698
20	142,7068	169,42	0,12	1 236,10	242 487,11	2,350437	238,9359	3,9354
21	140,3564	166,16	0,12	1 256,80	242 487,11	2,587010	217,0860	4,0013
22	137,7693	162,03	0,12	1 280,40	242 487,11	2,098010	267,6842	4,0764
23	135,6713	159,14	0,12	1 300,20	242 487,11	2,378399	236,1268	4,1394
24	133,2929	155,46	0,12	1 323,40	242 487,11	2,703749	207,7130	4,2133
25	130,5892	151,06	0,12	1 350,80	242 487,11	1,623056	346,0165	4,3005
26	128,9661	149,04	0,12	1 367,80	242 487,11	2,178324	257,8146	4,3547
27	126,7878	145,83	0,12	1 391,30	242 487,11	2,079516	270,0647	4,4295
28	124,7083	142,66	0,11	1 414,50	242 487,11	1,892808	296,7042	4,5033
29	122,8155	139,99	0,11	1 436,30	242 487,11	1,877680	299,0946	4,5727
30	120,9378	137,26	0,11	1 458,60	242 487,11	1,981784	283,3830	4,6437
31	118,9560	134,34	0,11	1 482,90	242 487,11	1,902348	295,2162	4,7211
32	117,0537	131,49	0,11	1 507,00	242 487,11	1,834936	306,0619	4,7978
33	115,2187	128,87	0,11	1 531,00	242 487,11	-	4,8742	4,8742

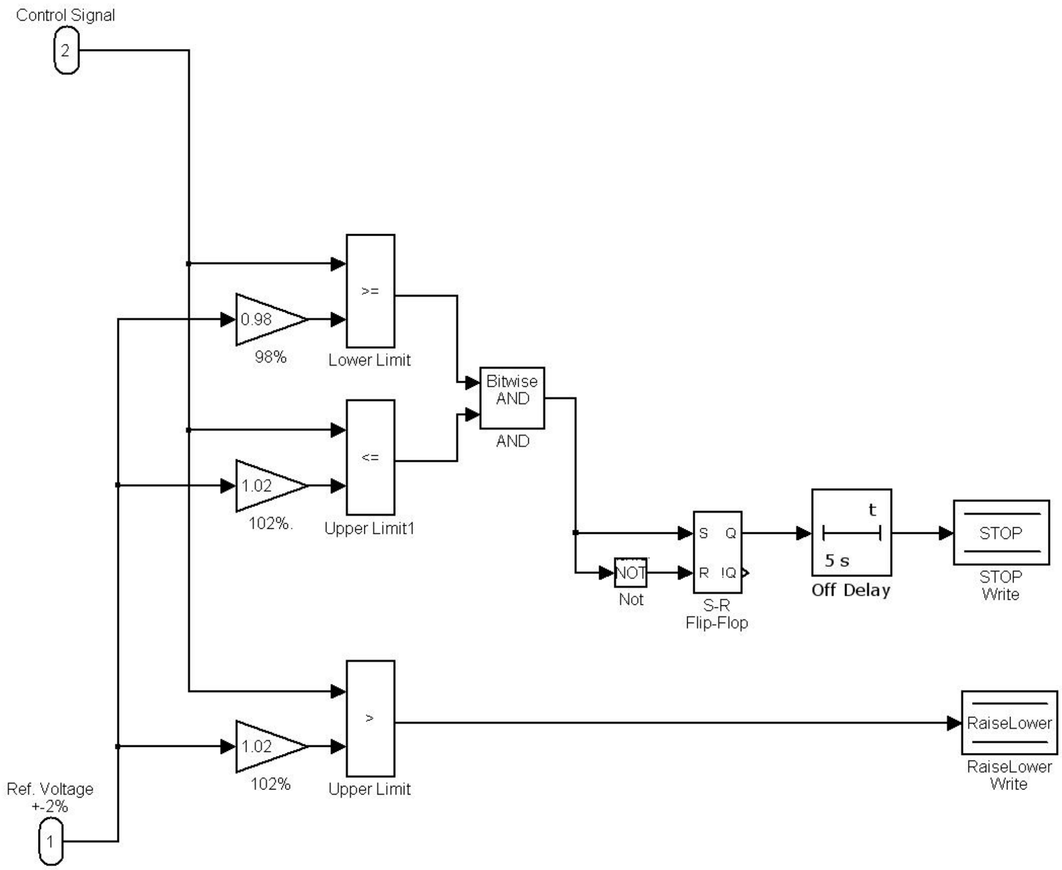


Figure 8-10: Logic for issuing Raise/Lower command

To interpret these commands for all the related switches in order to have proper tap changing, more logics are needed and specific control signal for each switch must be implemented. Figure 8-11, shows the control logic for switching of branch number 30 as an example. As can be seen, the logic is dependent on the present status of the next (lower number) switch as well as the present status of the switch itself which is intended to be controlled. In addition, the status of all the previous (higher number) switches have also been considered. The reason is that, all the switches have such control block and they all receive the Raise/Lower command at the same time, so by monitoring the status of all the previous and next switches the appropriate Close/Open command will be issued in order to have consecutive tap changing. In this control diagram, the Synch. Out signal will be the Synch. In signal for next lower number switch. For example, the Synch. In signal in Figure 8-11, is the Bitwise AND of switch number 32 and the Raise/Lower command. Eventually, if the binary output of Bitwise OR is 1, and there is no STOP command available, then a close command will issue for the controlled switch. As seen, a 5 Seconds time delay has been considered as the time interval between each tap. In practice, this is the required time for switching step reactance as well as the time for stabilizing the voltage.

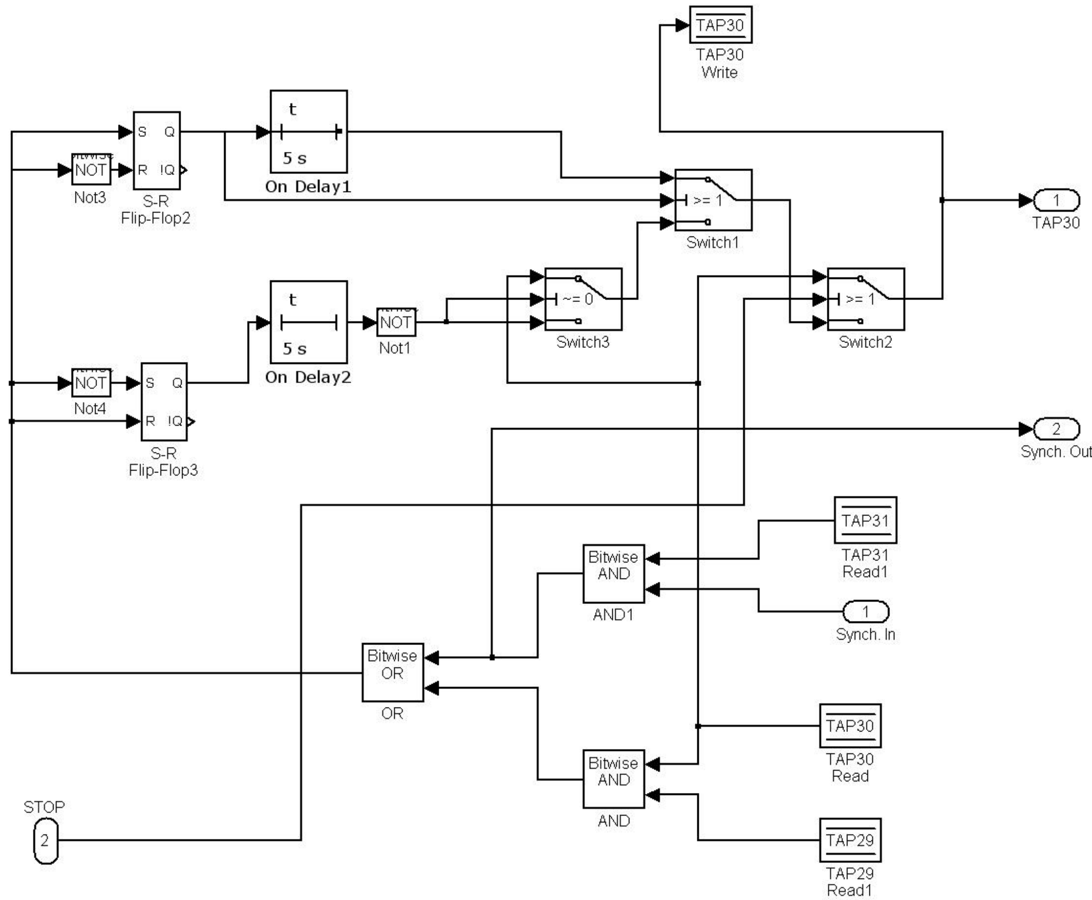


Figure 8-11: Control logic for switch 30 implemented in MATLAB simulation

Figure 8-12, illustrates the complete simulated model for VSR with automatic tap change control. As seen, each switch has its own control block and every block receives the STOP command individually. It can also be seen that the Synch. Out signal of each block is the Synch. In for the next upper block.

Figure 8-13, shows the final designed model for VSR with automatic tap change control system in MATLAB. As seen, two input signals are needed; one is the reference voltage and the other is the Control Signal. The control strategy of the VSR is in fact, the choice of suitable parameters and proper combination of them due to have as precise, robust, and reliable Control Signal as possible. In the following chapters, the choice of this Control Signal is discussed.

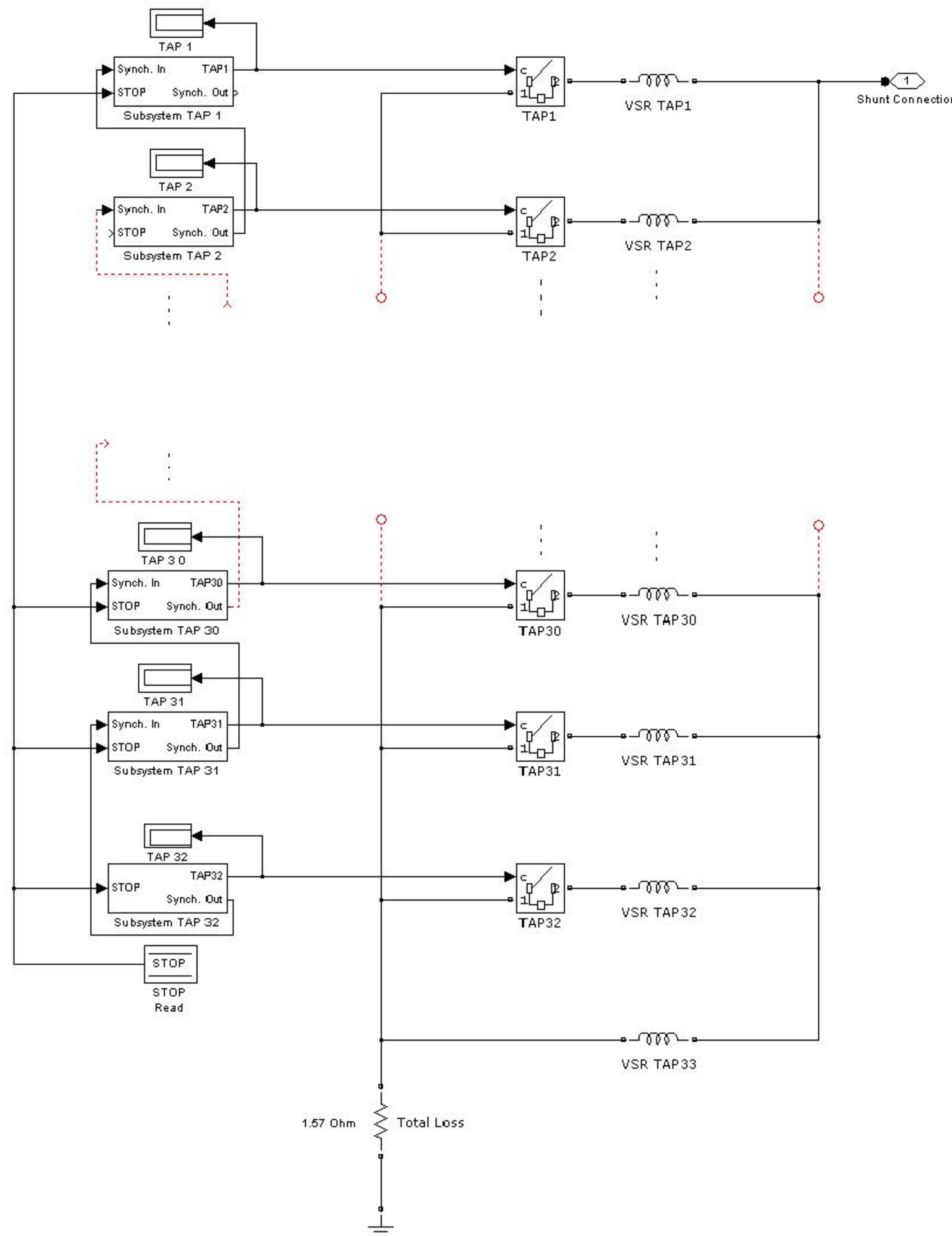


Figure 8-12: VSR parallel inductive branches and corresponding switches with their individual control blocks

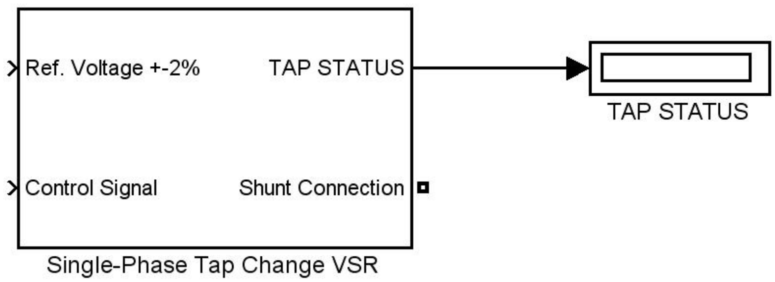


Figure 8-13: The final built model for VSR with automatic tap change in MATLAB

8.2.4. The Choice of Suitable Control Signal

8.2.4.1. Voltage as the Control Signal

The first simple idea to control tap-changing of Variable Shunt Reactor is to use the voltage magnitude at the busbar where the reactor is connected. Therefore, the busbar voltage is used as a feedback to control the reactor. In order to investigate the operation process, problems and results of using this control strategy a simple network has been simulated in MATLAB. Figure 8-14, shows a single phase pi model of a 420kV, 300km transmission line which is connected to a voltage source from one side and connected to a Constant Impedance Load at the other side.

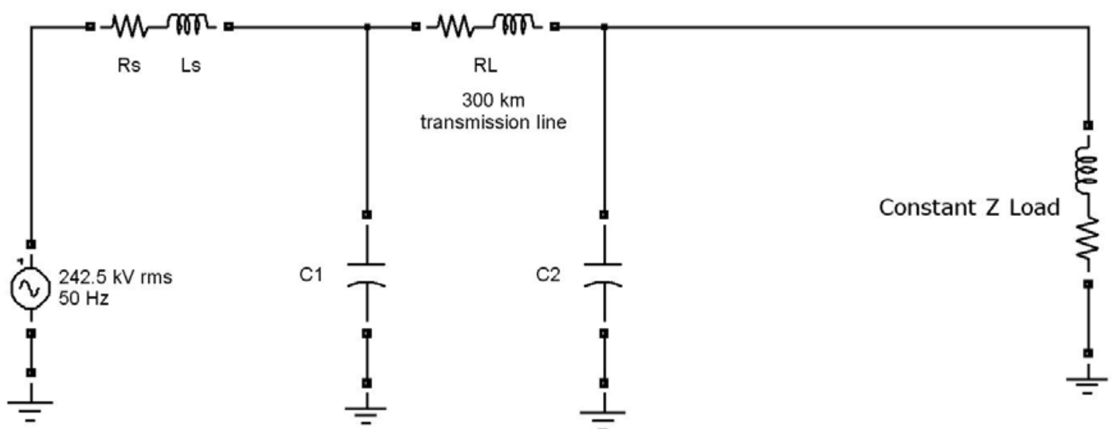


Figure 8-14: The Single Phase pi model of 300 km 420kV transmission line

Table 8-3, indicates source and line parameters of this simple network. These parameters are selected in accordance with Norway's transmission network parameters. According to these parameters, the SIL of this line is about 194MW.

Table 8-3: The parameters of the simple network simulated in MATLAB

Source Parameters		Line Parameters	
V_s	242.5 kV rms/ph	Length	300 km
f_s	50 Hz	R_L	0.02 Ω/ph.km
R_s	2.645 Ω	X_L	0.31 Ω/ph.km
L_s	70.2e-03 H	b	3.37 µs/ph.km

As it is described in section 4, Equivalent Π-Model of a Transmission Line, the capacitances C1 and C2 are equal to:

8-1 $$\boldsymbol{C1} = \boldsymbol{C2} = \frac{b}{2} \times \frac{1}{2\pi f}$$

Now it is the time to connect the VSR at the end of this line and try to control the load voltage in different load conditions. At the same time, the other network parameters are supervised so they can be used later to develop new control strategies. As illustrated in Figure 8-15, the voltage at the load busbar is measured and used as the Control Signal, and also the ideal single phase voltage is used as the Reference Voltage.

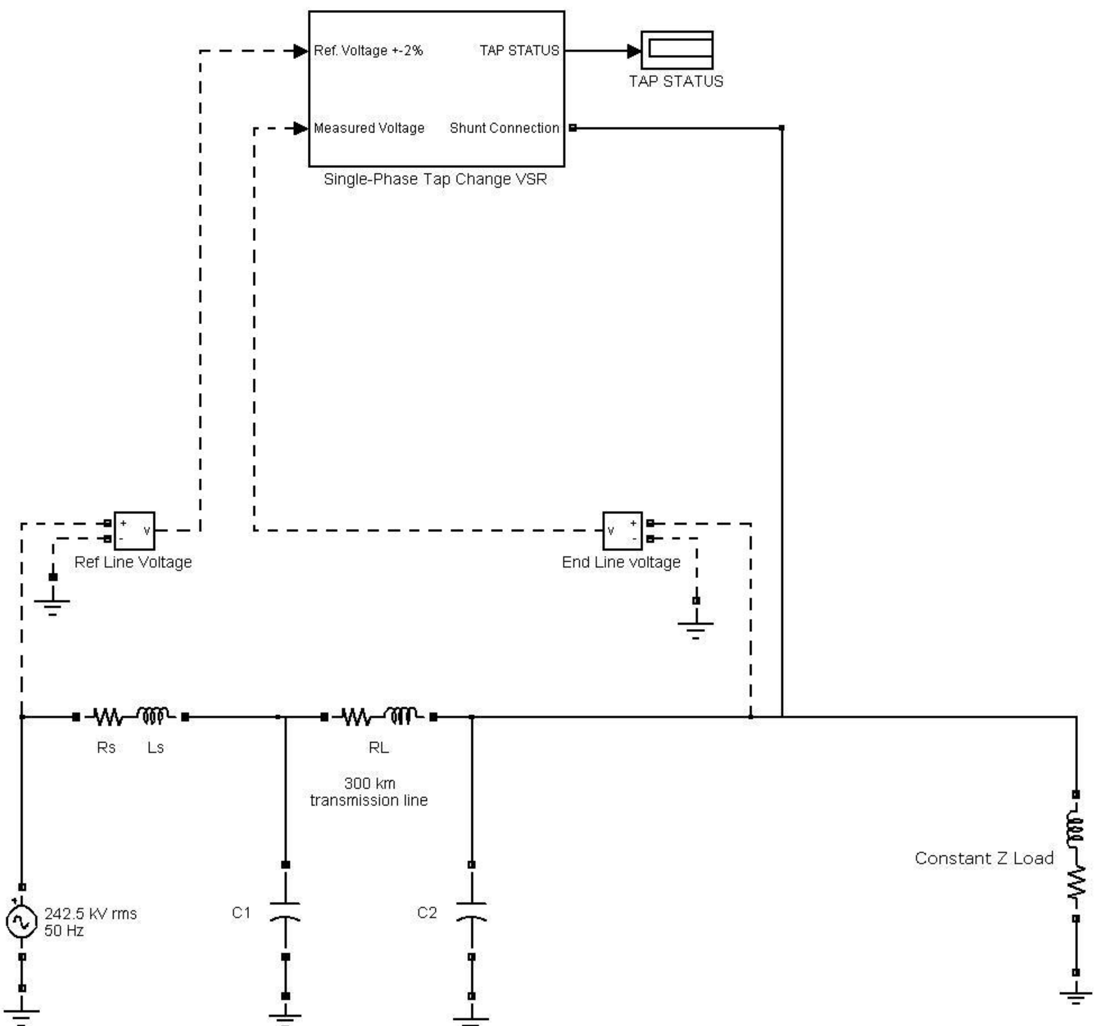


Figure 8-15: The VSR connected to the network using the voltage as control signal

Here, in order to simplify the analysis of VSR tap change process, the Constant Impedance Load has been selected. To have the Power Factor almost equal to 0.9 it is enough to set the Reactive Load about the half value of the Active Load.

8-2 $$\tan \emptyset = \frac{Q}{P} = \frac{1}{2}$$

8-3 $$PF = \cos \emptyset = 0.895$$

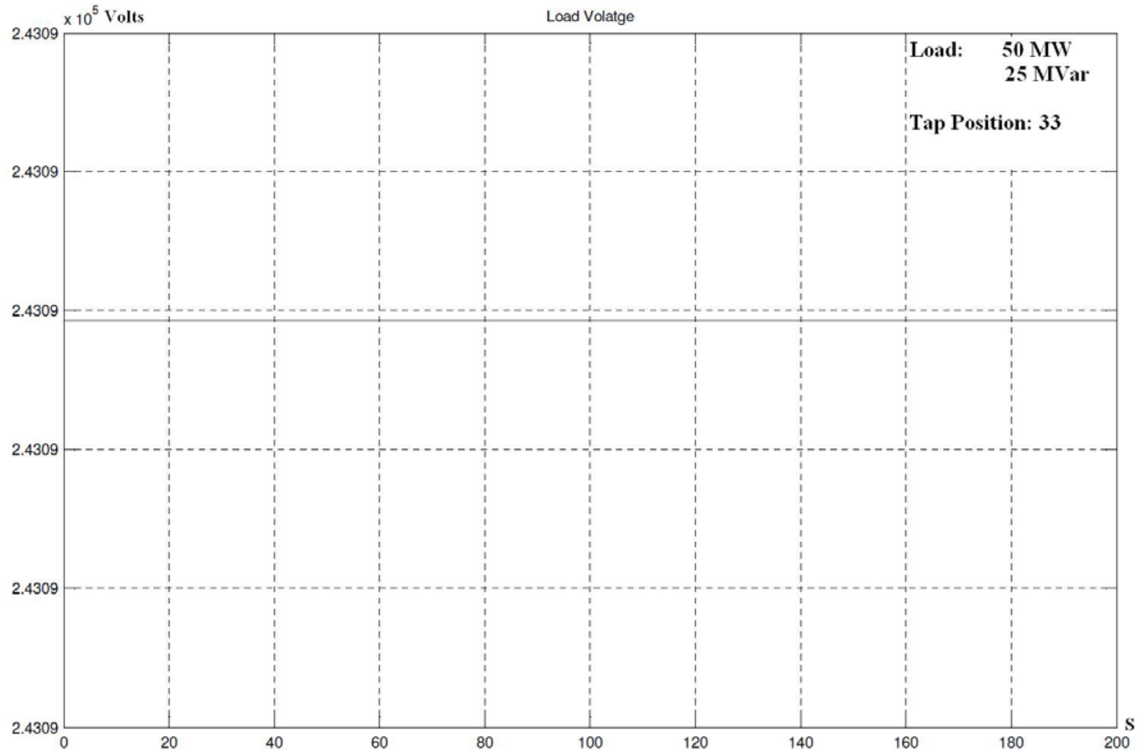
The different Load Levels for this experimental study are as follows:

- 50 MW - 25 MVAr
- 45 MW - 22.5 MVAr
- 40 MW - 20 MVAr
- 30 MW - 15 MVAr
- 20 MW - 10 MVAr
- 10 MW - 5 MVAr
- 1 MW - 0.5 MVAr

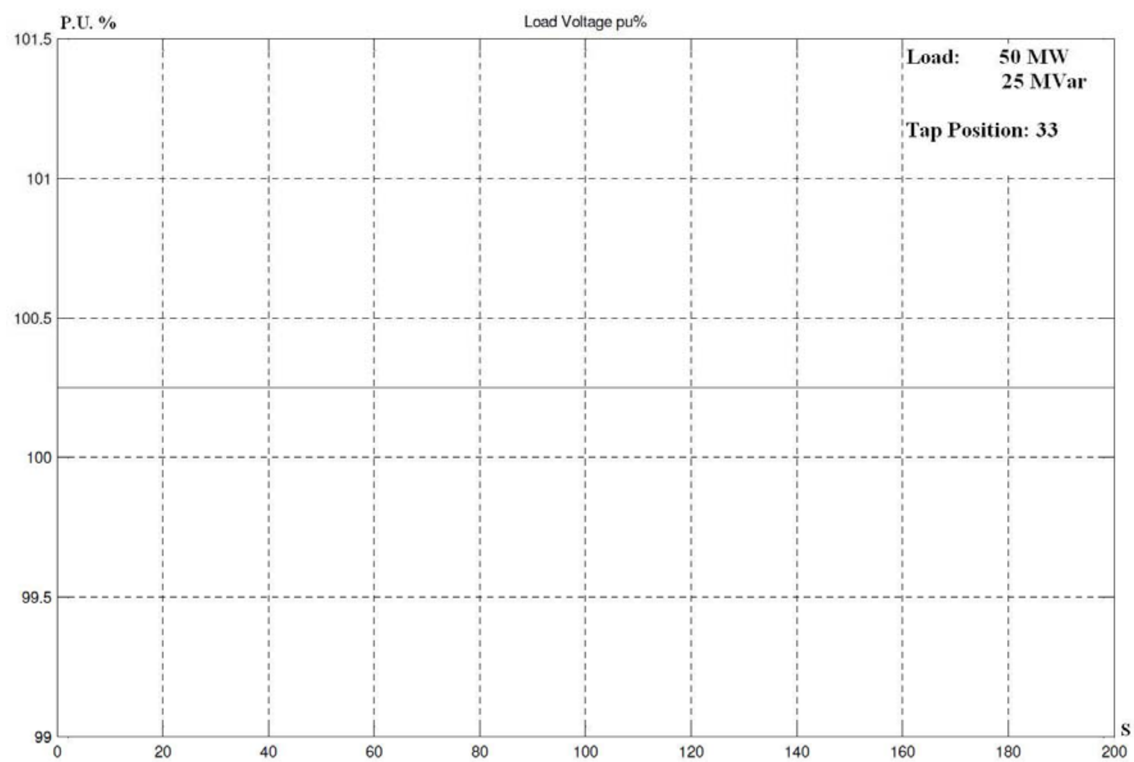
The simulation is run during 200 Seconds for each load level, and the resulting voltage at the load busbar is analyzed.

Figure 8-16-a, shows the voltage at 50MW - 25MVAr Load level. As seen, the voltage value remains constant at 243.09kV and there is no tap changing by the VSR. The reason is that since the VSR voltage regulation is set on ±2%, for the voltage magnitudes within this range the VSR does not change its tap position. The per unit percent value of voltage has been shown in Figure 8-16-b which is 100.25% of reference voltage. To explain more, as the load is slightly lower than SIL of the line, the capacitive effect of the line is not large enough to highly increase the voltage at the end of the line. Next, the load level has been decreased to have higher voltages at the end of the line.

As shown in Figure 8-17 and Figure 8-18, the voltage is still within the ±2% range and the VSR does not have any reaction. At the 45MW - 22.5MVAr Load level, the voltage is 244.65kV equal to 100.9% of reference voltage (Figure 8-17) and at the 40MW - 20MVAr Load level; the voltage is 246.21kV equal to 101.55% of reference voltage (Figure 8-18).

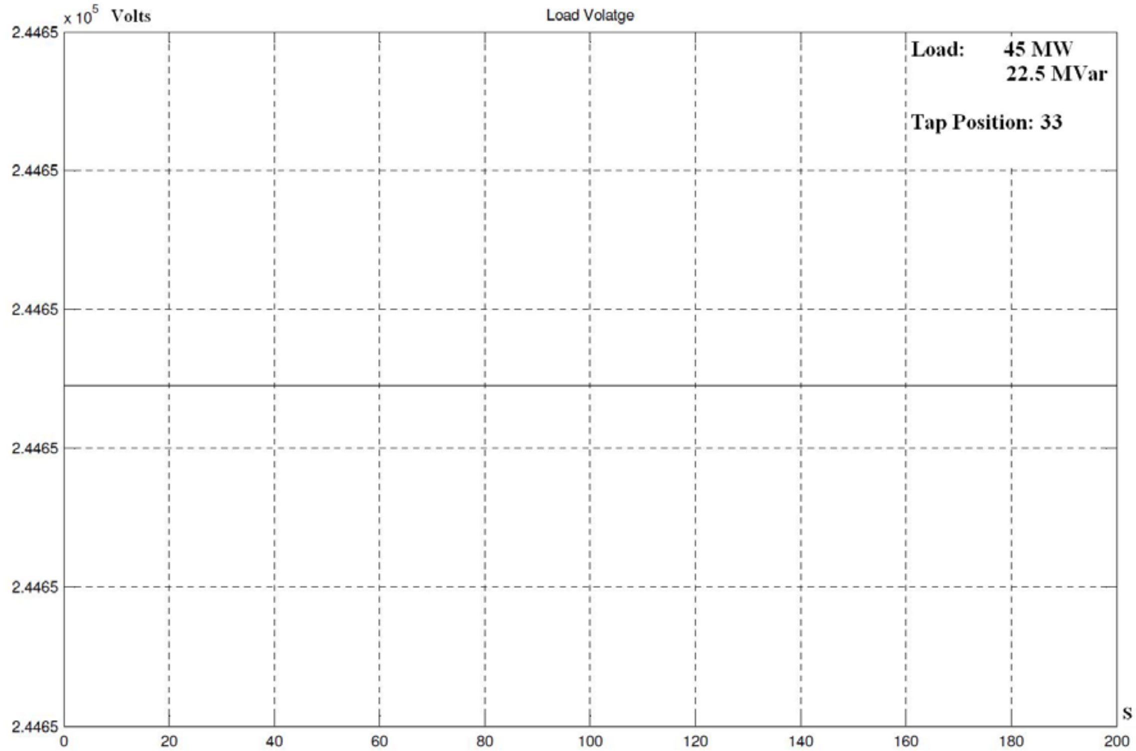


(a)

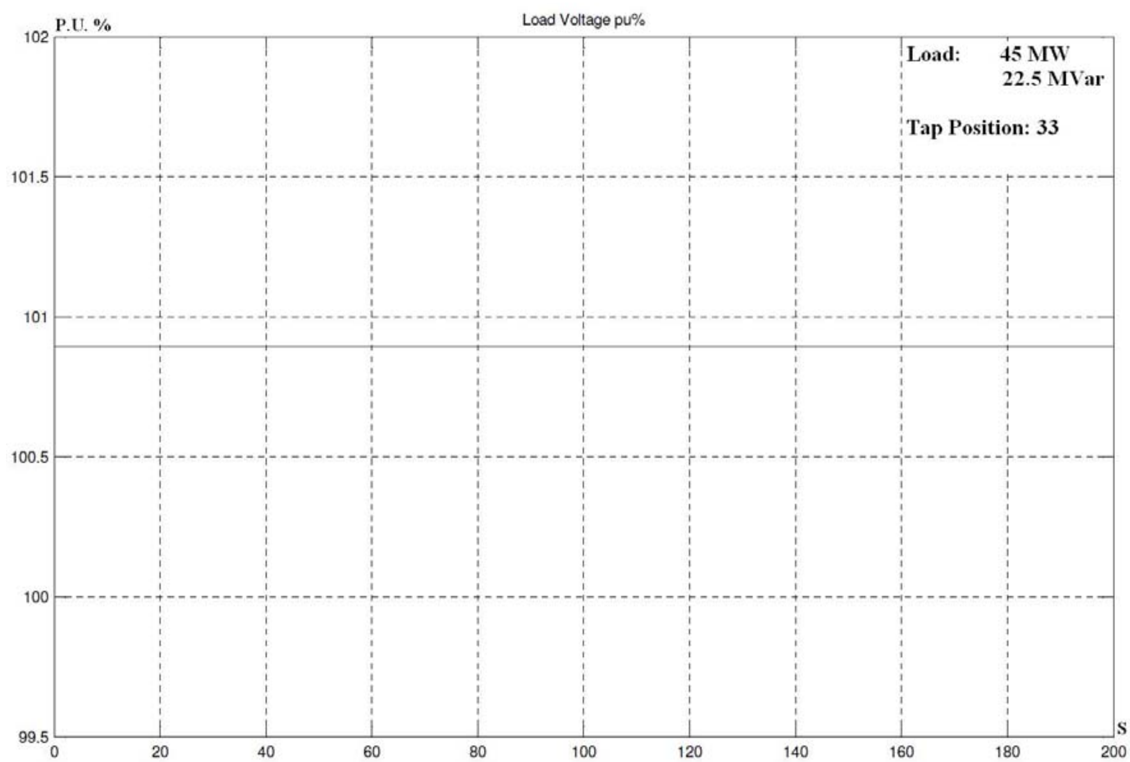


(b)

Figure 8-16: a) The actual voltage magnitude at the load busbar at 50MW-25MVAr **b)** Per unit percent value of voltage

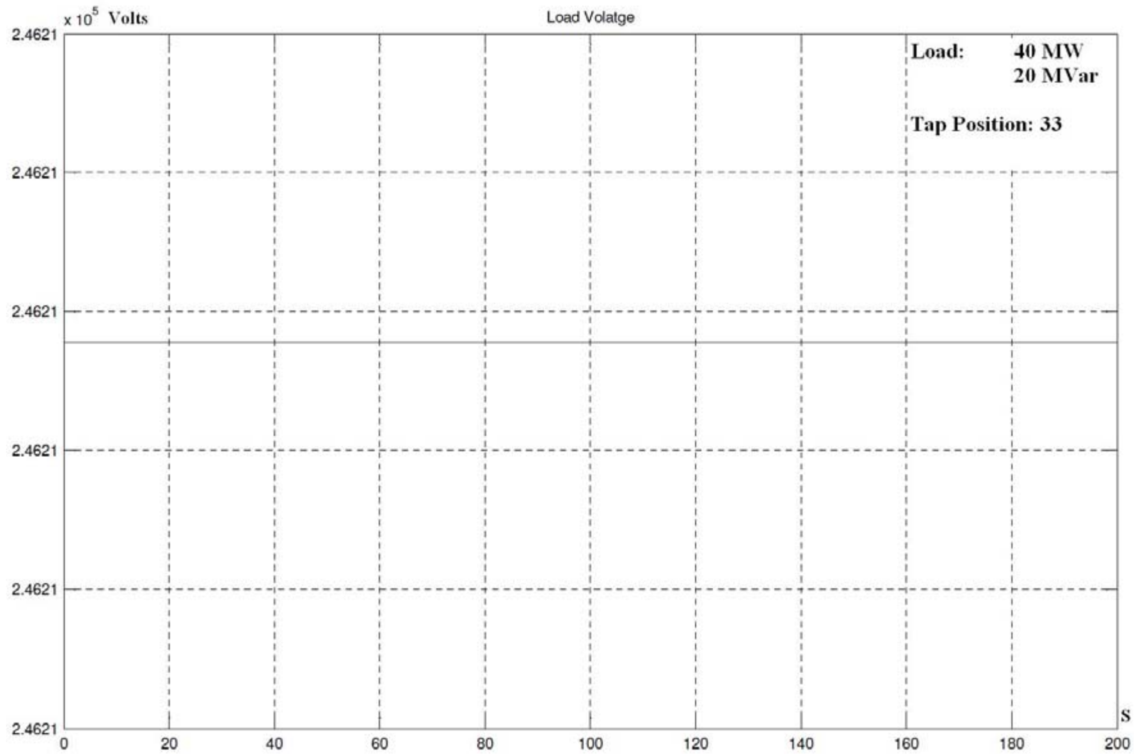


(a)

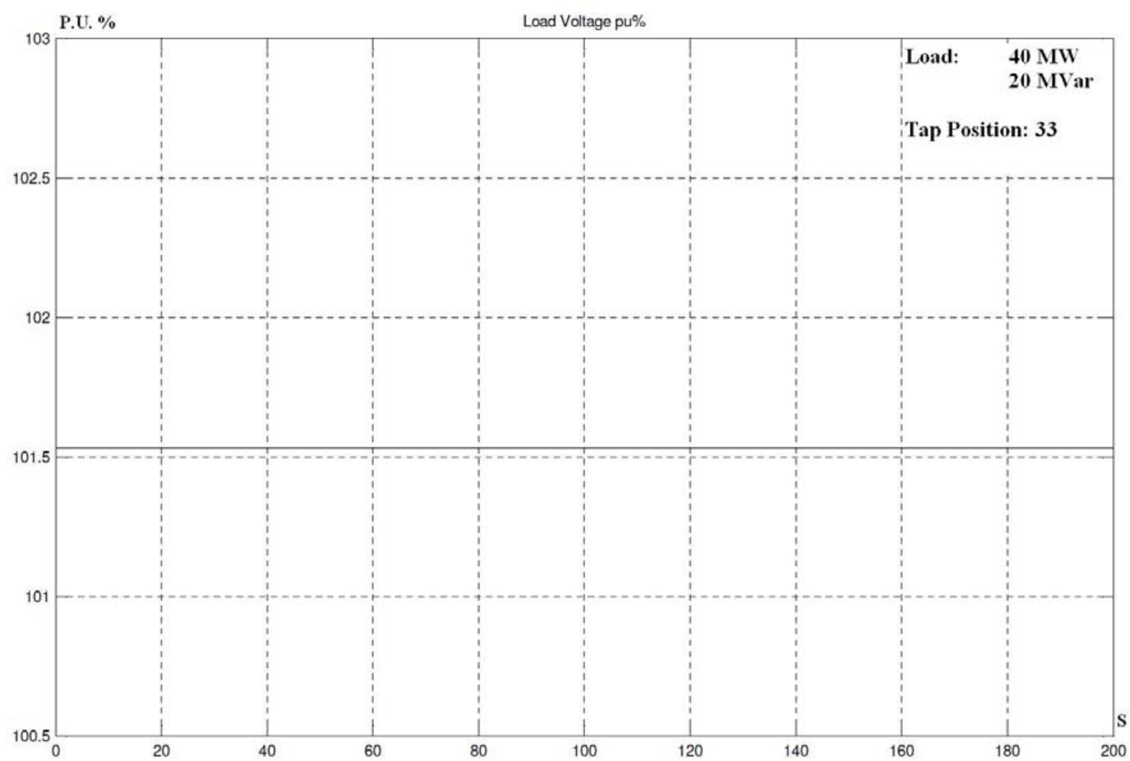


(b)

Figure 8-17: a) The actual voltage magnitude at the load busbar at 45MW-22.5MVAr **b)** Per unit percent value of voltage



(a)



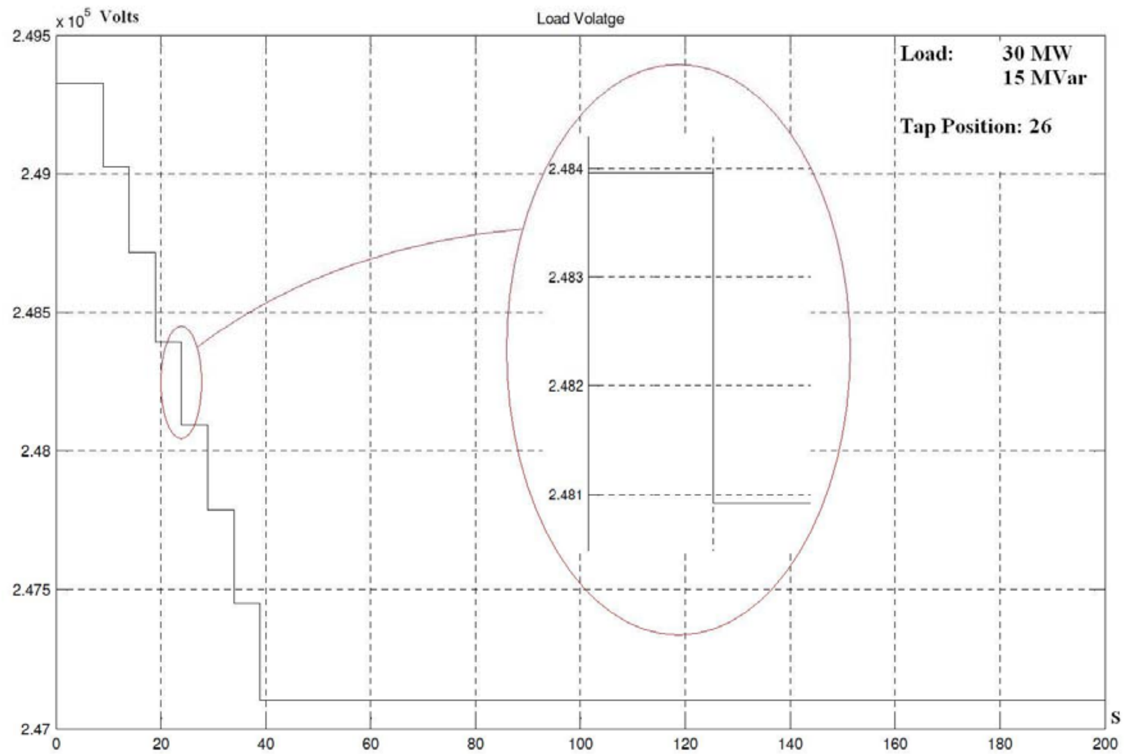
(b)

Figure 8-18: a) The actual voltage magnitude at the load busbar at 45MW-22.5MVAr **b)** Per unit percent value of voltage

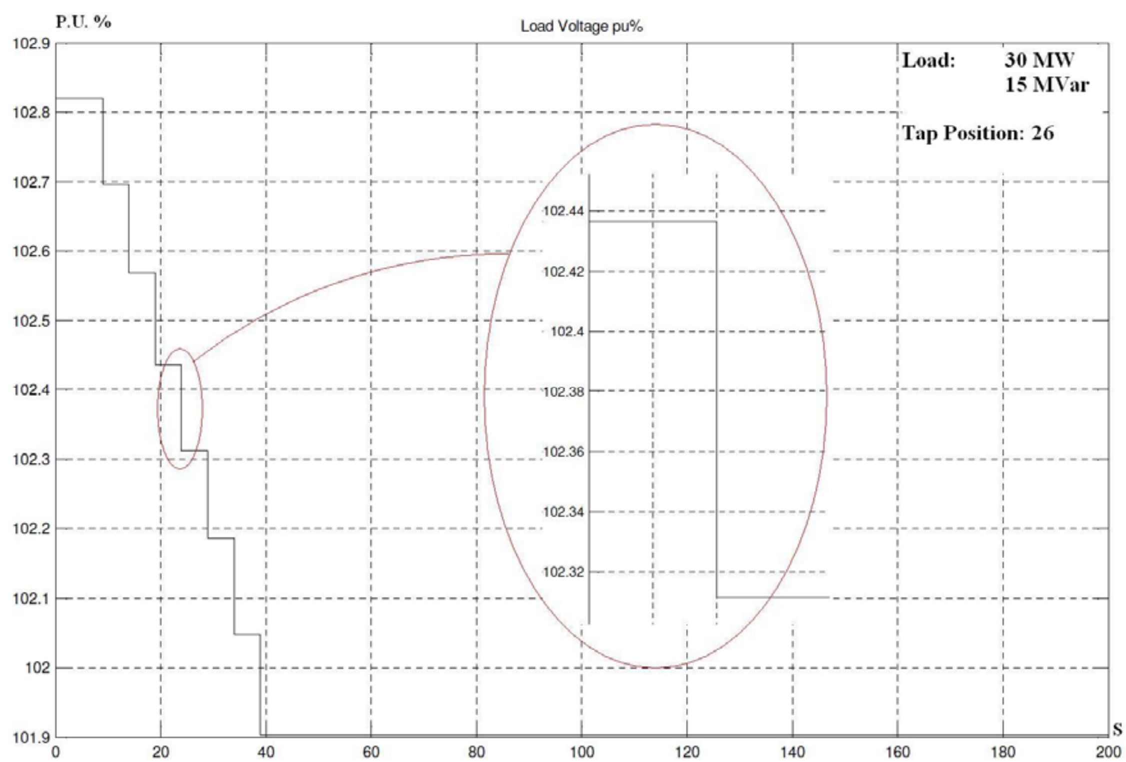
At the Load level 30MW - 15MVAr, initially the voltage becomes 249.3kV which is equal to 102.8% of the reference voltage (Figure 8-19). Consequently, since the voltage has exceeded its upper limit, the VSR starts to operate and steps down the voltage as it is expected. As shown in Figure 8-19, after 7 consecutive taps up, the voltage value becomes 101.9% of the reference voltage and the tap changing process stops as it comes within the range. After that the voltage remains at 247.2kV.

As illustrated in Figure 8-19-a, the voltage change in the fourth step (Tap position 29) is indicated in large scale. As seen, the voltage change in this step (step size) is equal to 0.3kV which is almost 0.12% of the reference voltage (Figure 8-19-b). Alternatively, the average voltage change in each tap can roughly be estimated based on total change in voltage during all 7 taps, which is almost 0.31kV.

At the Load level 20MW - 10MVAr, the initial voltage is 252.5kV which is equal to 104.1% of the reference voltage (Figure 8-20). Consequently, the VSR steps down the voltage and after 15 consecutive taps up, the voltage value becomes 101.9% where the tap changing process stops at 247.1kV. As seen in Figure 8-20-a, the voltage change in the 7th tap (Tap position 26) is magnified which is equal to 0.37kV and according to Figure 8-20-b, this value is 0.15% of the reference voltage. Alternatively, it can roughly be estimated as the average change in voltage during each tap, which is again 0.37kV.

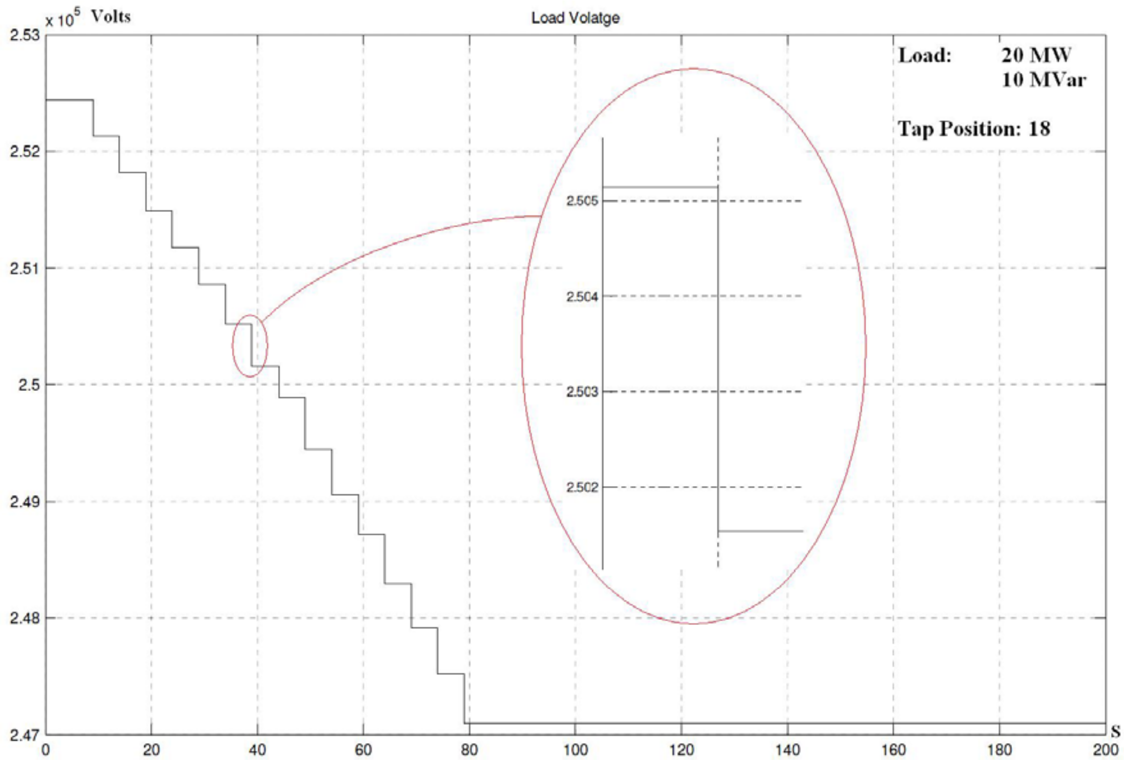


(a)

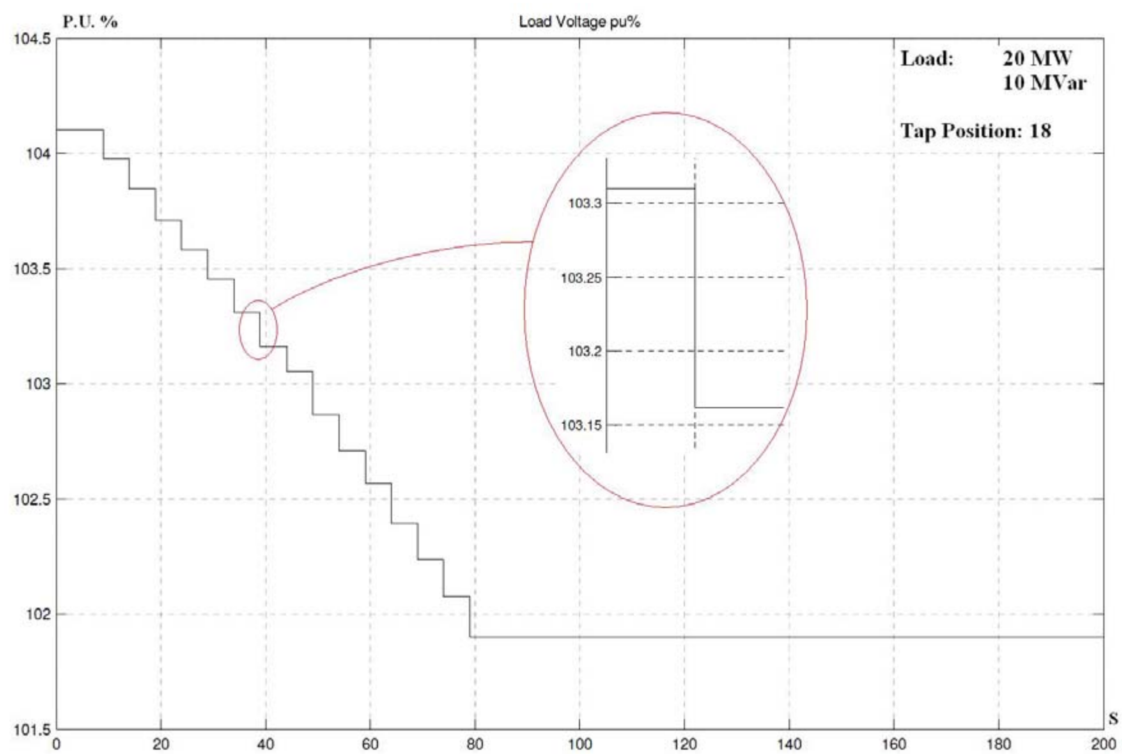


(b)

Figure 8-19: a) The actual voltage magnitude at the load busbar at 30MW-15MVAr **b)** Per unit percent value of voltage



(a)



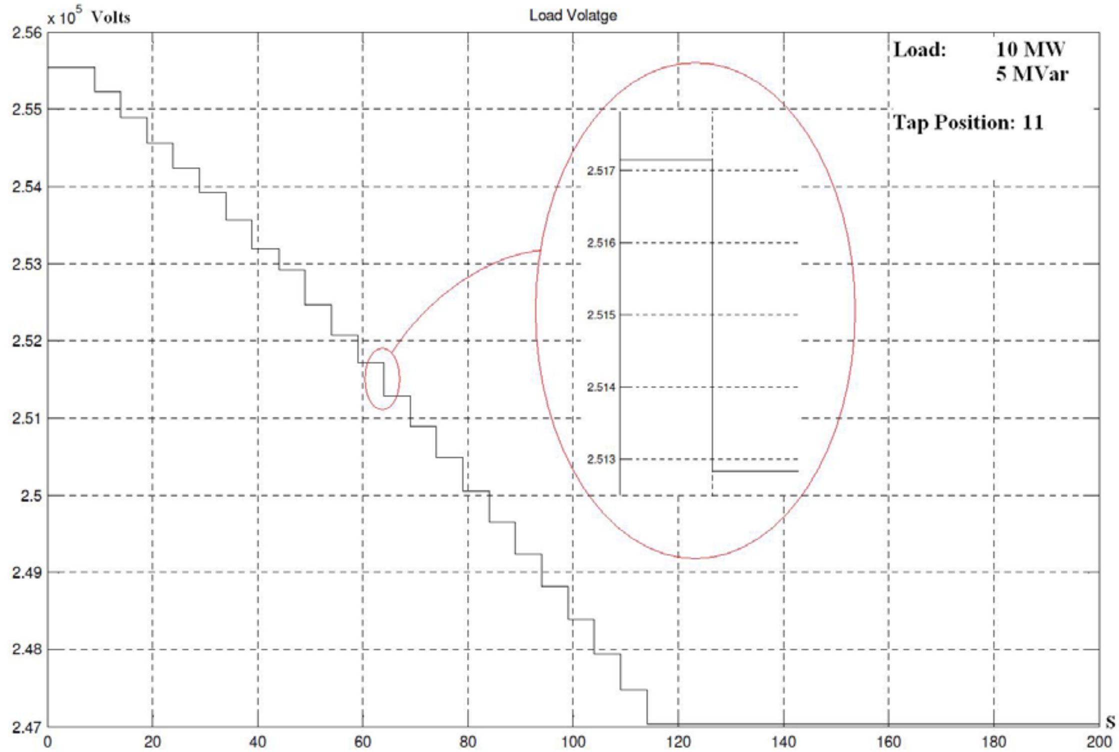
(b)

Figure 8-20: a) The actual voltage magnitude at the load busbar at 20MW-10MVAr **b)** Per unit percent value of voltage

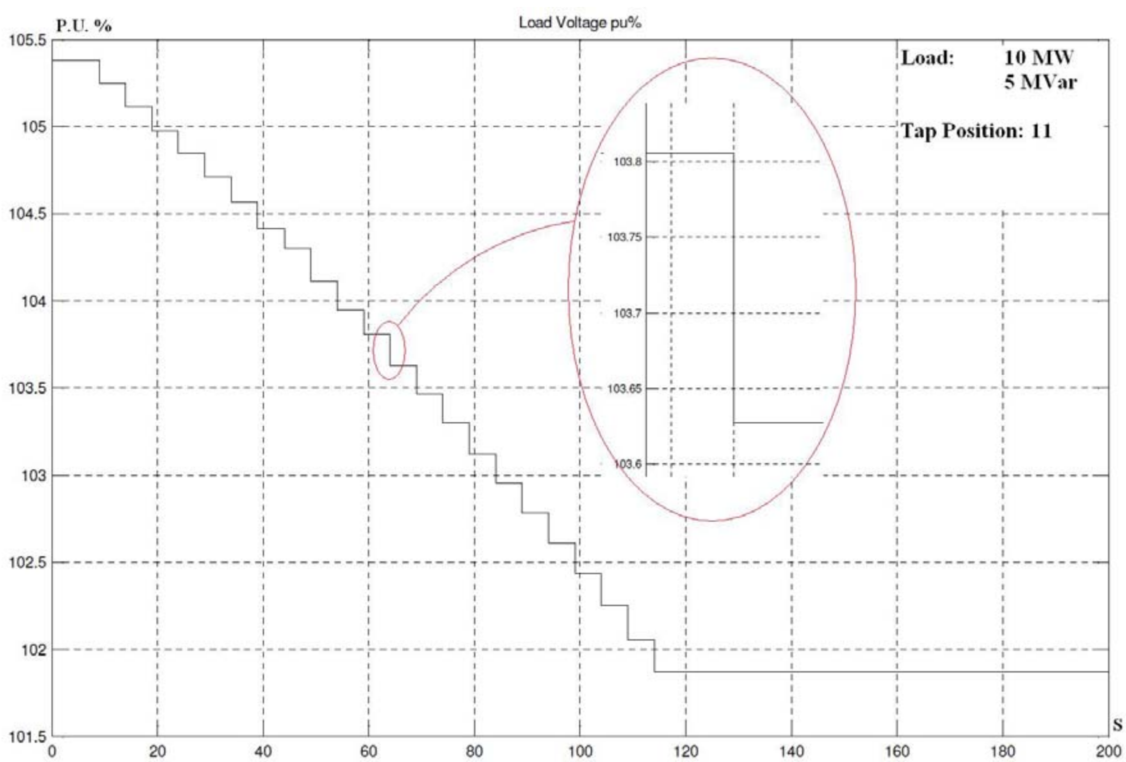
Decreasing the Load level to 10MW - 5MVAr, results in higher voltage at the load busbar (255.5kV) and after 22 consecutive taps up, the VSR steps down the voltage to 247kV (101.9% of reference voltage). Figure 8-21 shows the tap change process in this Load level. As the step number 21 is magnified in Figure 8-21-a, the step size is 0.43kV which is almost equal to 0.17% of reference voltage (Figure 8-21-b). Similarly, considering the average voltage in each tap, the value of 0.39kV is obtained which in this case is slightly different from the actual voltage change in the step number 12 (0.43kV).

Finally, at the Load level 1MW – 0.5MVAr, the initial voltage is 258.4kV which is equal to 106.5% of the reference voltage (Figure 8-22). This is the highest voltage at the load busbar compare to the other Load level conditions, as the capacitive reactive power of the line is increased dramatically. Consequently, the VSR steps down the voltage and after 27 consecutive taps up, the voltage value becomes 101.9% where the tap changing process stops at 247.1kV. As seen in Figure 8-22-a, the voltage change in the tap position 17 is magnified which is equal to 0.4kV and according to Figure 8-22-b, this value is approximately 0.17% of the reference voltage. Alternatively, it can roughly be estimated as the average change in voltage during each tap, which is 0.42kV.

By this time, the VSR has been tested for different low load conditions and has successfully lowered the voltage with proper tapping up. However, it still has not been tested for high load conditions, in the case that is needed to tap down again. For this reason, a voltage drop scenario is simulated in MATLAB to make sure that the VSR is working properly.

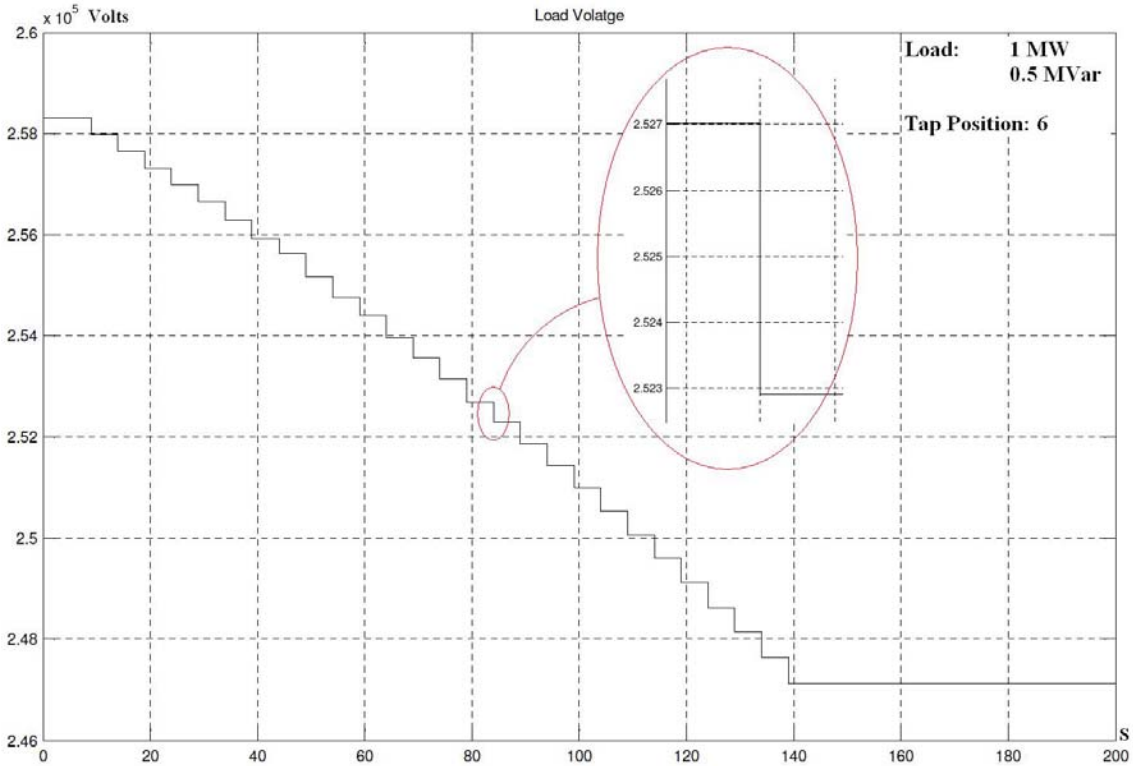


(a)

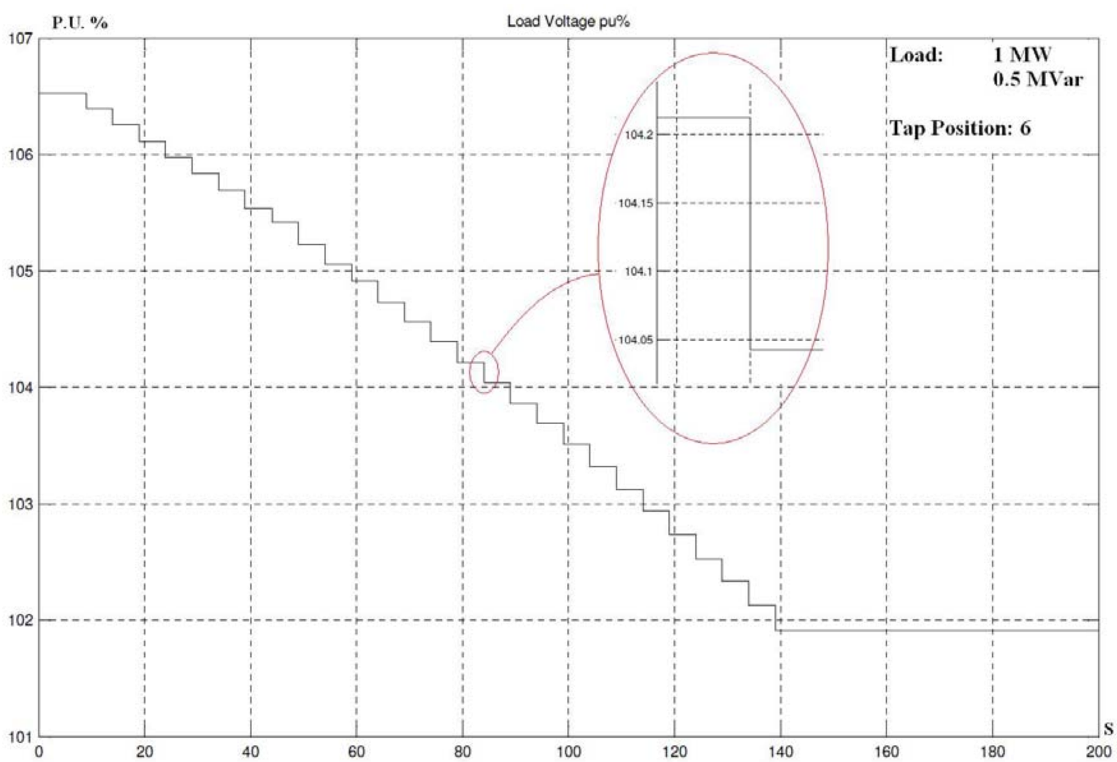


(b)

Figure 8-21: a) The actual voltage magnitude at the load busbar at 10MW-5MVAr b) Per unit percent value of voltage



(a)



(b)

Figure 8-22: a) The actual voltage magnitude at the load busbar at 1MW-0.5MVAr **b)** Per unit percent value of voltage

Figure 8-23, shows the same network as before but it is connected to extra switchable load. The scenario is that, initially the network is operating under low load condition (20MW - 10MVAr), but after 100 seconds, the load suddenly increases (An extra 40MW - 20MVAr load is switched on) and causes voltage drop below 98% of reference voltage.

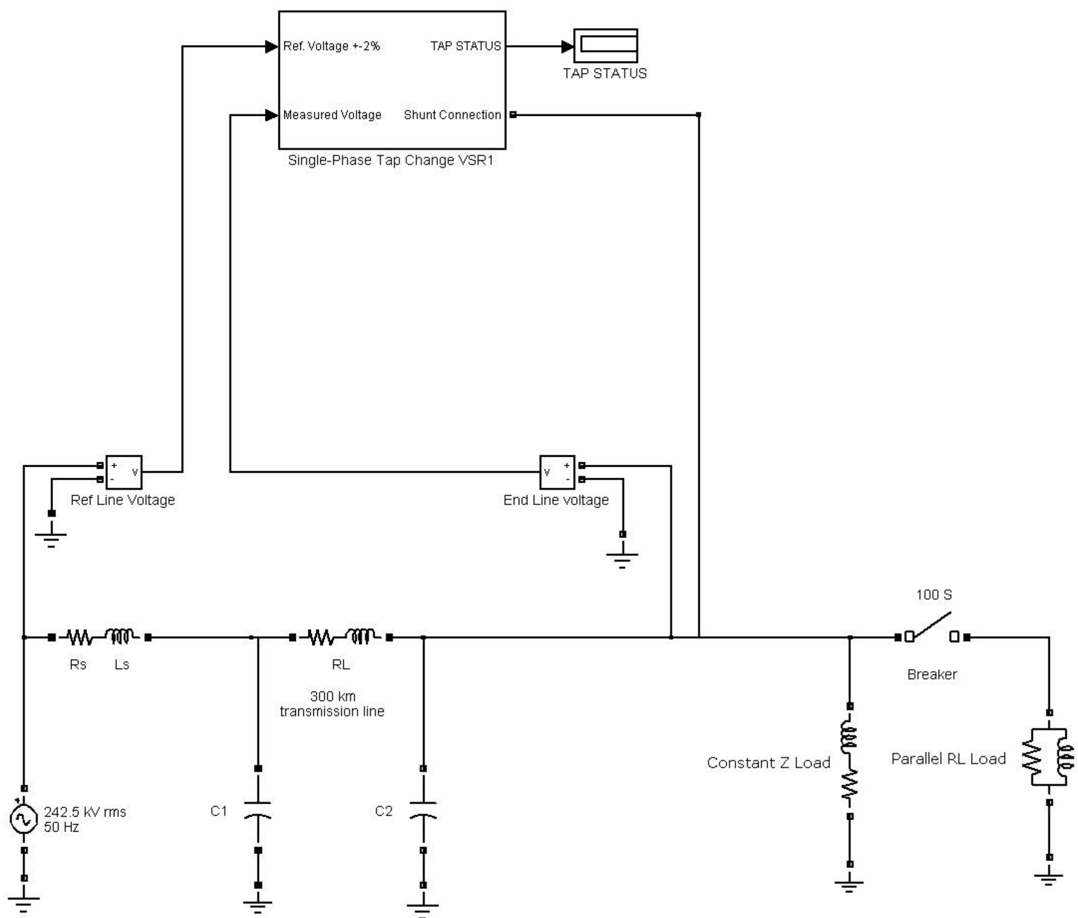
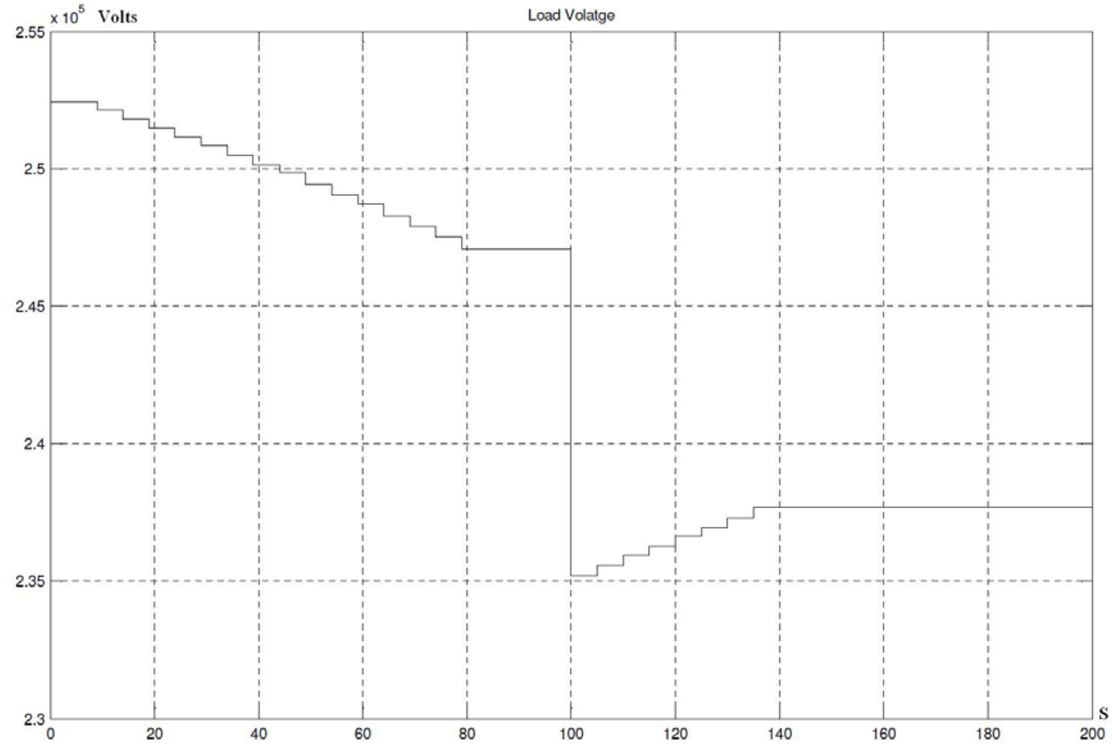
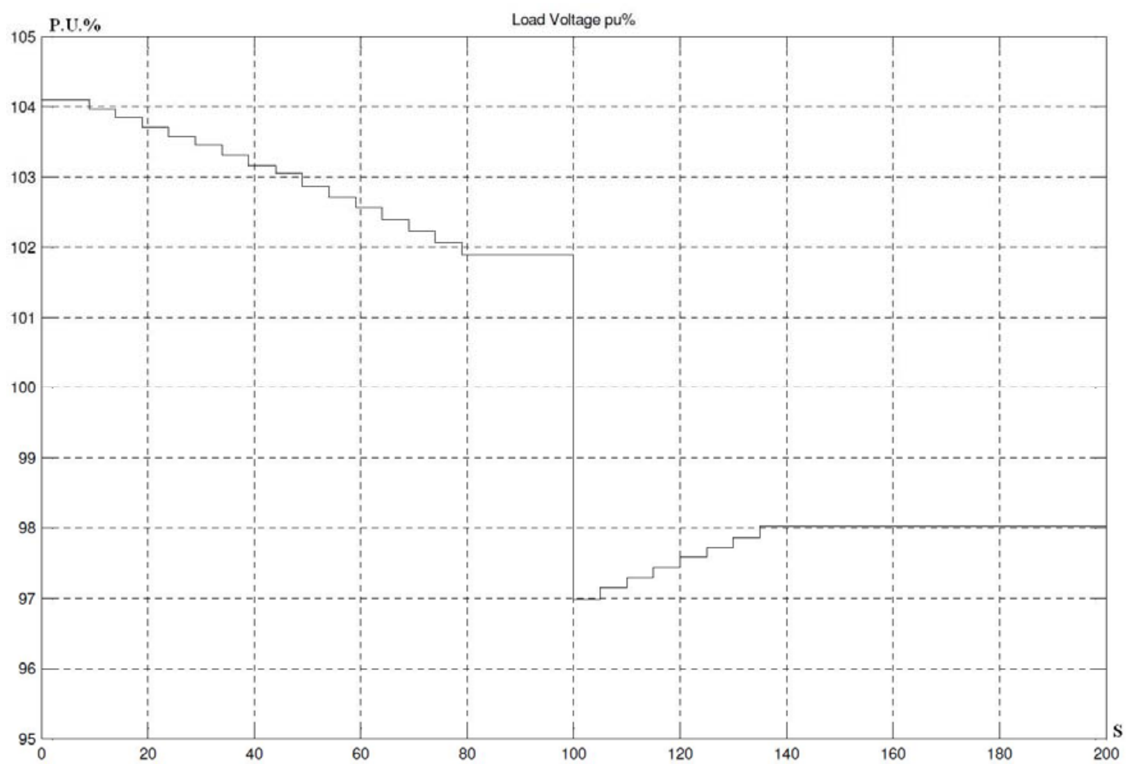


Figure 8-23: The Single Phase network model for voltage drop scenario with extra switchable load connected after 100 Seconds

As shown in Figure 8-24, initially the voltage is above 104% of reference voltage (252.5kV). Consequently, the VSR starts to tap up to step down the voltage and after 15 taps; it brings down the voltage to the regulating range. This tapping process takes about 80 seconds, however after 20 seconds the extra switchable load switches on and causes the voltage to fall down to almost 97% of reference voltage (235kV). At this point, the reactor starts to step up the voltage again by tapping down and after 7 consecutive taps down the VSR increases the voltage to the regulating range (above 98% of reference voltage).



(a)



(b)

Figure 8-24: a) The actual voltage magnitude at the load busbar during voltage drop scenario **b)** Per unit percent value of voltage

To sum up, as shown in Figure 8-16 - Figure 8-22, the VSR is working properly when using the voltage as the Control Signal. However, likewise the results obtained from DIgSILENT simulations, the voltage steps are small and in the range of 0.3kV – 0.43kV which are so small to be fairly detected by IED, equally, 0.12% - 0.17% of reference voltage. Let say, the minimum voltage change should be preferably 0.5% of reference voltage to be fairly detected by the relay. In practice, considering the measurement devices errors and noise, the control relay cannot detect these small changes in voltage which is a problem against having precise tap changing process. In such a case, three possibilities are likely to happen.

First, the initial voltage is high enough and the control system detects the voltage outside of the acceptable range. Consequently it starts to issue raise commands to lower the voltage, however, it takes about 3 to 4 taps up until the voltage difference becomes high enough to be detectable by the control system. At this point, if the voltage is still outside the regulating range, the control system issues more raise commands, otherwise it stops issuing raise commands if the measured voltage is in the acceptable range. These 3-4 consecutive taps to have sensible voltage difference are considered as "blind taps" as the control system has no control on each individual tap during this period, and it continues tapping during this period even though the voltage goes already down to the regulating range, which decreases the accuracy level of the tap changing process. It means that the final stabilized voltage could be either greater or lower than the regulating range's upper limit, to the extent of 3-4 taps (approximately 0.5% of reference voltage). Figure 8-25 shows these extra/infra blind taps.

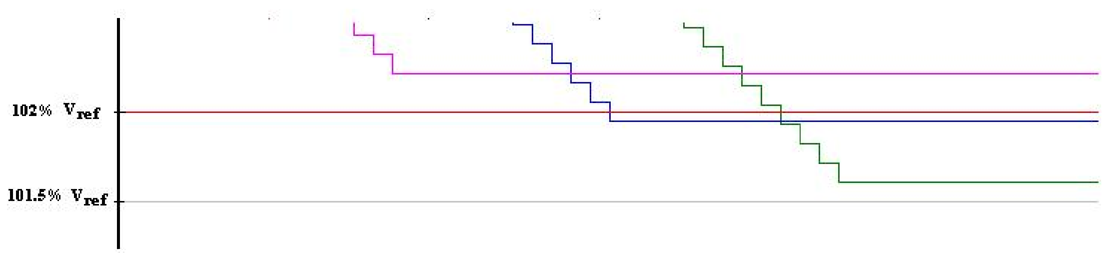


Figure 8-25: The negative effect of noise and measuring errors resulting extra/infra taps

Second, the initial voltage level is slightly higher (less than 0.5% higher) than the regulating range's upper limit. In this case, the control system may not detect the voltage as a high voltage and consequently it issues no raise command although the voltage is not in the range.

Third, the initial voltage level is slightly lower (less than 0.5% lower) than the regulating range's upper limit. In this case, the control system may detect the voltage as a high voltage (out of the range) and consequently it issues raise command to lower the voltage although the voltage is already in the regulating range. As a result, the voltage steps down further compare to what is decided in the control system setting (Figure 8-26).

Figure 8-26: Unwanted taps when the initial voltage level is slightly lower than the voltage upper dead band

Figure 8-27 shows how much voltage steps are small compare to the regulating range.

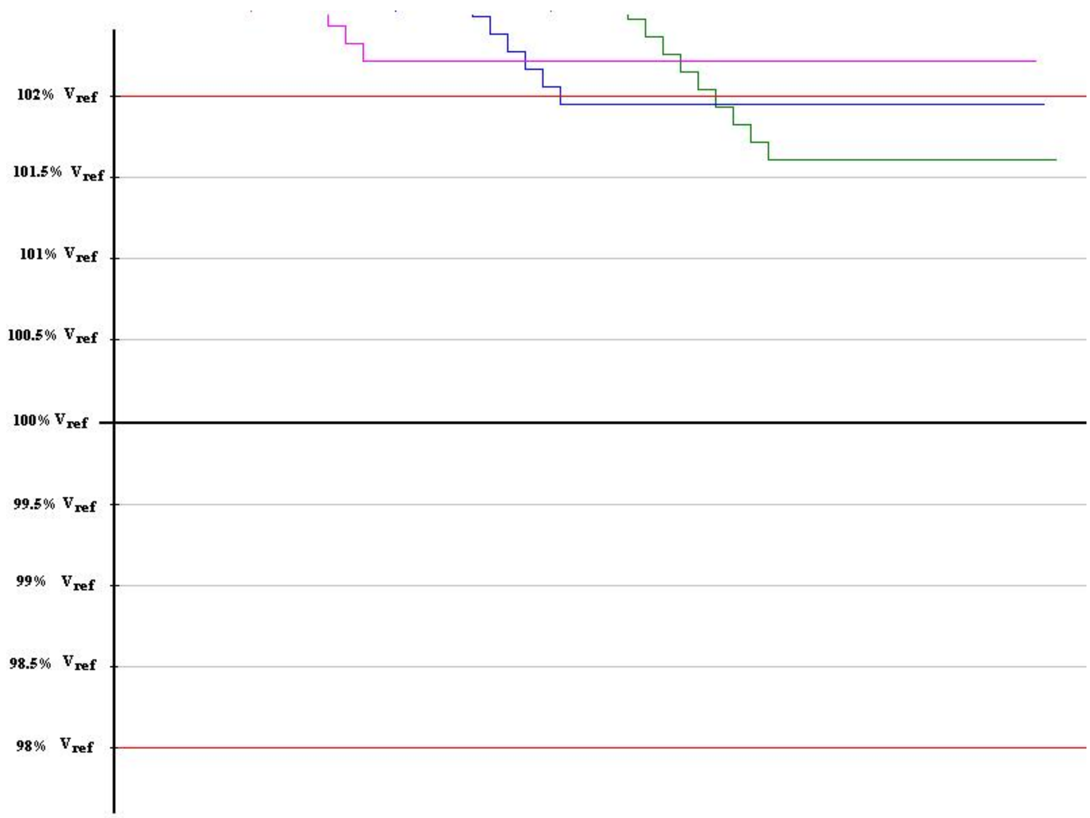


Figure 8-27: The magnitude of voltage steps compare to the regulating range (±2% of reference voltage)

In all these situations, the noise level and measurement errors are considered to be almost constant and always follow a same pattern, i.e. if the relative Voltage Transformer has ±0.2% error, it is assumed that it always measures the voltage 0.2% higher or vice versa [15]. Otherwise, there is a fourth case also possible which is the case that voltage is measured once lower than the actual voltage and the other time is measured higher than the actual voltage. Considering these three aforementioned cases, it might result in voltage oscillations around the upper voltage limit because of different voltage measurement's errors and noise. As seen in Figure 8-28, the VSR might frequently tap up and down around the upper voltage limit which results in wearing out the mechanical parts in the long run (moving parts of the tap changer).

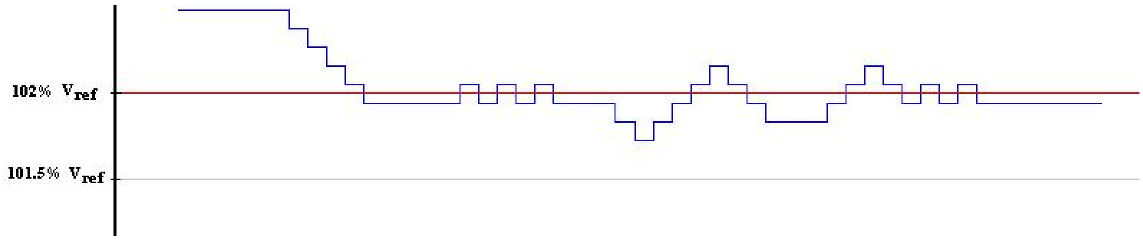


Figure 8-28: Voltage oscillations around the upper voltage limit

In conclusion, it is desired to have more intelligent, wise, and accurate tap changing process instead of having blind taps even in the required direction.

8.2.4.2. Reactive Power as the Control Signal

As it is mentioned before, a more robust control signal is needed in order to have more precise tap changing process. In other words, the Control Signal should be improved in order to have larger step sizes (higher than 0.5% of reference voltage). Hence, it is required to investigate and extract new parameters in the network which are following the same pattern as voltage change. Since the most important task of VSR is to compensate for the generated reactive power in the network during light loaded conditions, it would be advantageous to take a closer look to the reactive power behaviour in the system. From system point of view, the capacitive reactive power (Q_C) is produced in the network, while the inductive reactive power (Q_I) is consumed. The inequality between these two components results in higher or lower voltage conditions. The simulated network shown in Figure 8-15 is again under study. Figure 8-29 illustrates the same network showing the different reactive power components. As seen in Figure 8-29, Q_C is generated by the line capacitive reactance (X_C), and Q_I is consumed by the line inductive reactance (X_L). There is usually some reactive power consumed by the load (Q_{IL}) which is also inductive in most of the cases. And finally in case of low load condition, it is the VSR which is trying to make balance between these three reactive power components by consuming more inductive reactive power (Q_{IR}). Equation 8-4 shows the reactive power balance at the load busbar in order to keep the voltage at the acceptable level.

8-4 $$\boldsymbol{Q_I + Q_{IL} + Q_{IR} = Q_C}$$

Considering the pi model of the line, Q_C is the summation of Q_{C1} and Q_{C2}; where:

8-5 $$\boldsymbol{Q_{C1} = \frac{{V_{C1}}^2}{X_{C1}}}$$

8-6 $$\boldsymbol{Q_{C2} = \frac{{V_{C2}}^2}{X_{C2}}}$$

8-7 $$\boldsymbol{Q_I = X_L \times {I_L}^2}$$

8-8 $$\boldsymbol{Q_{IR} \approx \overline{V}\,\overline{I_R}^* = P_{IR} + jQ_{IR}}$$

Where X_{C1} and X_{C2} are the relative capacitive reactance in the pi model, I_L is the line current, and I_R is the VSR current.

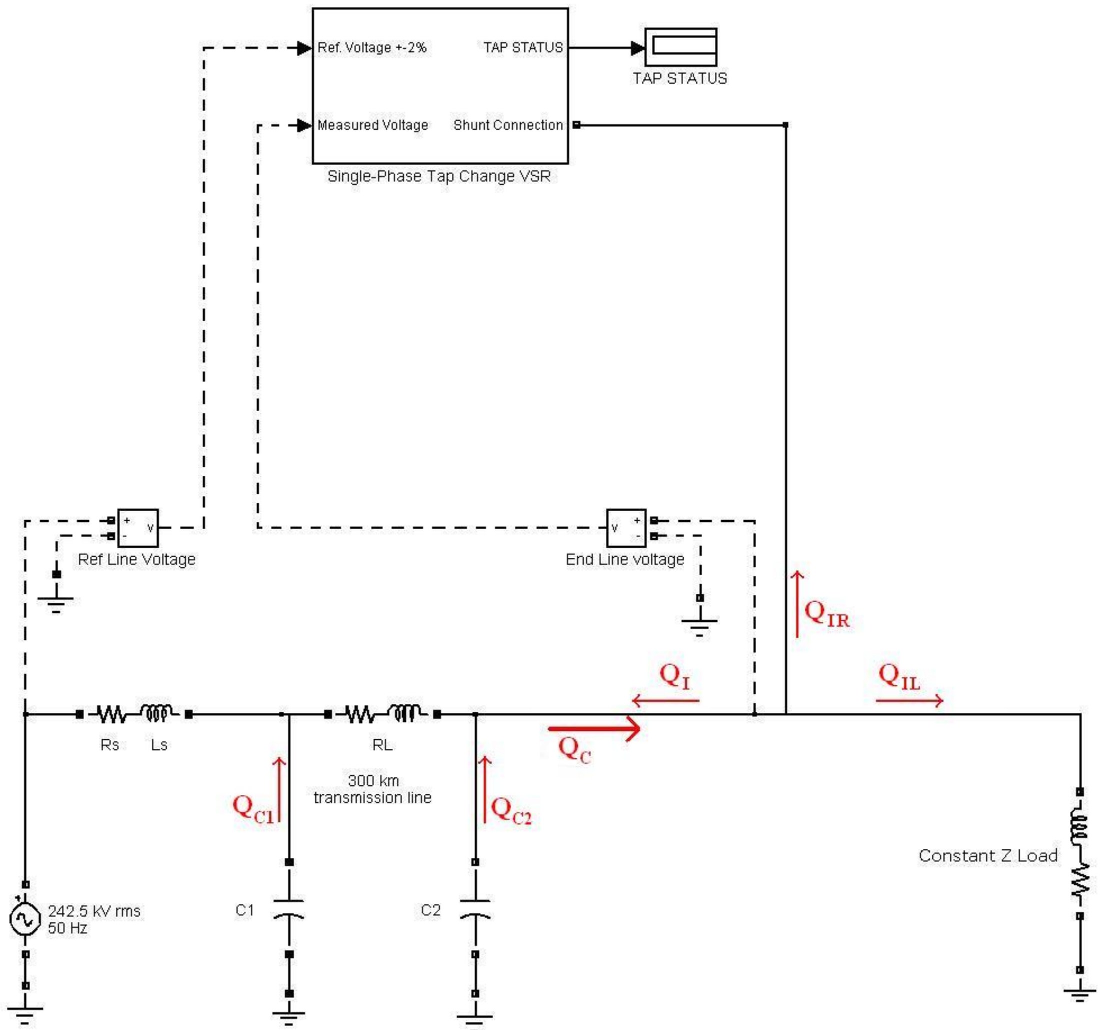


Figure 8-29: The reactive power balance in the simulated study network

As seen, Q_C is calculated from capacitance of the line (C) and the voltage level (V), while Q_I is calculated based on line inductance (L) and current flowing in the line (I_L).

However, there are some issues regarding reactive power balance in the network. First, it is not practical to measure reactive load (Q_{IL}) in the real network, since it is sometimes complicated and confusing to decide about load when there are several lines connected to the busbar. Second, one of the goals regarding ABB IED's design is being Self-Sufficient, which means the relay should be independent from extra measuring-metering equipments as much as possible. The ABB Transformer Protection & Control Relay, RET670, has maximum two Transformer input Modules (TRM), each has 12 input transformers (maximum 24 input transformers) as Analogue Inputs (AI) [16]. Although there are different combinations of voltage and current inputs, it is not still practical to have several AI from different lines or loads connected to the busbar. In other words, the VSR is practically limited to only compensate for a few numbers of lines (Max. 5) by receiving the current signals from each line separately as well as the busbar voltage; however this is not considered as a reactor constraint. Third, in a real network there are always a percentage of the target line which should be taken into account in the reactive power balance equation, i.e. the VSR is intended to compensate for a part of the line's generated capacitive reactive power according to the network topology. Finally, it should be mentioned that Q_C could easily be calculated by measuring the voltage level on the line. However in practice, it is not possible to distinguish Q_I from Q_{IL} and calculate only Q_I by measuring the line current. The reason is that the current itself is load dependent.

As a result, equation 8-4 should be written again as follows:

8-9 $$\boldsymbol{K_2 \,.\, Q_I + Q_{IR} = K_1 . Q_{C2}}$$

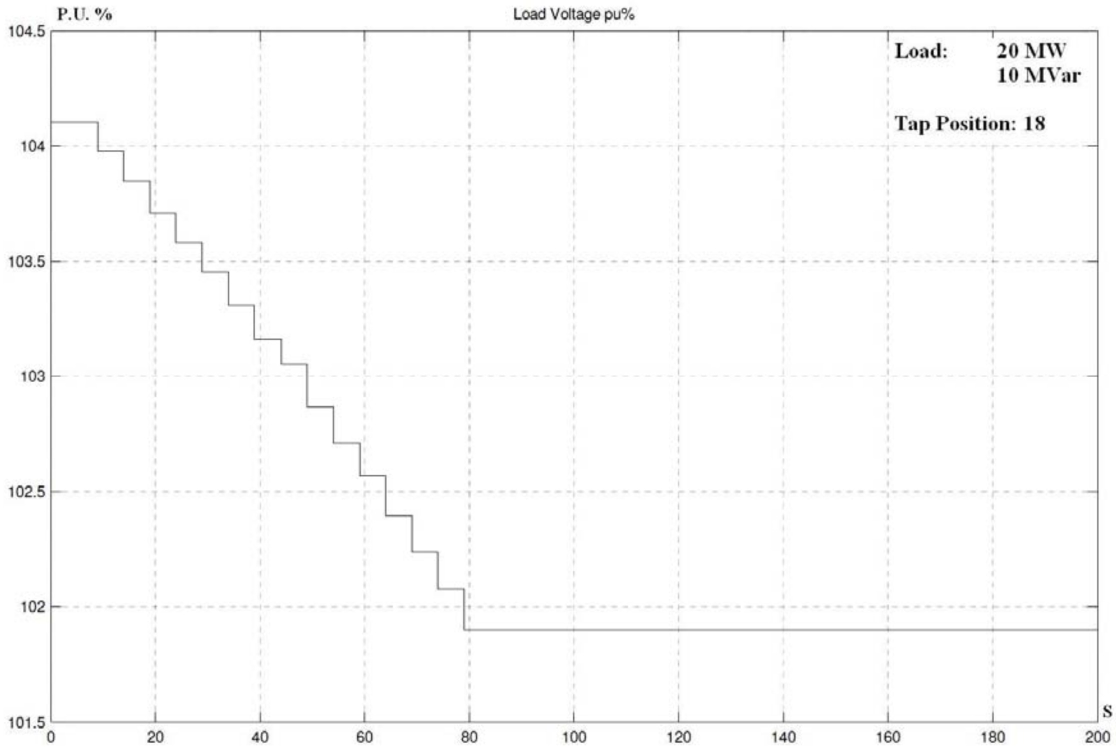
Where, K_1 and K_2 are the respective contributions of capacitive and inductive reactive powers of the line. It is assumed that in the pi model, the equivalent line capacitance which is closer to the busbar (Q_{C2}) has more contribution on reactive power balance and voltage stability on that busbar. Then equation 8-9 could be rearranged as follows:

8-10 $$\boldsymbol{K_1 . Q_{C2} - K_2 \,.\, Q_I - Q_{IR} = 0}$$

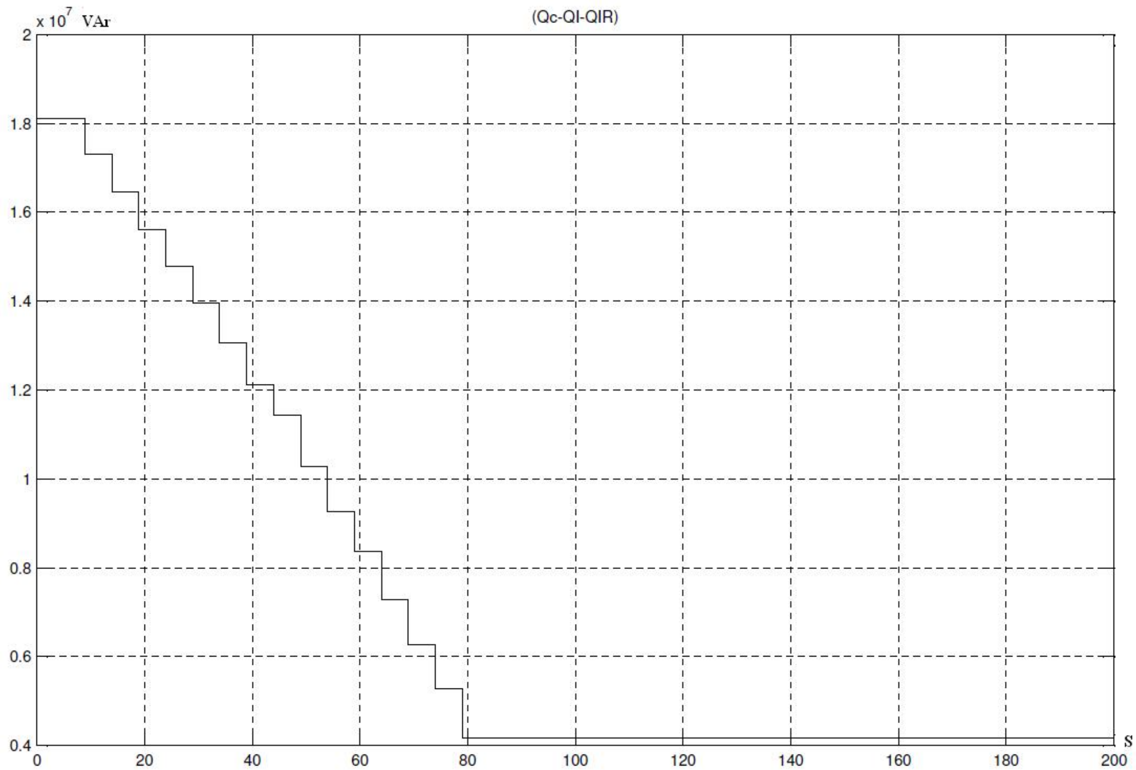
Since the left side of equation 8-10 is ideally desired to be zero in order to have reactive power balance and consequently no voltage deviation, it could be a good choice of Control Signal. When the capacitive effect of the line is more than the inductive effect, depending on the contribution of reactor, the signal has different positive values which approach to zero and it become zero if the reactor could fairly consume all the additional generated reactive power by the line.

In order to analyse the new Control Signal behaviour, the previous simulated network in MATLAB with the same voltage Control Signal as before is again under study. The goal is to investigate the behaviour of this new signal while the voltage is being regulated by the VSR with the former strategy. As an example, the Load level 20MW - 10MVAr is selected for this experiment. Both K_1 and K_2 factors are considered as 1.

Figure 8-30 shows how the reactive power balance Control Signal is approaching to zero while the VSR is lowering the voltage to the acceptable level. As shown, the new Control Signal is following exactly the same pattern as voltage, regarding the number of steps and tap changing time, and interestingly it has larger signal variation in each tap which is strongly desired. However, as seen in Figure 8-30-b, it does not become zero and has still a considerable value (4.15MVAr) at the end of tap changing process which could be a source of error.



(a)



(b)

Figure 8-30: a) The per unit percent value of voltage at the load busbar at 20MW-10MVAr using pure voltage control signal **b)** Reactive power balance control signal behaviour in actual values

Although this signal could be used alone as a Control Signal to control tap-changing process of VSR, it is not efficient to completely neglect the direct effect of voltage feedback to regulate the voltage at the desired level. Moreover, as mentioned before, this new reactive signal does not go to zero which will lead to extra/infra taps. Table 8-4 shows the residual reactive power in each load level resulting from unbalanced reactive power at the busbar after using pure voltage control strategy.

Table 8-4: Residual reactive power in each load level using pure voltage control strategy

Load		$(+Q_C-Q_I-Q_{IR})$		
MW	MVAR	K1=1	K2=1	
1	0,5	-7,24		Residual MVAr with Pure Voltage Control
10	5	-2		
20	10	4,15		
30	15	10,1		
40	20	13,5		
45	22,5	12,2		
50	25	10,8		

8.2.4.3. Combination of Voltage and Reactive Power as the Control Signal

In order to have a robust Control Signal working in different network conditions, it would be a wise choice to take the advantages of both voltage and reactive power to control the VSR tap changing process. To make a new Control Signal, which comprises both voltage and reactive power, one approach is to add up voltage and reactive power balance and make a new Control Signal. However, since the reactive signal variation is a couple of thousand times greater than the voltage signal variation, the contribution of voltage will be neglected. For this reason, both signals should have comparable values and have same dimensions. On the other hand, to make the control strategy insensitive to the remained reactive power unbalance value (Residual Reactive Power), it is desired to reduce the contribution of this reactive signal by making it smaller as much as possible.

In order to choose a factor to scale down the reactive signal, some considerations should be taken. First, the dimension of this factor should be Volts/VAr in order to make the final dimension as Volts. Second, as this factor has a direct effect on the signal's step size, it should be proportional to the voltage regulating range (±2% of reference voltage). On the other hand, it is a reasonable decision to use the rated reactive power of each VSR step (approx. 2.5MVAr) to make this signal relatively small and make the desired dimension. As a result, factor K is defined as follows:

8-11 $$\boldsymbol{K} = \frac{0.02 \times V_{ref}}{2.5\ MVAr} = \frac{4.85\ kV}{2.5\ MVAr} = \mathbf{0.0019} \approx \mathbf{0.002}\ \frac{kV}{MVAr}$$

Where, V_{ref} is the single phase reference voltage for a 420kV voltage level and is equal to 242.5kV.

Consequently, the final combined control signal would be as follows:

8-12 $$V_{Busbar} + K.(K_1.Q_{C2} - K_2.Q_I - Q_{IR})$$

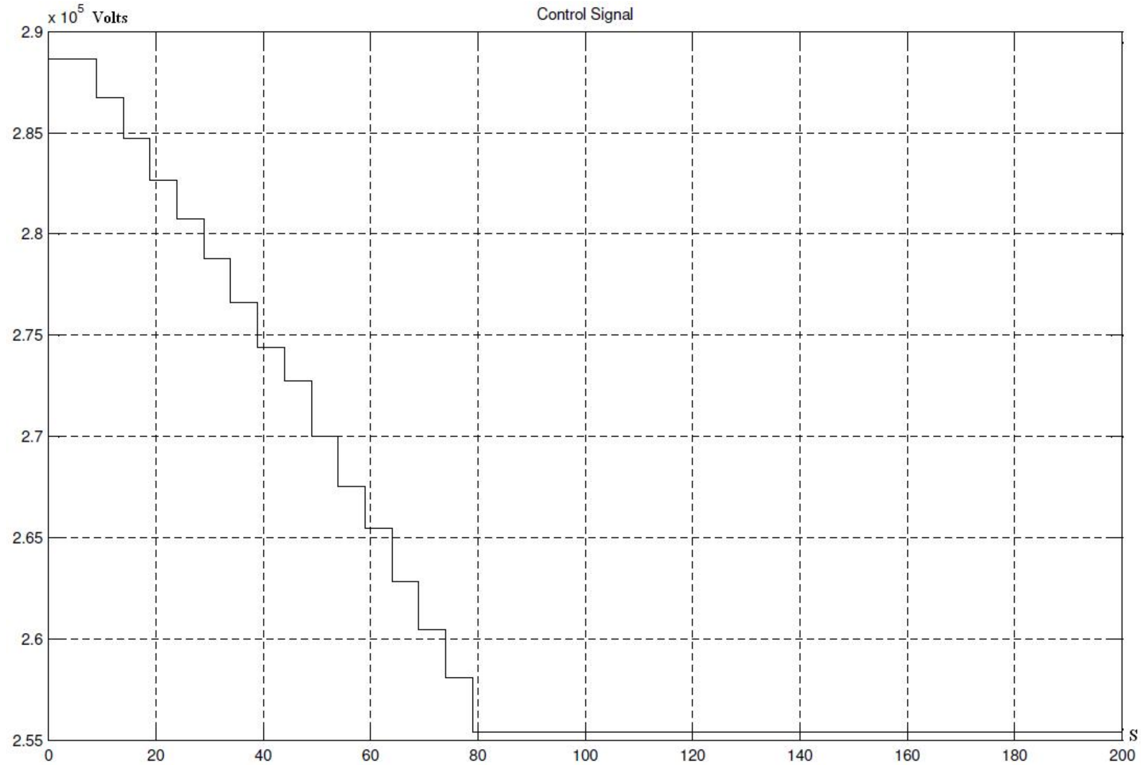
Where, V_{Busbar} is the voltage magnitude at the busbar which is intended for regulation.

As can be inferred from formula 8-12, this new combined control signal has the contribution of both voltage and reactive power.

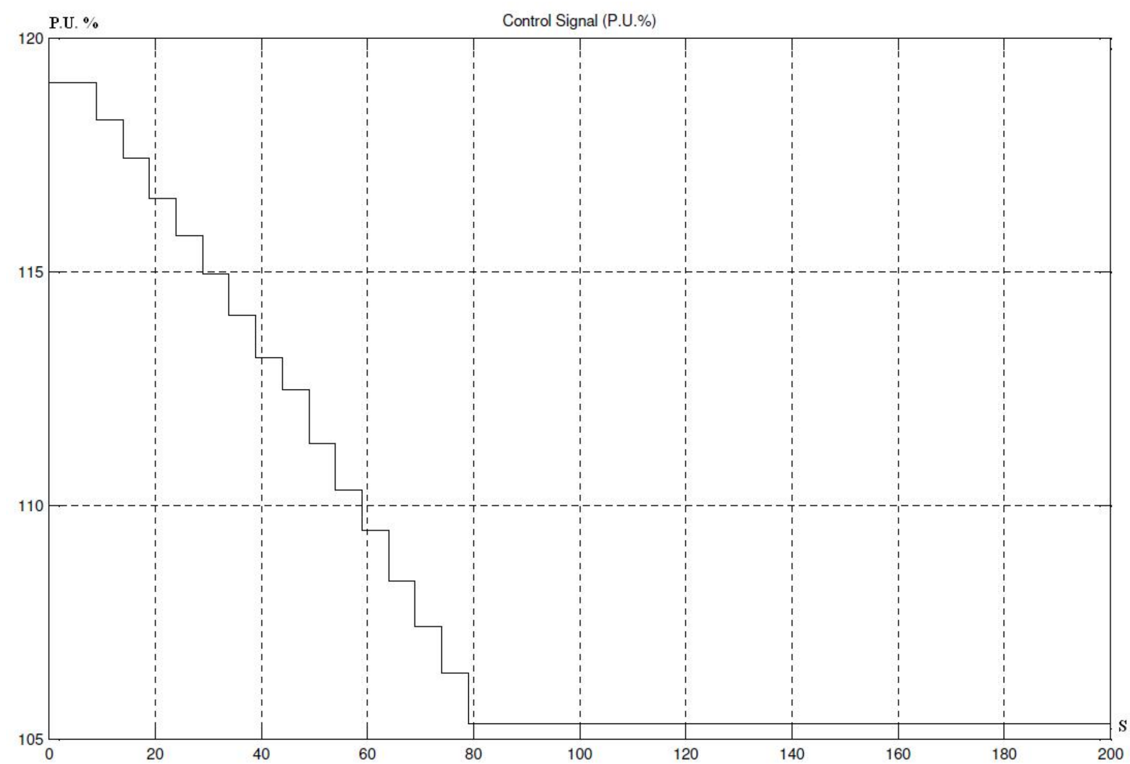
It should be noticed that even though the reactive signal's step sizes have been made almost as small as the voltage Control Signal's step sizes, those are still detectable for the relay. The reason is that the primary measured signal is big enough to neglect the effect of noise and measurement errors, and then it has been made small numerically after being measured. Therefore, regarding the step size, the reactive signal variations alone are more robust than voltage control signal variations.

In order to analyse the new combined Control Signal behaviour, the previous simulated network in MATLAB with the same voltage Control Signal as before is again under study. The goal is to investigate the behaviour of this new signal while the voltage is being regulated by the VSR with the former strategy. As an example, the Load level 20MW - 10MVAr is selected for this experiment. Both K_1 and K_2 factors are considered as 1.

Figure 8-31 shows the new combined control signal behaviour when using the pure voltage control strategy as before. As seen, the step sizes are significantly large; the minimum step size is approximately 1.6kV (0.65%) and the maximum is roughly 2.7kV (1.1%). In addition, as it is expected, this new control signal follows exactly the same pattern as Figure 8-20-a. However at the end of tap-changing process, the final control signal value is around 255kV which is a large value compare to that of Figure 8-20-a (approx. 247kV). As a result, considering the new step sizes, it can be a cause of about 4 extra taps which is a potential source of error. Since the new signal's step sizes are larger than what is required for proper relay detection, one way of decreasing this tap deviation is to lowering the contribution of reactive power balance by scaling down the factor K.



(a)



(b)

Figure 8-31: a) The combined Control Signal behaviour in actual values at 20MW-10MVAr using pure voltage control signal **b)** Control Signal behaviour in per unit percent value of reference voltage

In order to investigate the proper operation, robustness and accuracy of this new control strategy, the previous simulated network in MATLAB is again under analysis. Figure 8-32 shows the VSR which is connected to the same network as before, but using the new control signal to control the tap-changing process.

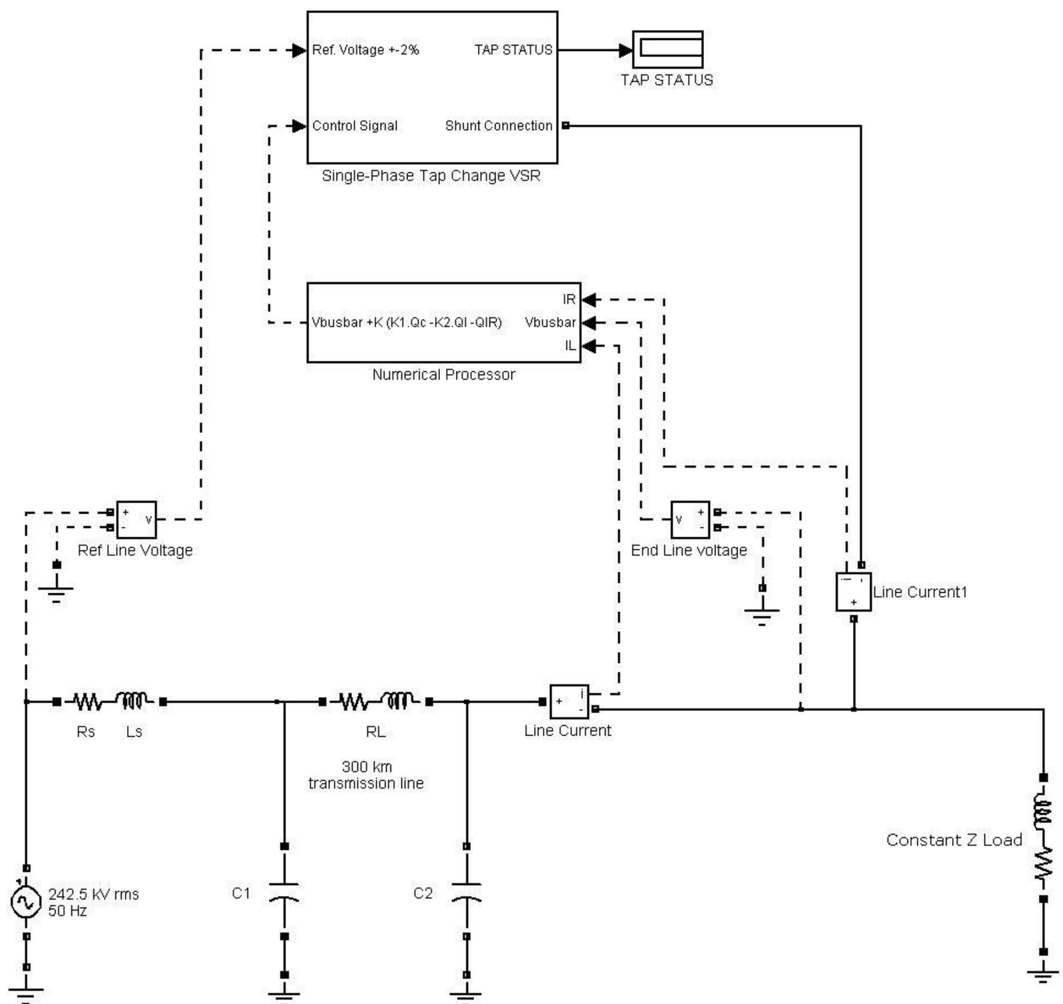


Figure 8-32: The VSR connected to the network using the combination of voltage and reactive power balance as control signal

As seen, three different measurements have been done to implement the new control signal mentioned in 8-12. Since V_{C2} is equal to V_{Busbar}, one voltage measurement is enough for this purpose.

Simulations have been done in MATLAB in order to analyse the VSR tap-changing process with the new combined voltage and reactive power balance strategy. The simulation is run during 200 Seconds for different load levels. Table 8-5 indicates the final tap position of VSR while using voltage control strategy and combined voltage and reactive power balance control strategy separately. The minimum and maximum step sizes of new control signal have also been written for each load level as percentage of reference voltage. As seen and mentioned before, the new step sizes are interestingly large, however the final tap position deviates from the previous pure voltage control strategy.

Table 8-5: Final tap position and step size in each load level using new combined control strategy

Load		Pure Voltage Control	V-Q Control ±2%		Signal Step Size	
MW	MVAR	V Control Setting: ±2%	K1=1	K2=1		
			K= 100%*(0.002)			
1	0,5	6	10		0.84% 1.2%	VSR Tap Position
10	5	11	12		0.7% 1.2%	
20	10	18	14		0.69% 1.12%	
30	15	26	17		0.68% 1.12%	
40	20	33	20		0.67% 1.09%	
45	22,5	33	22		0.65% 1.09%	
50	25	33	24		0.65% 1.07%	

As discussed before, considering practical issues in a real network such as noise, measurement errors, variable mechanical response time of VSR tap-changer, voltage stabilizing time, switching and also other transients in an actual power system, it is not practical and efficient to stick to ideal results (results obtained from pure voltage control strategy). In other words, once it is tried to be perfect in practice, it could be itself a source of more errors and uncertainties. The resulting tap positions from pure voltage control strategy are used as a reference to have a feeling of what ideal required tap position should be in theory. All the work which is tried to be done is to make efforts to get reasonable and acceptable practical results roughly the same as theoretical reference results but not exactly the same.

By this time, it is known that the unbalanced reactive power named as residual reactive power, is the source of infra/extra taps compare to theory; and it is possible to weaken its negative effect by lowering the scaling factor K. On the other hand, reducing K has a direct effect on the signal's step size. Therefore, there is a correlation between different K values and signal's step sizes which needs a trade-off between these two in order to find the optimal K value. For this reason, several simulations with different K factors have been done. Table 8-6 indicates the results of all these experiments for each load level. The results from pure voltage control strategy have been repeated in every part of the table which makes it easier to compare the results.

Table 8-6: The comparison between the results of pure voltage control and combined voltage and reactive power control strategy with different K values

Load		Pure Voltage Control	V-Q Control ±2%	Signal Step Size	V-Q Control ±2%	Signal Step Size	V-Q Control ±2%	Signal Step Size	V-Q Control ±2%	Signal Step Size	
MW	MVAR	V Control Setting: ±2%	K1=1 K2=1 K= 2.5%*(0.002)		K1=1 K2=1 K= 5%*(0.002)		K1=1 K2=1 K= 7.5%*(0.002)		K1=1 K2=1 K= 10%*(0.002)		VSR Tap Position
1	0,5	6	6	0.16% 0.23%	7	0.17% 0.27%	7	0.19% 0.29%	8	0.21% 0.31%	
10	5	11	11	0.16% 0.21%	11	0.14% 0.24%	11	0.16% 0.27%	12	0.17% 0.29%	
20	10	18	18	0.16% 0.21%	17	0.16% 0.23%	17	0.16% 0.25%	17	0.17% 0.28%	
30	15	26	25	0.16%	24	0.14% 0.23%	23	0.15% 0.25%	22	0.17% 0.27%	
40	20	33	33		32	0.15%	30	0.16% 0.18%	29	0.18% 0.20%	
45	22,5	33	33		33		33		33		
50	25	33	33		33		33		33		

Load		Pure Voltage Control	V-Q Control ±2%	Signal Step Size	V-Q Control ±2%	Signal Step Size	V-Q Control ±2%	Signal Step Size	V-Q Control ±2%	Signal Step Size	
MW	MVAR	V Control Setting: ±2%	K1=1 K2=1 K= 12.5%*(0.002)		K1=1 K2=1 K= 15%*(0.002)		K1=1 K2=1 K= 17.5%*(0.002)		K1=1 K2=1 K= 20%*(0.002)		VSR Tap Position
1	0,5	6	8	0.22% 0.34%	8	0.20% 0.36%	8	0.22% 0.37%	9	0.24% 0.41%	
10	5	11	12	0.19% 0.31%	12	0.23% 0.33%	12	0.22% 0.36%	12	0.27% 0.39%	
20	10	18	16	0.18% 0.30%	16	0.20% 0.33%	16	0.22% 0.35%	16	0.23% 0.38%	
30	15	26	22	0.18% 0.30%	21	0.19% 0.32%	21	0.21% 0.34%	20	0.22% 0.36%	
40	20	33	28	0.20% 0.22%	27	0.22% 0.24%	26	0.23% 0.27%	26	0.26% 0.29%	
45	22,5	33	32	0.20%	31	0.22% 0.23%	30	0.23% 0.25%	29	0.25% 0.26%	
50	25	33	33		33		33		32	0.25%	

Load		Pure Voltage Control	V-Q Control ±2%	Signal Step Size	V-Q Control ±2%	Signal Step Size	V-Q Control ±2%	Signal Step Size	V-Q Control ±2%	Signal Step Size	
MW	MVAR	V Control Setting: ±2%	K1=1 K2=1 K= 22.5%*(0.002)		K1=1 K2=1 K= 25%*(0.002)		K1=1 K2=1 K= 27.5%*(0.002)		K1=1 K2=1 K= 30%*(0.002)		VSR Tap Position
1	0,5	6	9	0.25% 0.44%	9	0.27% 0.46%	9	0.28% 0.50%	9	0.30% 0.52%	
10	5	11	12	0.25% 0.41%	12	0.27% 0.45%	12	0.27% 0.47%	12	0.29% 0.50%	
20	10	18	16	0.24% 0.40%	15	0.26% 0.42%	15	0.27% 0.45%	15	0.28% 0.48%	
30	15	26	20	0.24% 0.39%	20	0.25% 0.42%	20	0.26% 0.44%	19	0.28% 0.45%	
40	20	33	25	0.23% 0.31%	25	0.24% 0.33%	24	0.26% 0.42%	24	0.27% 0.45%	
45	22,5	33	28	0.26% 0.27%	28	0.28% 0.30%	27	0.29% 0.33%	27	0.32% 0.34%	
50	25	33	32	0.26%	31	0.27% 0.28%	30	0.29% 0.31%	30	0.31% 0.32%	

Load		Pure Voltage Control	V-Q Control ±2%	Signal Step Size	V-Q Control ±2%	Signal Step Size	V-Q Control ±2%	Signal Step Size	
MW	MVAR	V Control Setting: ±2%	K1=1 K2=1 K= 40%*(0.002)		K1=1 K2=1 K= 80%*(0.002)		K1=1 K2=1 K= 100%*(0.002)		VSR Tap Position
1	0,5	6	10	0.36% 0.61%	10	0.6% 1.02%	10	0.84% 1.2%	
10	5	11	12	0.36% 0.59%	12	0.58% 1%	12	0.7% 1.2%	
20	10	18	15	0.35% 0.56%	14	0.58% 0.96%	14	0.69% 1.12%	
30	15	26	19	0.33% 0.55%	17	0.56% 0.93%	17	0.68% 1.12%	
40	20	33	23	0.32% 0.55%	21	0.55% 0.9%	20	0.67% 1.09%	
45	22,5	33	25	0.32% 0.43%	22	0.55% 0.85%	22	0.65% 1.09%	
50	25	33	28	0.38% 0.40%	24	0.53% 0.9%	24	0.65% 1.07%	

As seen, in order to achieve signal's step sizes higher than 0.5% of reference voltage, the scaling factor (K) could be either 80% (K=0.0016) or 100% (K=0.002) of its original value. However, since there is no significant difference between the tap positions in these two cases, more robust signal will be achieved by choosing K equal to its original value (i.e. K=0.002) as there are larger signal's step sizes available in this case.

As mentioned before in equation 8-10, K_1 and K_2 are the respective contributions of capacitive and inductive reactive powers of the line. Since Q_{C2} is almost 50% of total generated capacitive reactive power, keeping K_1 equal to 1 means that the contribution of capacitive reactive power is 50% i.e. 50% of the line capacitive effect is contributing the reactive power balance signal. Similarly, to have 50% of the line inductive effect contribution, factor K_2 could be selected as 0.5. Table 8-7 indicates the final resulting tap positions and step sizes after changing the factor K_2.

Table 8-7: The final tap position of VSR and signal's step size using K_2=0.5 for different load levels and using combined control strategy

Load		Pure Voltage Control	V-Q Control ±2%	Signal Step Size	V-Q Control ±2%	Signal Step Size	
MW	MVAR	V Control Setting: ±2%	K1=1 K2=0.5		K1=1 K2=0.5		
			K= 80%*(0.002)		K= 100%*(0.002)		
1	0,5	6	8	0.57% 1%	9	0.68% 1.2%	VSR Tap Position
10	5	11	10	0.56% 0.95%	10	0.67% 1.15%	
20	10	18	12	0.55% 0.9%	12	0.65% 1.1%	
30	15	26	14	0.53% 0.88%	13	0.64% 1.08%	
40	20	33	16	0.52% 0.86%	16	0.62% 1.02%	
45	22,5	33	18	0.52% 0.84%	17	0.63% 1.03%	
50	25	33	19	0.5% 0.83%	18	0.60% 1%	

As can be seen, although the signal's step sizes have been slightly decreased in both cases (K equal to 80% and 100% of its original value), they are still higher than 0.5% of reference voltage. However, there is a tangible decrease in final tap position's number which makes it closer to the results of pure voltage control; especially in case of K equal to 80% of its original value. It should be noted that having more taps up, which is happened at higher load levels, is favourable since it makes the final voltage level to become closer to the reference voltage.

9. Conclusion

The tap-changing control of a Variable Shunt Reactor can be done by simply monitoring the voltage level at the busbar to which the VSR is connected. However, because of very small voltage step sizes, which in practice are not easily detectable by the relay, such control strategy is not robust and may be problematic. These problems include blind taps, unwanted tap-changing and tap-change blocking, and also frequent taps up and down with resultant wear on mechanical parts.

Although it is possible to make the control signal step sizes larger by using the reactive power balance as a control signal, there are still some sources of uncertainty as this reactive signal does not go to zero, which will lead to extra/infra taps. In addition, the voltage level is not supervised at all.

Finally it is investigated that in order to have a more intelligent, wise, and accurate tap changing process, it would be a good choice to take the advantages of both voltage and reactive power to control the VSR tap changing process. To implement this new signal, several simulation studies have been done and corresponding factors have been determined. Expression 8-12 shows the final resulting control signal. Nevertheless, some deviation is still observed compared to the ideal tap-changing process.

As discussed, one of the main problems regarding control of Variable Shunt Reactors is that the voltage steps resulting from the tap changing process are too small to be detected by the control relay. Although the implemented control signal is reliable and robust, these small voltage steps could still be considered as sources of error and uncertainty during the voltage control process.

In order to make these voltage steps bigger, there are two more alternatives available at the design stage of VSRs. First, it is possible to decrease the number of taps while having a fixed regulation range. For example in some applications, it is enough to only have 3 predefined tap positions to cope with reactive power variations; however, this is not feasible because the leakage flux inductance in the regulating circuit could reduce the available valid step power and step voltage for the tap. The second alternative is to widen the regulation range or have a variable regulation range with the same number of taps. Both alternatives are very much dependent on the network situation in which the VSR is intended to be used. As a result, it is really important to tailor make the VSR for each customer; and customers must provide their specific requirements when ordering a VSR.

To conclude, this work represents a pre-study on the control strategy of tap-change Variable Shunt Reactors. The results obtained are satisfactory, in this respect. The similarities between tap-changing control of parallel transformers, which is an existing function in RET670, and the new proposed tap-change control of VSRs, makes the integration of this new feature in RET670 quite feasible.

10. Future Work

Since the resulting control strategy is obtained by study and simulation on a unidirectional supply network (only one generation area) with only one single transmission line, a more reliable strategy could be achieved by further study and simulation on a multi-directional supply network (two or more generation areas) having parallel transmission lines.

In addition, as with the voltage control for transformers with tap changer, a more detailed documented strategy for both single and parallel control of Variable Shunt Reactors should be investigated and prepared.

Moreover, the maximum number of lines which the VSR should compensate for should be specified.

Finally, since the current work is a pre-study, in order to implement a final control function into an IED (RET670), all the aforementioned studies should be performed and subsequently all necessary verification should be done by means of simulation using a real time, digital network simulator.

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Appendix A

Part of Norway transmission network simulated in DIgSILENT.

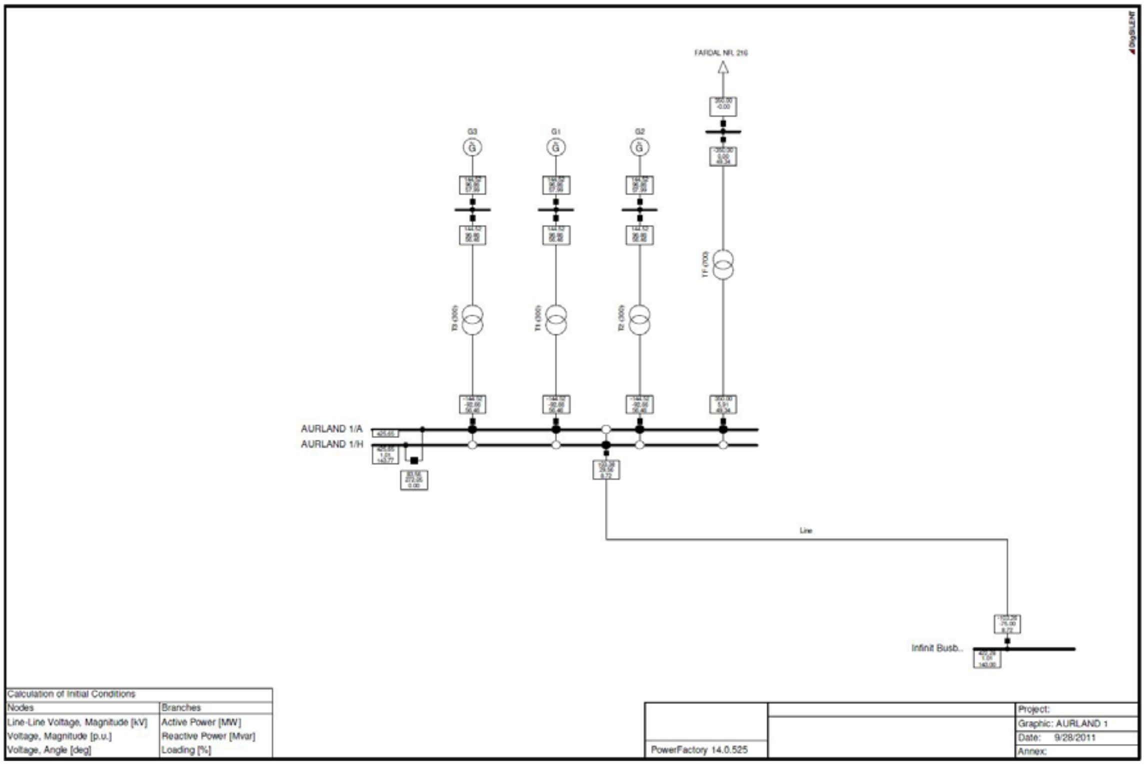

Figure A-1: The single line diagram model of Aurlanda 1 substation simulated in DIgSILENT

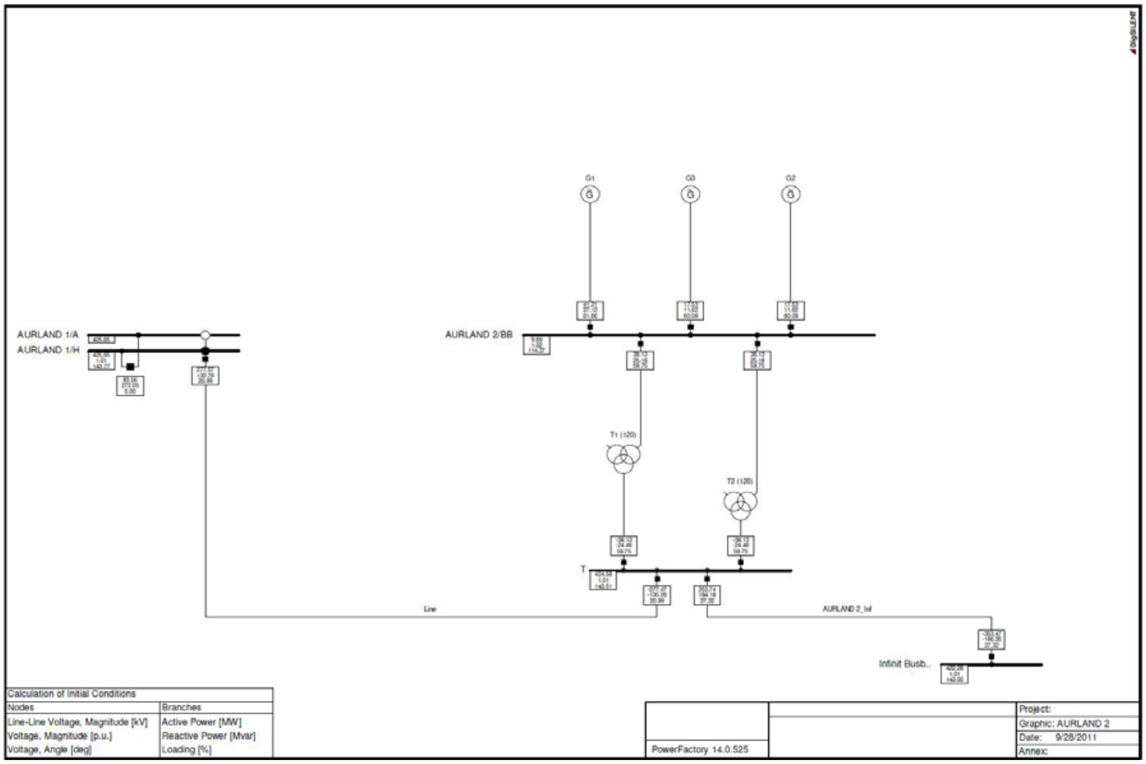

Figure A-2: The single line diagram model of Aurlanda 2 substation simulated in DIgSILENT

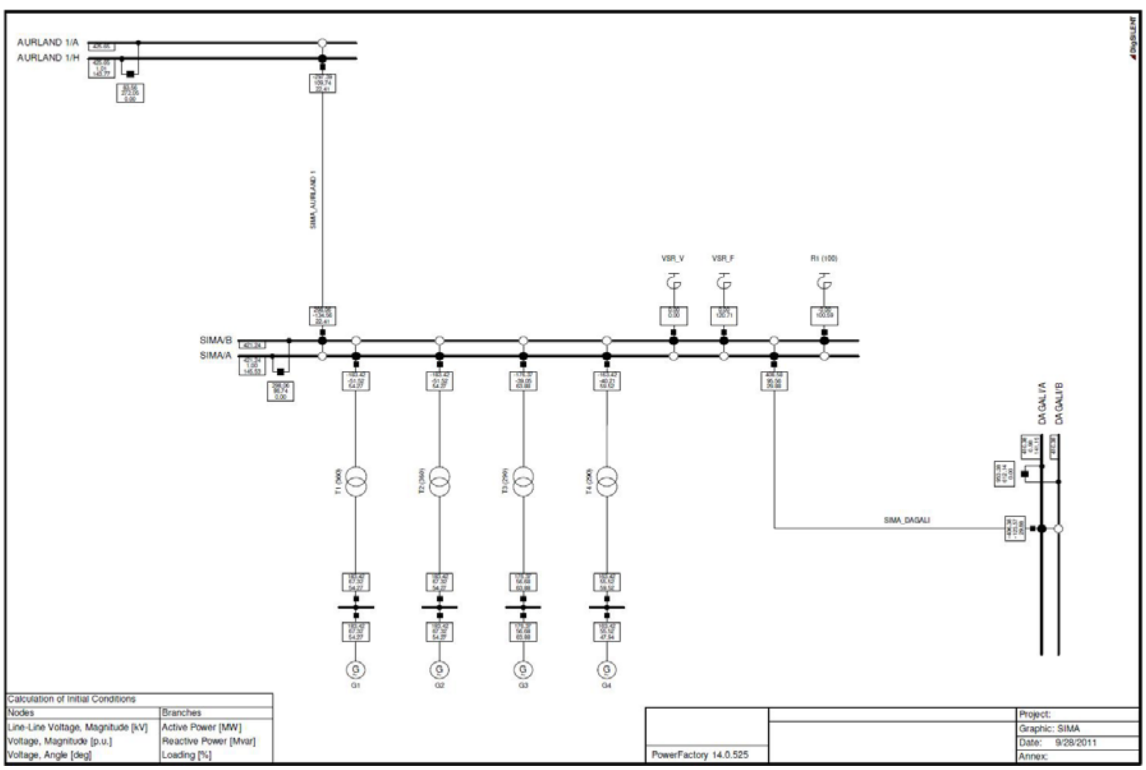

Figure A-3: The single line diagram model of Sima substation simulated in DIgSILENT

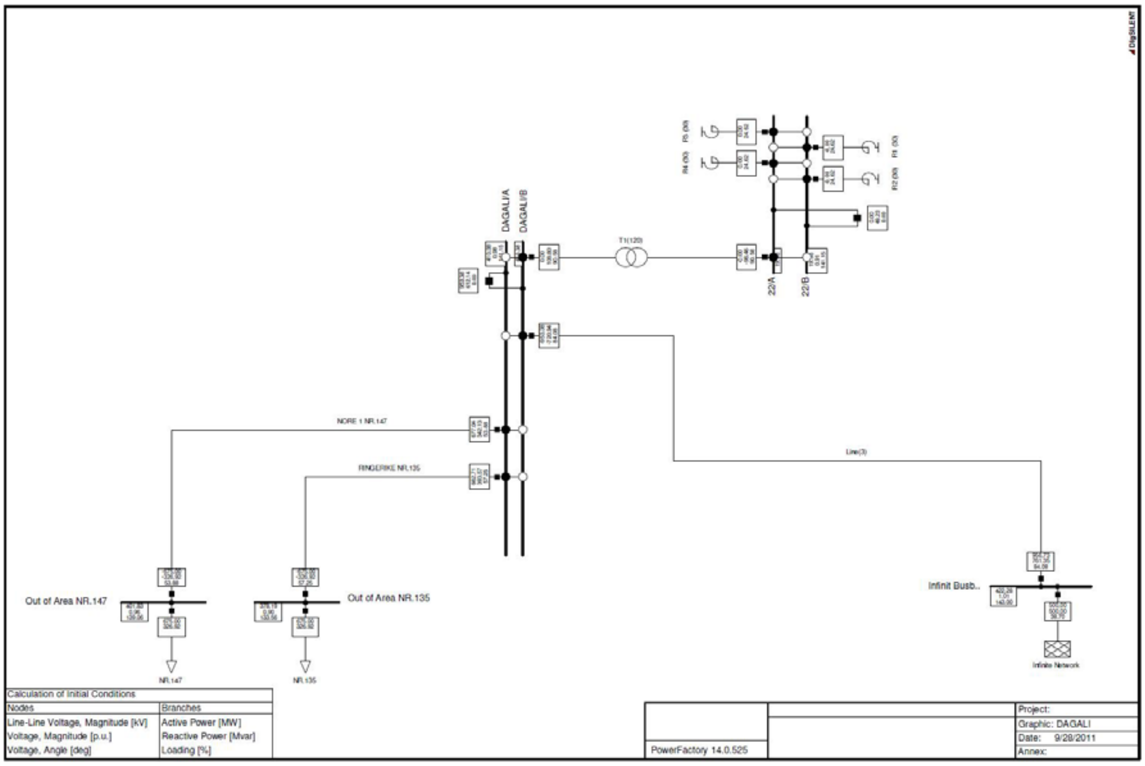

Figure A-4: The single line diagram model of Dagali substation simulated in DIgSILENT