UNIVERSITY of RWANDA

College of Science and Technology

AFRICAN CENTER OF EXCELLENCE IN ENERGY FOR SUSTAINABLE DEVELOPMENT

Title of the Project: **REACTIVE POWER CONTROL AND POWER LOSS MINIMIZATION IN ELECTRICAL NETWORK BY USING FACTS DEVICES.**

A project submitted to the African Center of Excellence in EnergyStudies for Sustainable Development (ACE-ESD) In Partial Fulfillment of the Requirement for the Degree of Master of Science in Electrical Power Systems.

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DECLARATION

I, the undersigned, confirm that this project work is entirely mine and that it has not previously been submitted for a degree at the University of Rwanda or any other institution. All components of materials used in this work have been fully recognized and cited in accordance with the University of Rwanda's requirements.

Names: Fabrice NYAGUSHIMWA Signature

APPROVAL

Submission Date: **05/11/2021**

This project has been submitted for examination approved by university Supervisor Dr. Ir Mulugeta Gebrehiwot Gebremichael

Thesis Supervisor Signature

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Abstract

The increase in power requirements causes the wide expansion and development of power systems, resulting in high demand in power systems. The most common power system problems are uncontrolled reactive power and power loss during transmission and distribution; thus, electricity almost requires a network for transmission and distribution to the customers. The FACTS devices are useful for increasing the efficiency of power system, power factor improvement and harmonic reduction. The reactive power is used to regulate the voltage levels in the transmission system and to improve the efficiency of system on various busbars.

The electrical network benefits greatly from reduced reactive power, energy losses and voltage in accepted limits. This project will use a proper FACTS device controller to regulate reactive power and voltage profile, allowing it to provide active and reactive regulation to achieve transmission line loss minimization, real power transfer at maximum, system stability, voltage profile improvement. The effects of reactive power have been discussed, the total losses reduced from 5% to 0.5% and reactive power were controlled in this work with different techniques by using capacitor banks and static VAR compensators, Thyristor controlled reactor (TCR), SSS, STATCOM and Unified power flow controller (UPF) were simulated by using MATLAB/SIMULINK software version 2017b.

Keywords: Reactive power, MATLAB, FACTS Devices, Voltage, overvoltage, and power loss.

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List of Abbreviations

TCSC	Thyristor Controlled Series Capacitor or Compensator
FACTS	Flexible Alternating Current and Transmission System
MATLAB	Matrix Laboratory software
VSC	Voltage source converter
SVC	Static VAR compensator
IPFC	Interline Power Flow Controller
TCPS	Thyristor Controlled phase shifting Transformer
STATCOM	Static Synchronous Compensator
SSSC	Static Synchronous series Compensator
UPFC	Unified Power Flow Controller
VR	Receiving End Voltage
VS	Sending end voltage
Z	Impedance
P	Power
Q	Reactive Power
AC	Alternating Current

CHAPTER I. INTRODUCTION

Electrical power demand has increased substantially in recent years, owing to rapid population growth and rapid technological advances. This issue has resulted in a heavily stressed traditional power system, which needs either network expansion or network operation at or near its technical limits. The moderate solution is usually preferred over network expansion, which is limited due to environmental concerns and high costs. In most countries, approval to build new transmission lines is rarely granted, so existing transmission equipment should be enforced to meet changing requirements. The update solutions in the field of reactive power control have been used to not only cost reduction of using reactive power but also to improve the quality of the energy system. High quality electrical power in terms of voltage is ensured by compensating the reactive power in the grid and filtering the harmonic of undesirable currents, and voltage failures or voltage drop and reduced power loss.

Most of the time, the electrical network has a high demand for reactive power from the transformer system, which causes it to be overloaded. Initially, this problem was solved by connecting a capacitor in parallel with the load to correct the power factor and minimize losses. The load that run on alternating current needs apparent power, which is made up of real power plus reactive power as a vector. The Power plants, capacitors, static compensators, and synchronous condensers can all generate reactive power. Reactive power generation by power plants has two issues: first, the reactive power generation capacity of a power plant is limited, and second, this massive power consumes transmission line capacity, transformer capacity, and imposes some system losses. The presence of reactive power sources closer to the consumption not only reduces cost, but also increases the transmission line's capacity [1]. They are many factors influencing system losses[2]. Most of them are Circulating current, Voltage regulation, Phase balancing and Power factor.

1.1 Background

The importance of the electric network is critical in the energy market and its operation is governed by physical law. The electric network has a fixed structure made up of different voltage levels, with the highest levels used for transmission and the lowest levels used for a variety of tasks. The increasing power requirement in power system networks has resulted in the widespread growth and power systems development today.

The purpose for this technological advancement is the scarcity for sources of energy which limits power generation[3]. However, many companies are forced to use existing resources which are increasing the loading of transmission lines. This resulted insufficient stability and voltage regulation , so in order to enhance performance of alternating current in power systems, the reactive power is efficiently controlled which is known as reactive power compensation[4]. The implementation of the reactive power compensator in the appropriate location for a given system is critical in a transmission network.

In general, the ideal location is shown by running power flow so that the line with highest power flow taken as the best location for the FACTS connection[5].

The line stability index is used to make judgement of stability of network. By using the equation below.

$$L_{mn} = \frac{4Q_r X}{[V_s Sin(\theta - \delta)]^2} \qquad (1.1)$$

Where $\boldsymbol{L_{mn}}$:line stability index, $\boldsymbol{Q_r}$: $receiving\ end\ reactive\ power$, $\boldsymbol{V_s}$: $sending\ end\ voltage$,

$\boldsymbol{\theta}$: $line\ impedence\ angle\ and$

$\boldsymbol{\delta}$: is the angular difference between the supply and receiving voltages. When the value of this index is less than one, the system is said to be stable. A value of the index that is close to one indicates that the system is on the verge of instability.

In general, reactive power compensation issues are taken from two cases: load compensation and voltage support.

The goals of load compensation are to raise the value of the system voltage, which means improving power factor, balance the real power drawn from the ac supply, compensate voltage profile, and minimize harmonic currents as shown in Figure1.1. Voltage support is intended to provide vitality and to stabilize voltage flow in the network, as will be discussed in this work. To improve the power factor in general , equipment drawing roughly the same reactive as the load kVAr, but in phase opposition should be linked in parallel to the load [6].

The capacitor connected in parallel with the load improve the power factor and this method is mostly used in power system network.

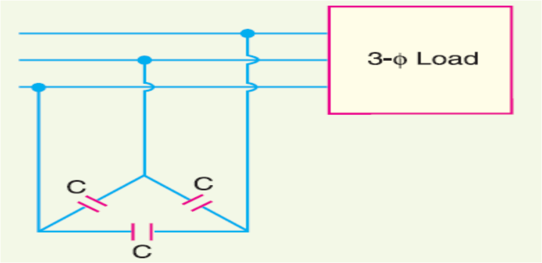


Figure 1. 1: Capacitor connected in parallel with load[7]

The losses in the transmission line are more than 19.41 percent in 2019/2020, according to the Rwanda network grid, because the transmission lines have long distance and the majorities of them are aged.

1.2 Problem Statement

Electrical power demand has primarily increased in recent years because of rapid population growth and rapid technological advances. In power generation, transmission and distribution system, the problems of undervoltage, overvoltage on the bus bars and power losses are due to uncontrolled reactive power and other technical problems. Generally, in power system transmission loss are due to many factors concerning on the system configuration.

The resistance of the line and the reactive element respectively, lead both real and reactive loss. For the utility, real power losses must be considered because they reduce efficiency. As result, to address and resolve the problems of line losses and voltage levels in transmission, the Rwanda energy group intends to construct a new transmission line even though it will be difficult and expensive. As a result, a control mechanism for minimizing power loss and regulating voltage profile by using FACTS Controller is required.

1.3 Objectives

1.3.1 Major objective

The primary goal of this research is to minimize the problems of losses and voltage drop due to uncontrolled reactive power, which means line loss minimization in transmission, regulating the voltage profile, and increasing the capacity for power transfer in existing transmission line using the FACTS Devices Controllers.

As a result, my goals are divided as follows: Controlling reactive power, increasing power factor, and reducing power loss with Mitigation techniques involving FACTS devices, as well as determining the ideal location of FACTS devices in transmission line.

1.3.2 The Specific Objectives

Specifically, goals of this research are as follows:

1. To investigate power flow and losses in the interconnected network.
2. To evaluate the Voltage drop data on different busbars(substation).
3. To mitigate the real power losses and evaluate the performance of the transmission network.
4. To evaluate ideal location of FACTS Devices by inspection.
5. To Design and simulate by using MATLAB software and SIMULINK.

1.3.3 Research Questions

What effect does uncontrolled reactive power flow have on real power flow and load?

What is the positive impact for controlled reactive power on utility and customer side?

As review what are the recommendations required to mitigate with voltage drop and power factor problems and how to minimize power loss at possible minimum point?

What is the optimality location in transmission line to install the FACTS devices?

1.4 Scope of the Study

This academic research aims to control the reactive power, power loss minimization Electrical network and the simulation to compare with expected data. After the analysis of main factors which affect the power system stability such as reactive power, power factor and harmonics, the FACTS devices with control system should be designed and other measures to mitigate voltage drop as well as power losses.

1.5 The outcomes Expectation and significance of the study

1.5.1 The outcomes Expectation

This research will provide the stability of electrical network in region since it will provide measures and automatic control of reactive power. With this completed project, it will have good impact on the social economic development of country and for the researcher in power system network.

1.5.2 Significance of the Study

This research will be useful for planning, demand of load forecasting and taking decision because it will show reason for power lost in the transmission network as well as bus voltage deviation. Rwanda Energy Group (REG) is exporting energy and importing energy will have a way to increase energy exports and reserves of energy from loss reduction will benefit the utility to get more financial income.

The electrical power network possesses numerous interruption due to lack of stability, low power factor, and uncontrolled reactive power, since this results to blackouts and instability in network, the mitigation measures and control will benefit both utilities and customers in this regard.

1.6 Methodology used for the Study

The primary goal is to achieve the study's objectives, and there are several steps to be considered. The first method for processing the work begins with a review of various literatures during the proposal, which includes all theoretical information about transmission line losses, reactive power, voltages, and FACTS devices. In addition to the literature review, data collection and verification for the analysis are carried out, and the results have been analyzed in MATLAB.

1.7 Report Arrangement

This research work is aimed to control the reactive power and power loss minimization for utility grid and simulate selected FACTS devices to mitigate voltage drop and power loss at predetermined period.

Chapter one presents work as introduction with the problem Statement, **Chapter two** part is concerned with the theoretical background and literature review of the problem formulation, which is primarily Reactive Power Control and Transmission line Losses.

Chapter three focus on developing good methodology and data collection on the fields.

Chapter four presents Design and Simulation for proper consideration.

Chapter five represent the Results and Conclusion for each simulated network.

Finally, **Chapter six**, general conclusion recommendation and future work. the result for implementation (where possible) in electrical network by using Fact’s devices. This will improve power quality problems and increase power system reliability.

CHAPTERII.THEORITICAL ASPECTS AND LITERATURE REVIEW

2.1 Brief Introduction

The variation for voltage level of the network and its operation are closely related to the reactive power levels of the system network. Regulation of reactive power in multiple nodes not only reduces active power loss and reactive network losses, but also maintains property voltage levels and improves power system stability, ensuring that the power system can operate safely and economically[8].

The nodes where reactive power compensation is required would be determined as for improving voltage stability or economic operation. The most technical challenge in power system network is the control of power generated by renewable sources. This is due to the fact grid connected renewable energy sources cause power fluctuation since the wind speed and solar radiation intensity highly depend on weather conditions[9] . The next technical issues is the reactive power monitoring in power plants like photovoltaic power plants which are keep changing according to the amount of power generated at different wind speed and solar radiation respectively.

The process of voltage ampere reactive regulation encompasses a broad and diverse range for network and customer problems, specifically those related to quality of power because most them are resolved through proper control of reactive power in any given network [10].

2.2 Electrical Power system Network

The Electrical system network is composed with different parts like generating station, transmission station and distribution station as well as protection associated with whole system. The impact for improper working of the system are high electrical energy demand , balancing supply and stability of interconnected network[11].

The main impact of the above leads non- optimality operation of the power system network,then as solution the power system planner construct other new transmisssion line which is not feasible option economcally. Many research works have been done to solve the problem and creating new algorithm for power system stability as well as reliabilty by incorporating the Flexible alternating curent Transmission devices abbreviated as FACTS .

They serve the primary purpose of ensuring fast and continuous power flow in transmission lines by keeping the voltage within an acceptable range. These devices have been used in a variety of applications, including power dispatch economically and system security, to ensure that power is available without compromising network constraints[12].

2.3 Components of power system network

The primary goals of power system network are to deliver electrical energy to the consumer or load in a safe, cost-effective, and dependable way. This energy is consumed by the load once the following steps are completed, which means that electrical power must be generated and then transmitted. The transmission and distribution are only two possible ways to transmit electrical energy to the user. The first task of a power system is the generation, transmission, and distribution of electrical power, while the second task is one of three core functions, which include metering or measurement, protection, and control. These options are carried out by the first and second options in power systems, respectively. Figure 2.1 illustrates a schematic representation of the configuration option for an electrical power system. Power system network is complex because is made up by meshed transmission line that pass across region and to which more power plants and loads are connected, resulting in the interconnected power system network .

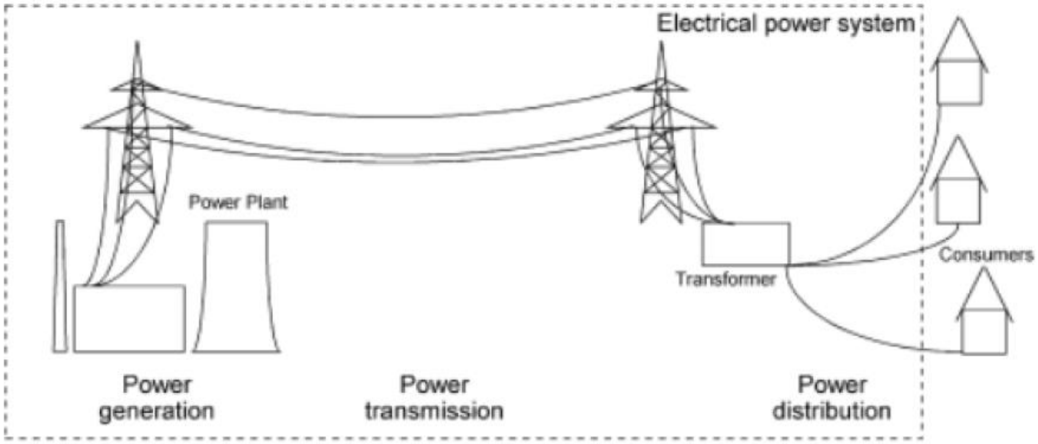


Figure 2. 1:Diagram of the Electrical power system network [13]

2.4 Overview of Reactive Power

Because of transmission power loss and copper loss, reactive power generation has a considerable effect on total power generation costs. As a result, to reduce the total loss, reactive power should be taken as variable, and the loss can be reduced through compensation.

Furthermore, insufficient reactive power support from the generator is the primary cause of voltage instability or voltage collapse.

The reactive power is required in electric power transmission and distribution networks to meet the requirements of proper working, so the actual magnitude and direction of the reactive power in such networks vary according to level of load and ratio of resistance to the impedance.

Reactive power is required for the working of a power system because different types of loads, such as induction motors and light loads, need reactive power for proper function. The circulation of reactive power, on the other hand, has an impact on the working of various power system components and their small system, such as lines for transmission and cables. The voltage drop can be generated or absorbed by an electric generator due to the flow of reactive power, which can result in voltage disturbance. It is primarily determined by the delivered active power, thermal limit capability, and the terminal voltage's accepted range[14]. When the length of the line is extended, the reactive power generated by the line can cause instabilities and deterioration of system performance. Then, controlling reactive power is required because it will improve voltage fluctuations, increase transmission system stability, capacity, and power quality, adjust voltage to user-determined level, dampen power oscillations in network, avoid system interruption, and reduce transmission system losses[15].

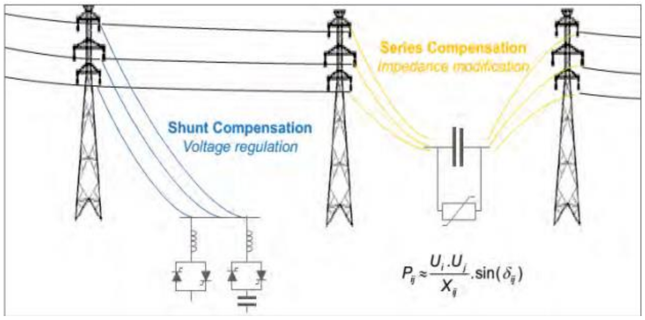


Figure 2. 2: Connection of shunt device and series controller[15]

2.5 Overview on the FACTS-Devices

The innovation for those devices began with the extending capacity in power electronic devices. The high power level and high voltage levels have been made in the converters for various fields and the elements of network influence reactive power or impedance of electrical power system components which results overall starting guides .

The primary role of FACTS devices are, voltage control, Power flow control, stability improvement, increased transmission capability, power quality improvement, flicker mitigation, renewable energy interconnection, distributed generation, and storage[16].

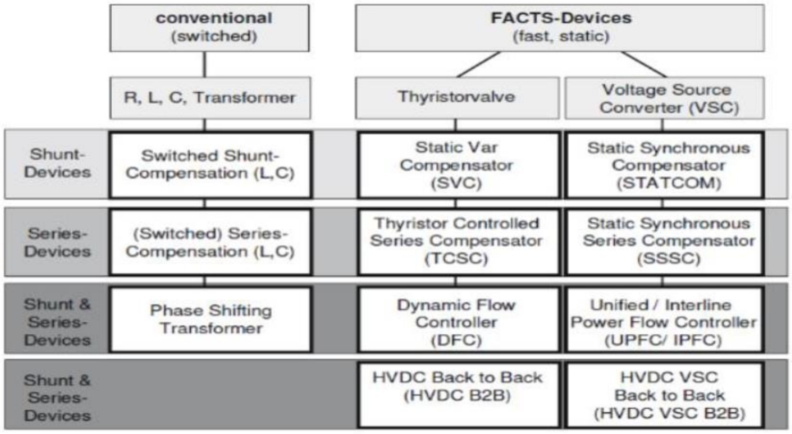


Figure 2. 3:Overview for some FACTS devices[16]

2.6 Types of FACTS Devices

A FACTs device is made up of a collection of fixed elements that work together to improve the power transfer capacity and control of an alternating current using power electronics devices. In a brief, a FACTS devices used for Controller are based on power electronic system and other fixed equipment's that controls one or more parameters of an AC transmission system. Those controllers are installed in series to the line on platforms and the manufacturers mention series devices, which is mostly used in static configuration. The reason for this is that most parts and system configuration require the some extra knowledge on those devices, but the series compensator is protected by a thyristor – bridge [16].

The main purpose for controlling reactive power in a system is for voltage stabilization, power losses reduction ,ensuring high stability and better usage of the machine linked to the system and to prevent voltage collapse as well as voltage sag[17].

FACTS used as controllers in the control are categorized as those having variable impedance and voltage source converter (VSC). There are controllers which are having variable impedance such as SVC, TCSC and TCPST Again, the controller based on Voltage source controller are: STATCOM, SSSC, IPFC and UPFC. The FACTS devices used for controlling are divided into four different ways: Shunt, series, series-series, and series-shunt combined controllers.

2.6.1 CONTROLLERS CONNECTED IN SERIES

From fixed or mechanically switched compensations to TCSC or even VSC, Series devices have evolved. They should be those for varying impedance, such as a capacitor, reactor, or power electronic-based variable source supply frequency and frequencies of harmonics to meet the requirements, and they should be able to inject voltage in series into the line[18].

The reactive power can be supplied or consumed once the voltage is in phase quadrature with the line current by injecting line voltage in it. The voltage is impedance times and is variable since the impedance is variable.

The external energy source is required whatever the case device supplies or absorbs for voltage which is more than or less than 90 degrees out of phase with the line, like in static synchronous series compensator (SSSC).

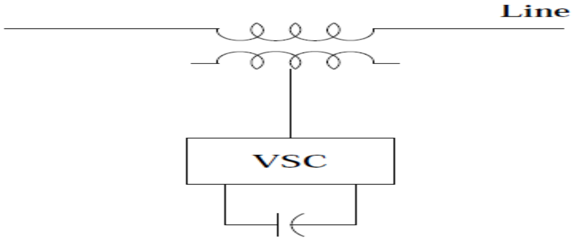


Figure 2. 4:Serie Devices[19]

The working principle of those devices depends on their characteristics either inductive or capacitive variable impedance connected in series as shown in Figure 2:5

It functions as a variable capacitive or inductive impedance that can be adjusted in series with the transmission line to dampen oscillations in the system, as illustrated in figure 2.5.

If the line voltage and current are in phase quadrature, the controller sinks or generates reactive power; otherwise, the controller sinks or generates active and reactive power according to the status of network.

The real power and reactive power flow is governed by the equation (2.8) and (2.9).The method of connection in transmission line is shown on the Figure 2.5.

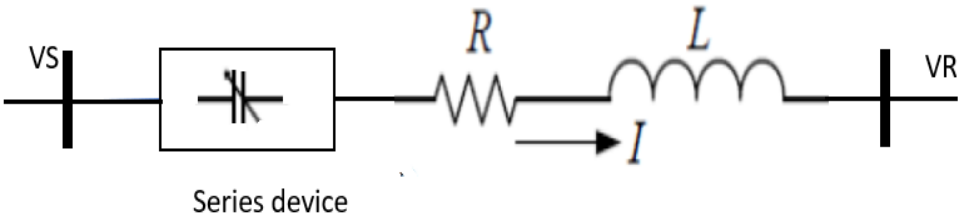


Figure 2. 5:Operation of series FACTS Devices[20].

$$P_R=\frac{V_R V_S}{X} Sin\theta \qquad (2.8)$$

$$Q_R=\frac{V_R V_S}{X} Cos\theta \; - \frac{V_R}{X} \qquad (2.9)$$

2.6.2 SHUNT CONTROLLERS

They can also be impedance and source which are variable, or a combination of impedance and source. As a general concept, most shunt controllers sent current at the point of connection. The shunt controller can only generate or consume reactive power if they inject current in phase quadrature with the line voltage. STATCOM is an example of such a controller.

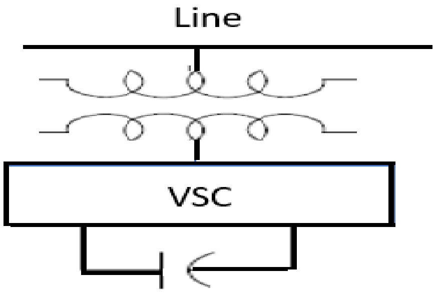


Figure 2. 6:Basic shunt FACT Device[19].

A shunt device's operating principle is to generate reactive power necessary for load by changing its impedance and injecting reactive current Ish, thereby controlling the line current I.

If the voltage at supply end (Vs) is constant, and the receiving end (Vr) can be controlled by a shunt controller as shown below [21] .

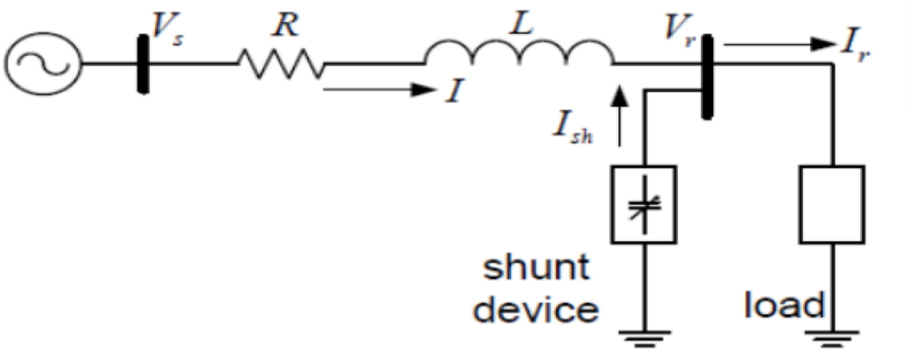


Figure 2. 7:Shunt device operating principle [21]

The following equation describes the relationship between the injected current Ish by the shunt device and the voltage at the receiving end Vr.

$$V_R=V_S-IZ \qquad (2.10)$$

$$=V-(I_R-I_{Sh})Z \qquad (2.11)$$

Where $Z=R+j\omega L$

Because of its variable impedance, the shunt device can control the voltage magnitude. In a heavy load condition, the line current (I) causes a voltage drop, which is mitigated by the shunt current Ish, which acts as a partial compensation for the large load current Ir.

2.6.3 COMBINED SERIES-SERIES CONTROLLER

It could be a series combination of separate controllers controlled in a coordinated manner for a given transmission system, or it could be a unified controller in which the series controller provides independent series reactive compensation for each line while also transferring the real power in the line via power links. This controller type includes interline power flow controllers (IPFC)[22].

2.6.4 COMBINED SERIES-SHUNT CONTROLLER

It is a combination of separate shunt and series controllers controlled in a coordinated manner or a unified power flow controller with series and shunt elements.

The combined series and shunt controller injects current into the system with the shunt part of the controller and voltage in series as the operating principle[19].

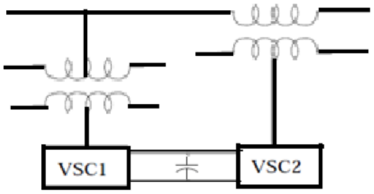


Figure 2. 8:Basic Series-Shunt FACTS Device[21]

FACTS DEVICES' BENEFITS

The advantages of FACTs devices are summarized below:

- FACTS Devices can help to reduce voltage fluctuations and dynamic over voltages.
- They help to optimize system operation by lowering power losses and improving voltage profile.
- Because of the high controllability, power flow in critical lines can be improved while operating margins are reduced. In general, the power carrying capacity of lines can be increased to a value up to the thermal limits (imposed by current carrying capacity of the line).
- Increase transmission system reliability and availability by making better use of existing transmission lines as much as possible.

The most common FACTS devices, along with their control mechanisms, are listed in the table 2.1:

Table 2. 1: FACTs devices with their control mechanism

FACTS Devices	**Control Mechanism**		
	Voltage control Device	**Impedance control device**	**Angle control Device**
SVC	YES	-	-
STATCOM	YES	-	-
TCSC	-	YES	-
SSSC	YES	YES	YES
UPFC	YES	YES	YES
IPFC	YES	YES	YES

2.7 Static VAR Compensator

The SVAR is a shunt-connected device that can operate as a static Var generator or absorber, with the output adjusted to exchange capacitive or inductive current for the purpose of keeping or trying to control specific electrical power system parameters, namely bus voltage[19]. The voltage on the busbar is controlled by switching between the capacitive and inductive currents delivered by SVC. It switches using a thyristor, which does not have the ability to be turned off the Figure 2.9 illustrate the characteristics [23] .

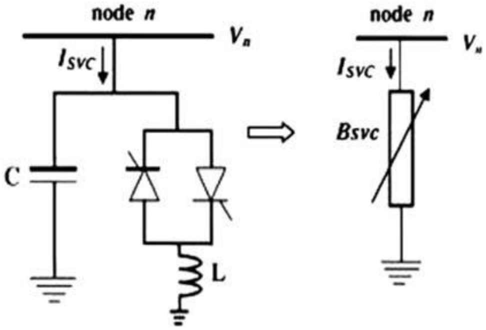


Figure 2. 9 :Variable shunt susceptance model of SVC[22]

Because the load change from hour to hour and the reactive power balance in a grid. This can result in unacceptably large voltage amplitude variations or high voltage deviation.

A fastly working Static Var Compensator (SVC) can provide the reactive power required to control the voltage at running condition under, improving power transmission and distribution in terms of stability[24].

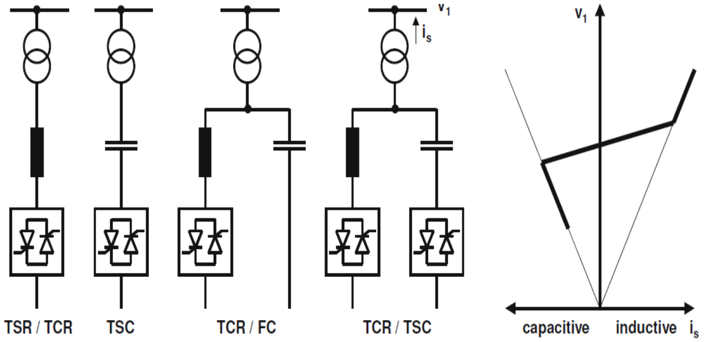


Figure 2. 10:Diagram of SVC with its voltage / current characteristic[16].

2.8 STATCOM

This type of FACTs device has similar characteristics to synchronous condensers it has no inertia and outperforms synchronous condensers in several ways since it is including better dynamics, low cost, and low operating and maintenance costs.

It is constructed with thyristors with turn off capability, like GTOs or IGBTs, and is generally designed to control transmission voltage through reactive power shunt compensation. It is generally made up of connecting transformer, an inverter, and direct current capacitor.

STATCOM can control the voltage of the local bus to which it is connected, as well as the impedance, voltage injection of a remote bus, reactive power flow, apparent power, or current control of a local or remote transmission line.

Control of the voltage of the local bus to which the STATCOM is connected, again this is commonly well-known control function among the FACTS devices.

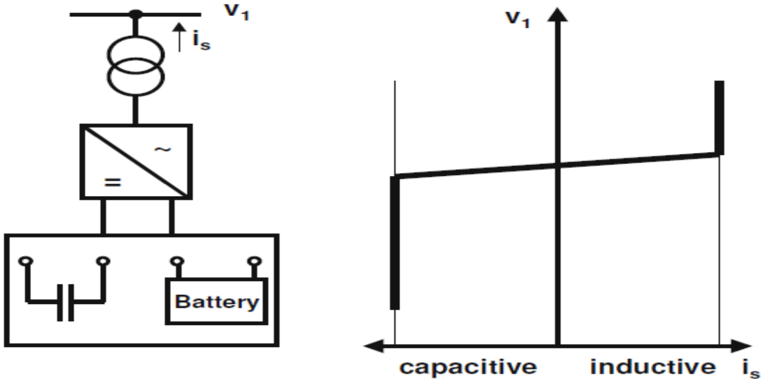


Figure 2. 11:Diagram of STATCOM with its voltage / current characteristic[21].

2.9 Overview of Electrical Power Loss

For consumption, power must be transmitted from the generating station to the customers station via wires or cable. Some of the generated power is lost along the channel for a variety of reasons. This is the question for energy efficiency issues, whether this loss is in the smallest possible range. It is useful to classify electrical system losses into two types for easy investigation: technical losses and non-technical losses[25].Transmission of energy and power must be done with as few technical and non-technical losses as possible, which are calculated as total losses during transmission[26].

2.9.1 Technical Losses (TL)

These losses that can be calculated and not eliminated ,power dissipation in electrical power equipment such as transmission and distribution lines, power transformers, and other electrical power equipment causes technical losses[27].

Technical losses are classified as resistive, leakage, or corona losses based on their source. The leakage losses are caused by the insulation materials made the resistance.

Partial discharges in the air surrounding overhead lines cause corona losses. As the voltage level rises, the air molecules become ionized and conductive. Ionization produces light, audible noise, radio noise, conductor vibration, ozone, and causes energy dissipation, resulting in line losses [28]. Load losses and fixed losses are two common classifications of technical losses (no-load losses). This classification method is useful when investigating the relationship between losses and power flow[29].

2.9.2 Losses from Load

The losses can occur in any network element via current flows. Variable losses are approximately to the square of the current and vary with the electricity distributed to the customer. They are simply made of copper or I2R. Variable branch or equipment losses range from 66.67 percent to 75 percent of total technical losses[29] .

2.9.3 Losses from NO- Load

Those losses are due to the reading which indicate the voltage on elements and are very small in comparison with overall peak losses. Constant losses, on the other hand, are independent and occurs during working elements.

Fixed losses exist all of the time means 365 days ; the only issue affecting measurement accuracy is determining the scope of the losses in general [25]. The main sources of no-load losses are iron cores of transformer due to eddy current and hysteresis losses, losses in transformer primary windings, corona discharges, and voltage coils of energy meters [30].

Losses from no-load are easily identified in electric system and range from 20percent to 40percent of total energy. Measurement of technical losses can be found by considering network components such as resistance, inductance, capacitance, voltage, current, and power.

2.9.4 NON-TECHNICAL LOSSES(NTL)

Most non-technical losses are unrelated to the electrical power system's characteristics and functions. These losses are not considered to be consumption losses, and as a result, they are classified as losses with no consumption cost. Their evaluation is based on the difference between generated and sold energy. Non-technical losses include incorrect meter readings, unpaid energy consumption (theft), failure of energy meter , and billing shortfalls [31].

The research shown that in Rwanda Network by Considering transformer losses, the total active power losses were obtained as 4.85MW and were reduced from 4.85MW to 3.42MW by adding an identical parallel line to each of the three lines that have a high contribution of the line losses, which is equivalent to a 29.5 percent reduction[26]. Figure 2.12 illustrates the variation of loss before and after controller connected.

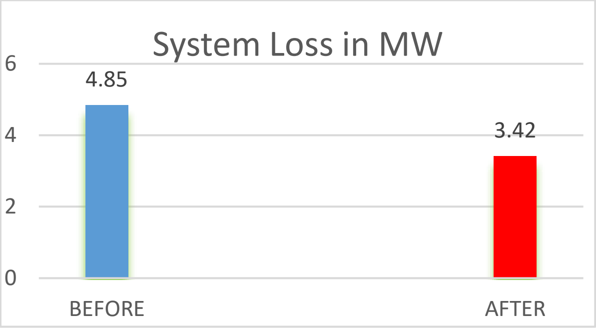


Figure 2. 12:Change in power losses after addition of parallel lines of the same impedance.

According to the loss reduction rate model, the rate of line loss rate can be reduced by adjusting the injected power to the nodes and reactive power consumed at nodes in order to minimize power utility grid line losses[32]. By adjusting the injected power, the two cases are sensitive to reducing line losses. In the past, Rwanda Energy Group has launched programs to reduce technical and commercial losses to improve the utility's overall efficiency. Losses have already been reduced to 22 percent and are expected to be reduced to 15percent by 2024[33]. Each of the stages identified in is prone to losses, presenting an opportunity for efficiency improvements.

The cumulative benefits can be enormous, Because losses occurs along the way, a one-kilowatt (kW) load reduction at the customer's end translates into more than a one-kW load reduction sometimes much more – moving "upstream" to the distribution, transmission, and generation levels[34].

The sequence of the power system network is shown in the Figure 2.3 from generation up to end users. The protection for the net work is not shown but at each stage of generation there is special protection to ensure the network stability and reliability.

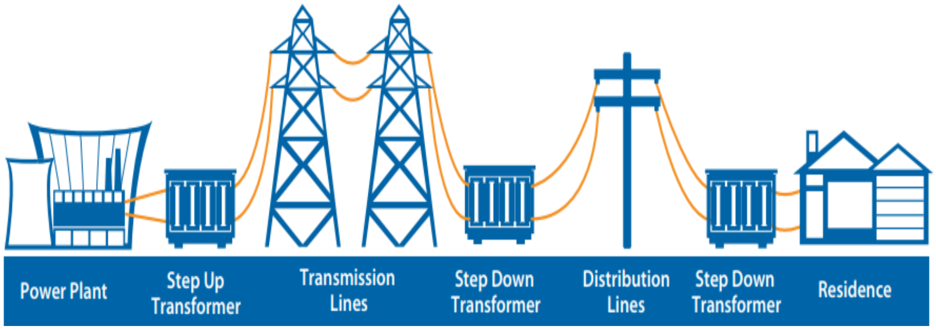


Figure 2. 1:Simple Diagram of Electric Transmission and Distribution System [34]

Technical studies on Rwanda's power grid revealed that the current network has high losses in transmission and distribution lines, with a loss of 23% at the end of 2011. During system operation, transmission, and distribution of energy with low losses (commercial and technical) were considered in high and medium voltage systems.

The construction of a 110kv network to secure electricity supply in Kigali city, the addition of new distribution lines and substations around Kigali to handle the rapidly increasing electricity demand, and loss monitoring are all being considered as recommendations[35].

2.9.5 Minimization of losses in Transmission lines

The highlighted options to reduce the losses include improving the connection quality of cables (power lines), replacing the bad sized transformer, and increasing the accessibility of reactive power by installing capacitor banks in the transmission lines or special controllers where this research will be focused. Losses in electricity supply to the final consumer, refer to amounts of power in the grids that are not paid for by users. The lowest losses contribute to lower air pollution emissions and lower consumer electricity cost.

Technically, total transmission line power losses can only be kept to a bare minimum if power is transmitted at a very low current along transmission lines which will decrease the ohmic or line loss on the conductors.

As confirmation, always electric power transmission should consider the scenario below:

(i) the working voltage is the same as the critical disruptive voltage. When this occurs, there is no ionization of the air surrounding the conductor, and thus no corona is formed. As a result, corona loss will not occur, and

(ii) the distance between transmission lines should be within acceptable limits. This is due to the fact that increasing the spacing between conductors reduces electrostatic stresses and as a result, the corona effect[36].

2.10 CALCULATION OF LOSSES

Various techniques can be used to calculate the losses in an electrical system. For the low current resistive material must have the low losses and the voltage of the system is adjusted [37]. The losses electric power system can be calculated using a variety of formulas/techniques that consider the arrangement of generation stations and loads, using any of the following methods: Using I2R to calculate transmission losses and method of differential power loss.

2.10.1Calculating transmission losses as I^2R

Assume two different points of transmission line like generating and receiving ends, as shown in figure2.14.below, with the generated power P G, resistance of line R, reactance (jx) of line,and load[37].

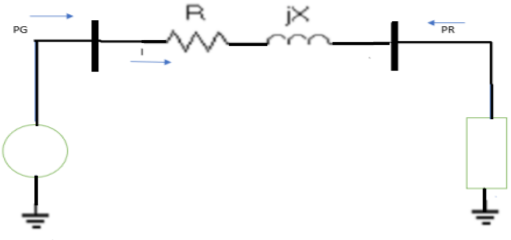


Figure 2. 13:Single line diagram with one generator and load[37]

The real power loss of a transmission line is calculated as

$$L_{osses} = 3I^2R \quad (2.1)$$

The current flowing in the line is given as

$$I = \frac{P_G}{\sqrt{3}V_G COS\emptyset_G} \quad (2.2)$$

Where P_G,V_G and $\emptyset_G$:generated power, generated voltage, and generator power factor respectively. Use (2.2) into (2.1)

$$P_{LOSS}=3\left(\frac{P_G}{\sqrt{3}V_G COS\emptyset_G}\right)^2 R \qquad (2.3)$$

by assuming the generator voltage and power factor constant

$$P_{LOSS}=B{P_G}^2 \qquad (2.4)$$

$$\text{Where } B=\frac{R}{{V_G}^2(COS\emptyset_G)2} \qquad (2.5)$$

2.10.2 Differential method

The difference between transmitted and received power should be considered to calculate real power loss for transmission network[31]- [37]

$$P_{LOSS}=P_{Sent}-P_{Received} \qquad (2.6)$$

Line losses of transmission can be easily calculated taking the difference between the receiving end power and the sending end power, as shown in equation 2.14. However, this method is only used if both the power at sending point and power at receiving end are known.

Because the system is complex, for large interconnected systems the mentioned method is not applicable. Otherwise consider two consecutive buses. Additionally ,transmission & distribution losses (T&D losses) are calculated as [38].

$$\text{T\& D Losses} = \left(1-\frac{Total\ energy\ Billed}{Total\ Energy\ in\ the\ system}\right) \text{ x } 100 \qquad (2.7)$$

Losses incurred as a result of technically and commercially failures are given below

AT& C Losses = (1-$Billing\ efficiency$ x collection Efficiency) x 100

$$Efficiency = \frac{Total\ unit\ Billed}{Total\ unit\ inputs} \qquad (2.8)$$

$$\text{And Collection efficiency}=\frac{Revenue\ collected}{Amount\ Billed} \qquad (2.9)$$

2.11 Related works

E. D. Dinu, D. Ilisiu[9], This paper discusses the main technical issue of power and reactive power control for wind farms and photovoltaic systems that cause power fluctuations. Voltage instability is likely when there is a high level of reactive power. The unfavorable problems of reactive power flow rise the current drawn from the load which increase the losses and the operating costs as well as maintenance and reduce power stability margin.

A.A. Abdel Hafez, S. H. Airways [14], This paper describes the flow reactive power with real dilemma while providing the proposed possible strategy, conventional and updated solutions. A series inverter in the unified power flow controller can control the active and reactive power flow of the transmission line.

S. H. Hosseini and M. R. Banaei[39], This paper discusses the principle objective of a series power converter, which is used for in rind distribution system for loss reduction as voltage source to manage the power flow in te system .Also for harmonic current reduction and courent sourse to compensate reactive power due to nonlinear load, shunt inverter is involved.

I. T. Papaioannou, A. Purvins, and C. S. Demoulias[40], presents theory concerned with practical studies for reactive power compensation (using circuits for connecting capacitor banks, structural circuit diagrams for automatic control reactive power level, and measuring capacitor bank values). Power quality is ensured in terms of voltage and the grid reactive power, this reduces power losses and filtering the harmonics of undesirable current and voltage. however, this method does not consider an automatic way of controlling reactive power.

A. A.Abood, F. M. Tuaimah, and A. H. Maktoof[41], SVC is an important reactive compensation device that has been used in power systems to maintain bus voltage at a constant level, improve transient stability, dampen systems, and suppress voltage flicker. According to the author Static VAR Compensator (SVC) is one of the shunt-connected devices that can be used for voltage and reactive power control in power systems. It provides an excellent source of rapidly controllable reactive shunt compensation for dynamic voltage control via the use of high-speed thyristor switching/controlled reactive devices.

2.12 Research gap

The network stability is required for all over the world, then the operator and the customer need to have stable network for easy access of electricity. According to the literature review from above Rwandan grid has significant losses due to voltage increase and as normal most of utility grid has voltage drop which cause the network interruption like blackout. This research will help the dispatching center to rectify the voltage drop and losses by controlling the reactive power using specific FACTS devices in optimal location.

Furthermore, the primary goal of this research is to determine how to maintain efficiently the reliability of the power system network, which will be accomplished by reducing power losses due to uncontrolled reactive power and other internal or external factors.

Chapter II: METHODOLOGY

3.1 INTRODUCTION

The single line diagram is the heart of an electrical power grid system. Figure 3.2 represents various Rwandan substations; simulation was carried out and the results were compared to data collected for this research.

3.2 DATA COLLECTION

The equipment used to collect data, such as a paper questionnaires, personal computer or laptop, discussion, are referred to as data collection tools. Data was taken using a range of methodologies, including Checklists, Discussions, Observation, and Questionnaires. The data collected include line resistance, line reactance, line length, transformer data, load (peak, minimum and average) for transmission in each, export and import energy, shunt reactor contribution at two substation SHANGO, and BIREMBO and capacitor bank rating.

3.3 ANALYSIS FOR LOAD FLOW

The load flow analysis is the root foundation of a power system; it will be used to find the parameters in network like real power, voltage, current, reactive power and losses in interconnected network. The load flow will be used to determine the voltage profile at each bus bar during various load conditions, such as full load and light load.

The power system operator must have a thorough understanding of load flow analysis studies to improve the current system condition, as well as to plan for future expansion. It is critical for existing system planning, control, and protection should be based on system configuration when new load and new generating station is added. Load flow studies also enable in the selection of power electronics (FACTS device)-based devices and their optimal placement to reduce losses, regulate voltage profile and of course, reactive power. It is obvious that load flow can solve the problems of unknown voltage at the bus, unspecified generation, and complex networks.

The analysis of load flow can be used to calculate total transmission loss. It provides both real and reactive power at various buses. The algebraic sum of powers injected at all buses can be used to calculate total transmission loss. This research will look at load flow analysis to determine bus voltage profiles, active power flows, reactive power flows, and transmission line losses.

3.4 Research steps

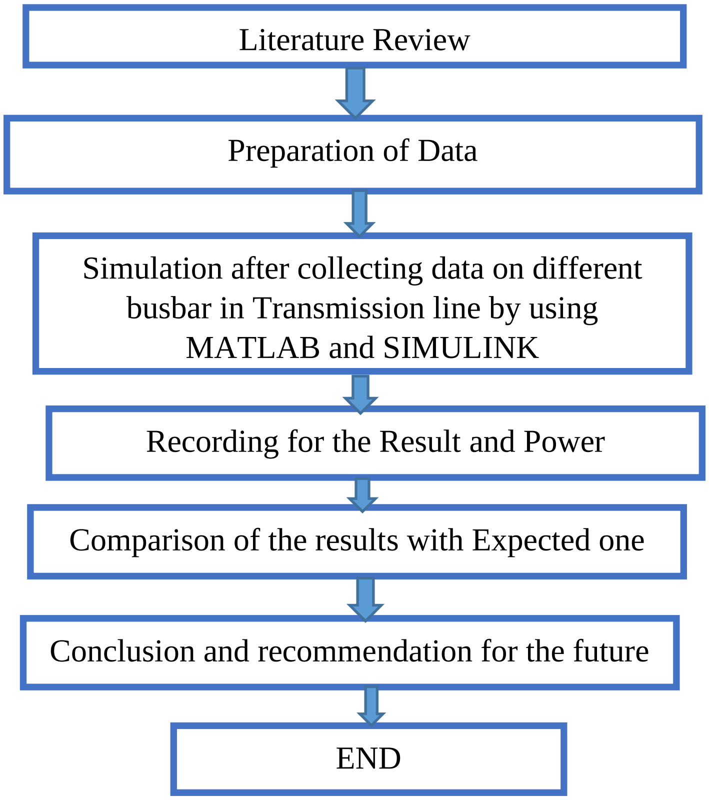


Figure 3. 1:Research steps

3.5 SINGLE LINE DIAGRAM

A single line diagram, also called the one-line diagram is a symbolic or graphical representation of a three-phase power system. It has a diagrammatic representation of all the equipment and connections. Electrical elements such as circuit breakers, transformers, bus bars, and conductors, are represented using standardized schematic symbols so that they can be read and understood easily.

In a single line diagram, instead of representing each of three phases with separate lines, only a single conductor is represented using a single line. A single line diagram makes it easy to understand an electrical system, particularly in the case of complicated systems in substations. It helps in a detailed study and evaluation of the system and its efficiency.

The single line diagram is the most important component of an electrical power system. The Figure 3.2 depicts various substations in Rwanda where this thesis will compare simulated cases with data collected.

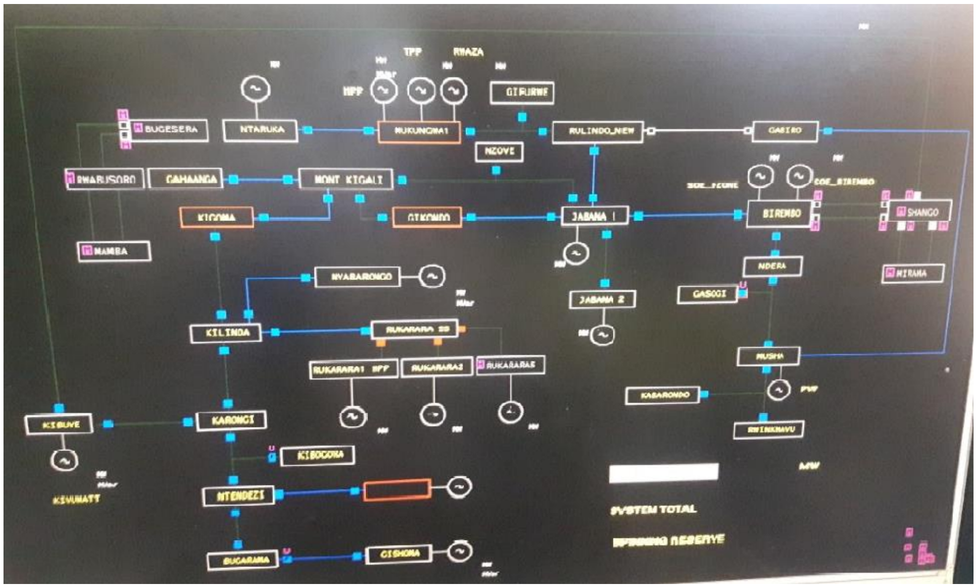


Figure 3. 2:Transmission Network of Rwanda

3.4 ANALYSIS OF DATA

After visiting different substations in Rwanda, the data have been recorded in terms of voltages and power. According to weather condition the power generation was recorded for all power plants in different month like March to April and July -September in the year 2021. According to the field interview made, the site engineers confirmed that in Rwandan grid a shunt reactor is employed.

3.4.1 Interpretation of the data collected (Appendix A)

According to the data tabulated above the total power is changing, this shows that the behaviors of network are changing time to time and the generation of power plant responds depending on the state of electrical network. The allowable voltage limits are _+10%, then the line of gikondo national dispatching center connected on busbar has different voltage due that allowable limits as shown in appendix A. The first simulation in MATLAB shows two busbars where the case is overvoltage or Ferranti effect.

As per the interview conducted with dispatch operator, there is only voltage swell which demanded the installation of a shunt reactor for proper matching voltage levels at both ends. Appendix B shows the data for shunt reactor with its contribution as well as its location in electrical networks. The data are taken in two substation Shango substation and Birembo substation. Data was recorded for the first and last day of April and July 2021 respectively.

3.4.2 Interpretation of the data collected in the substation (Appendix B)

From the first day of march there was no reactor switched on, it was clear that the network was in stable state in the range up to five hours and there are no records at that time. but when the last day of July there was involvement of shunt reactor due to high voltage in the line, this condition will be simulated for the case one. From the first day of July and the last both cases had the shunt reactor connected in network however there was low power factor due to high current in the line for the thyristor switched capacitor.

3.4.2Transformer data

The data collected is for two winding transformers and are recorded below and let us select at least 3 transformers.

Table 3. 1:Transformer Data

substation	Transformer no	Voltage primary(kv)	Voltage secondary(kv)	Transformer capacity(MVA)	Turn ratio	connection
Birembo	1	110	15	20	7.3333	YNyn0+d11
shango	1	220	110	93.8	2	YNa0d11
jabana	2	110	15	10	7.333	YNyn0+d

Table 3. 2:Data for Total energy generated and exported/April ,2021

Power plant	**Active energy(kwh)**	**Reactive energy(kvarh)**
National	**72,523,360.51**	**5,285,088.78**
EXPORT		
Cyanika-Gisoro	**444,943.30**	**6,523.5**
Gisenyi-Goma	**-**	**-**
KAMANYOLA	**159,870**	**48,132**
MURURU II	**-**	**4,406,000**
Total Export	**604813.3**	**4,460,656**
IMPORT		
RUSIZI I	**2,006,000**	**50,000**
RUSIZI II	**6,590,000**	**4,000**
KABARE UATCL	**738,860.1**	**358,298**
Total import	**9,334,860.1**	**412,298**

The import energy is very high than export through the interconnection because we have some time high demand and most energy is lost in transmission line and electrical network.

Electricity is generated by generating stations and transmitted to load centers from where it is distributed to end consumers. These load centers are controlled by distribution utilities, and there is an inter-change of energy between different utilities connected to the grid.

Consumers connected to the distribution utilities, though consuming active energy may or may not consume reactive energy. There may be consumers whose loads are predominantly inductive and other consumers whose loads are predominantly capacitive. There may be bulk consumers who have their own generators who operate their generators in synchronism with the grid, drawing active energy from the system or even exporting active energy into the system.

The exchange of electricity is complex in such situations, and four quadrant energy measurements are needed to accurately measure the active and reactive energy under different export/import conditions for both active & reactive energy.

Energy measurement under such situations will depend on applicable tariff structures, and hence to cater for different tariff structures in the environment of import/export of active/reactive energy special data logging/measuring features are required in meters. In this regard there are three forms of measurements to deal with (in metering) and these are active energy, reactive energy & apparent energy.

3.5 Diagram configuration for the simulation of SVC

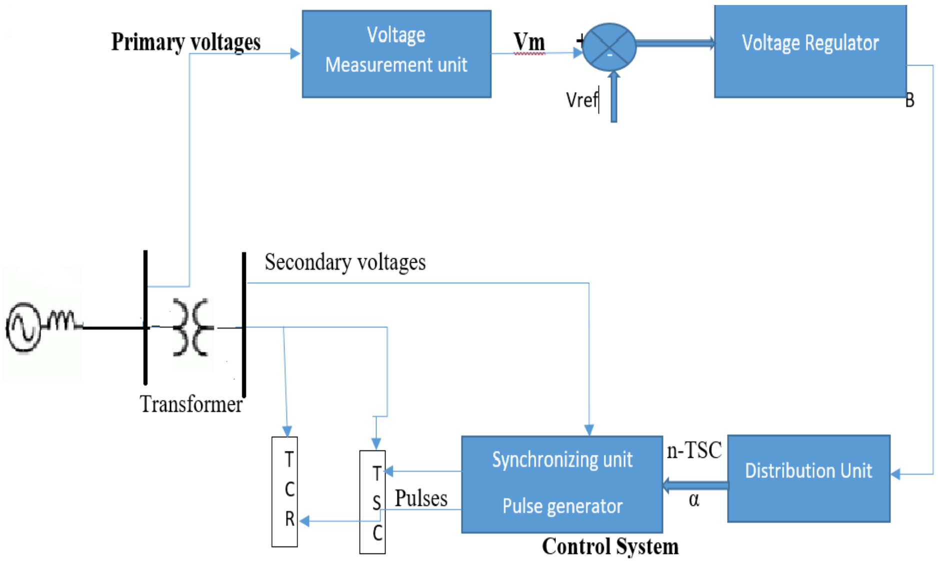


Figure 3. 3:SVC With its control system

3.5.1. Details of Control System Parts.

1.**A measurement part:** for controlling the voltage. One cycle running is used in a Fourier-based measurement system.

2.**A voltage regulator** the difference between the measured voltage Vm and the reference voltage Vref means voltage error is used to calculate the SVC susceptance B required to provide invariable system voltage.

3.**A distribution unit** that calculates the angle alpha of TCRs and determines which TSCs (and eventually TSRs) must be switched in and out.

4. **A synchronizing unit** made of a phase-locked loop (PLL) synchronized on secondary voltages and a pulse generator that sends required pulses to the thyristors.

Diagram configuration

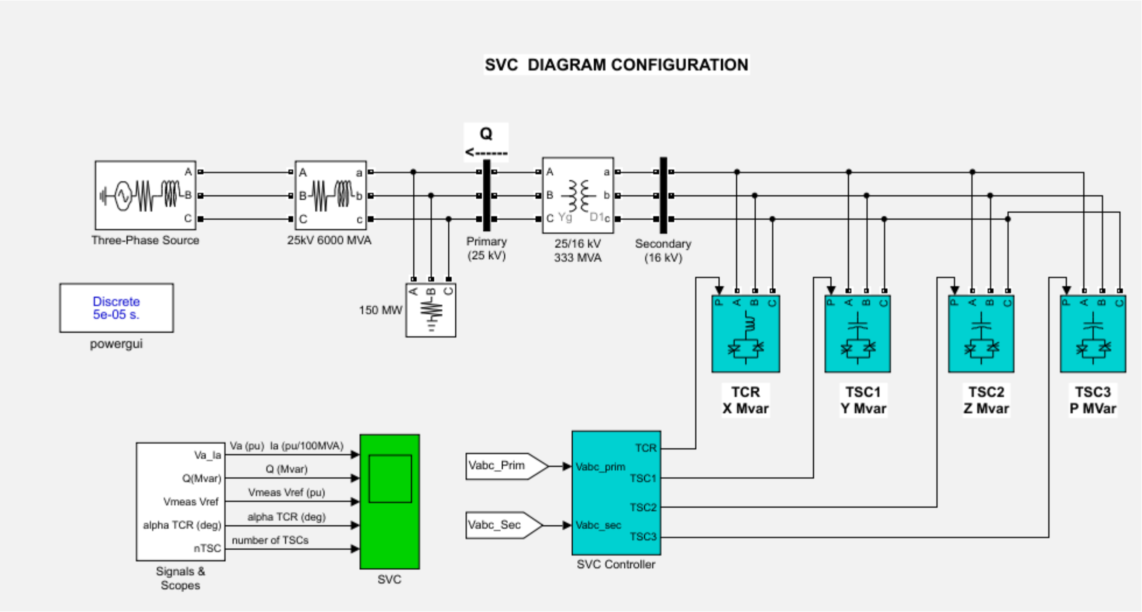


Figure 3. 4:SVC Model from Simulink and their working principle

Explanation of each part:

i. Three phase generator sources: this is used as source to generate the power required.

ii. Three phase RL and parallel restive load branch are used to limit the current coming from the source.

iii. Transformer is used for stepping up or boosting the voltage.

iv. Using its control system, the SVC controller can control the reactive power by turning on or off the number of TCR or TSC by varying the firing angle. The primary voltage Vabc is controlled atVref within the maximum inductive and capacitive susceptibility at Bref in voltage control mode (this is less than 0 in inductive mode). Thyristor pulses are synchronized on the coupling transformer's secondary line-to-line voltages (Vabc sec), assuming a Wye/Delta (D1) connection).

The control ratings of the TCR and TSC in Figure3.4 are changing depending on the system configuration as it is represented by the letter X, Y, Z and P respectively.

3.5.2 Types of bus that will be used for Simulation

The Slack Bus (suing bus): The angle of voltage and magnitude are specified on a slack bus, but the active and reactive power injections are unknown.

The known voltage of the slack bus is used to calculate the angles from all remaining buses. In most systems, slack bus should be one . However, in some production grade programs, more than one bus may be included as distributed slack buses.

Bus from PV:The real power injected and voltage magnitude are known on a PV bus, but the voltage angle and reactive power injected are unspecified. PV buses are typically generator and synchronous condenser buses.

Bus from PQ. The real and reactive power injections at a PQ bus are known, but the voltage magnitude and angle at the bus are unknown. A load bus is commonly referred to as a PQ bus.

Chapter IV: DESIGN AND SIMULATION

4.1 SIMULTION FOR TWO BUSBARS

The design of transmission line here will be in two categories where for the first case i have AC generator, transmission line π model, load, two busbar and one of shunt controller either TCR or TSC.The Figure 4.1 is the single line diagram:

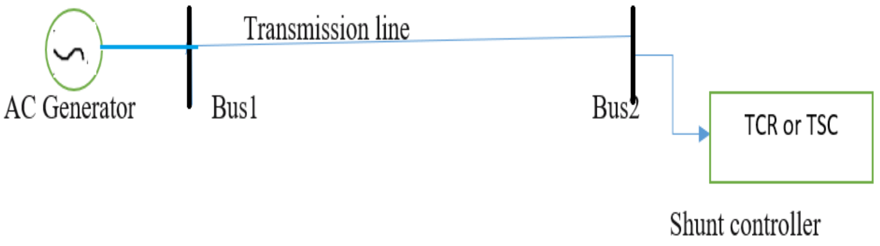


Figure 4. 1:Model for two busbar and transmission line(π)

The lists of these parameters are required to simulate for the above single line diagram

Programmable voltage sources(3phases)
Serie resistance (small value)
Two busbar or voltage measurement
Transmission line (π model)
Display (6)
Shunt capacitor(3phase)
Load (3phase)

There are two scenarios: one in which the voltage is lower than the receiving end voltage and one in which the receiving end voltage is greater than the sending one (Ferranti effects).

Case one

The case below are the voltage at busbar 1 or three phase voltage measurement is 31.17kv and at receiving end is 26.73kv this is cause the shortage for power transferred and a special controller is at bus 2 for compensation.

The simulation diagram is shown on Figure 4.2 and the results are displayed.

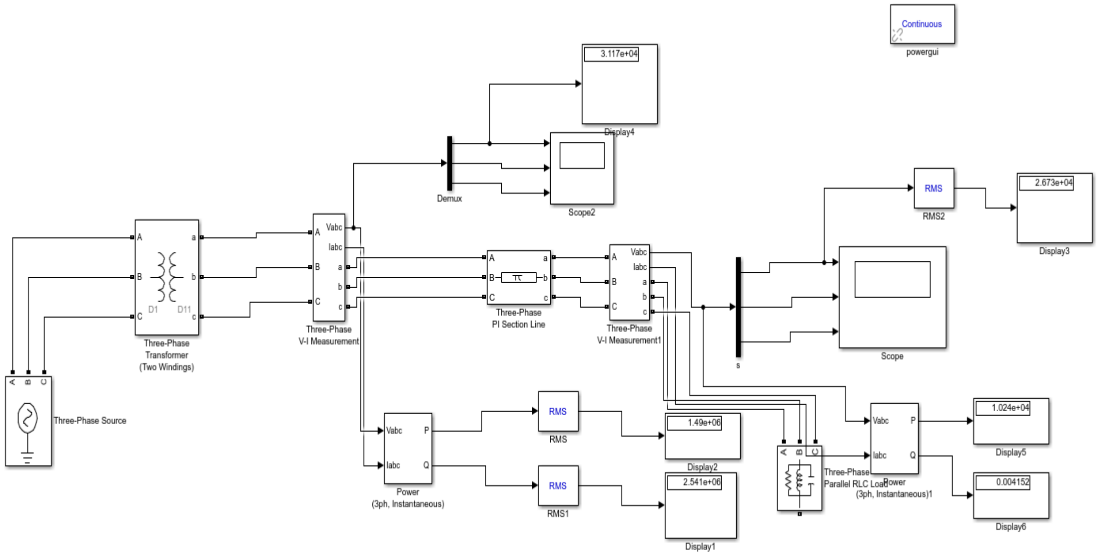


Figure 4. 2:Under voltage due to low Reactive Power

	P(MW)	Q(Mvar)
Total generation	0.280872	-1.42795
Total PQ load	0.01	-1.1E-07
Total Z shunt	0.269345	0.269387
Total ASM	0	0
Total losses	0.001526	-1.69734

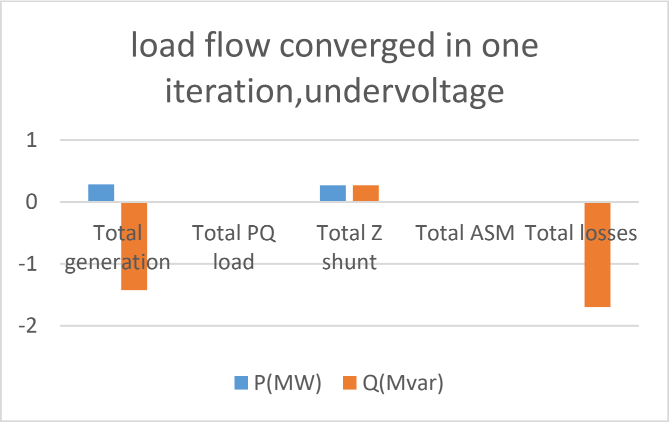


Figure 4. 3:Power losses before control

The above case of undervoltage is due to uncontrolled reactive power in the network and refer to the Figure 4.3 reactive power is high than the real power and of course this cause problem of power losses and voltage drop.

The Figure 4.4 is the simulation block with shunt capacitor installed at the receiving end for proper compensation.

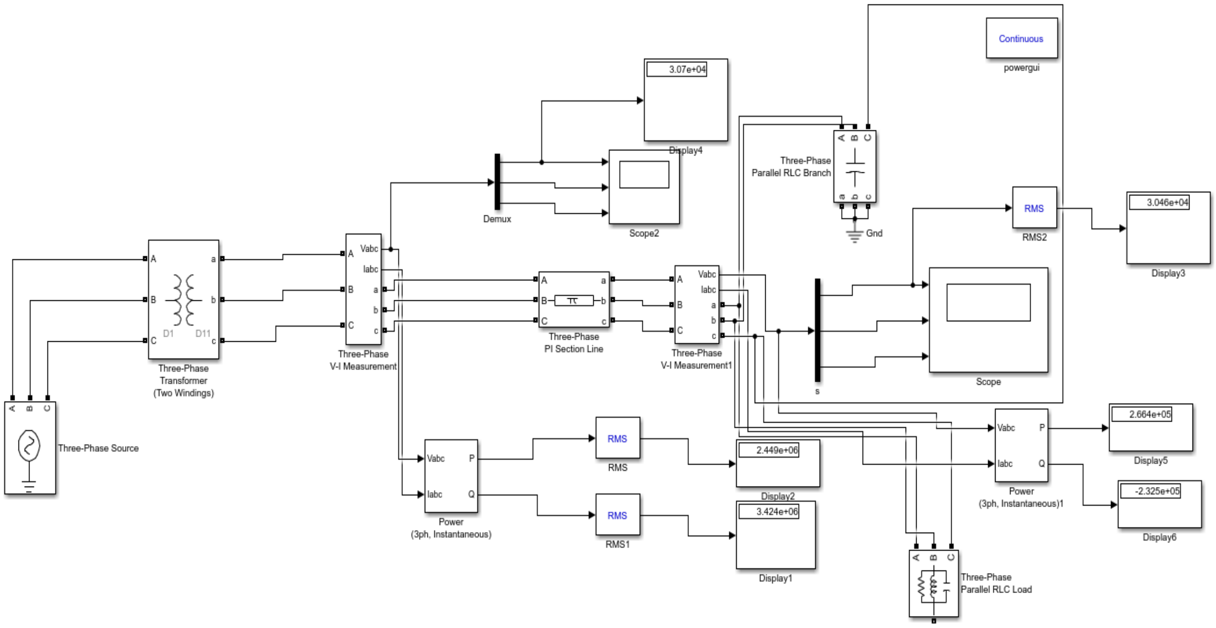


Figure 4. 4:Compensation with Capacitor connected in shunt at bus Two

	P(MW)	Q(Mvar)
Total generation	0.281536	-1.61141
Total PQ load	0.009996	-0.00081
Total Z shunt	0.269404	0.077435
Total ASM	0	0
Total losses	0.000213	-1.68803

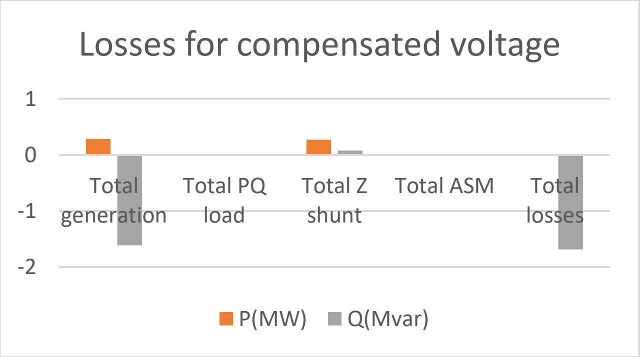


Figure 4. 5:Losses after Control

The three-phase capacitor is connected at receiving end and there are some small because the controller is shunt connected. sending end voltage is 30.7kv and receiving end voltage30.46kv this matching is due to capacitor connected for proper compensation although there is small deviation.

Case Two

The same material as above simulation, except the source which is programmable, and no transformer and all the case are simulated for the purpose of finding the possible solution.

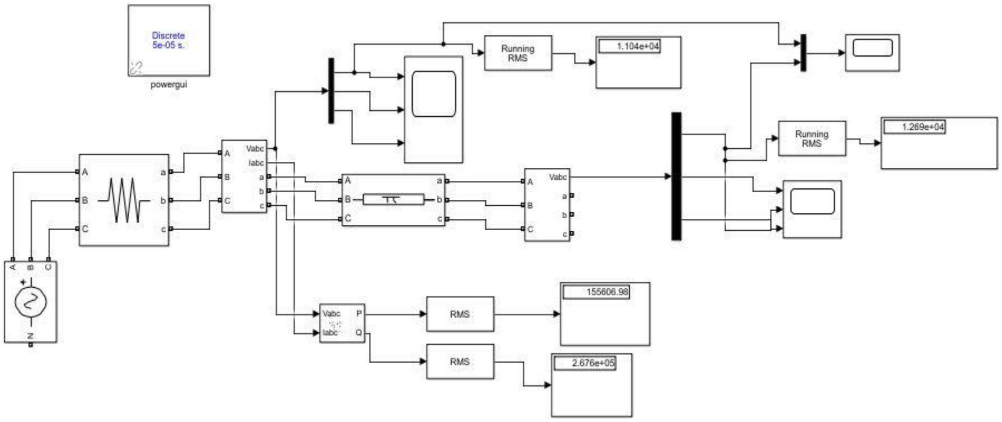


Figure 4. 6:Overvoltage due to more reactive power

Discussion: The results displayed have special consideration in electrical network because there is Ferranti effects as you see there his high voltage on receiving end 12.69kv and the sending end is 11.04kv. There is more reactive power and as possible solution in any given network shunt reactor and TCR is going to be installed on the receiving end however TCR is very accurate due to its electronic control. The simulation below is for the stated case.

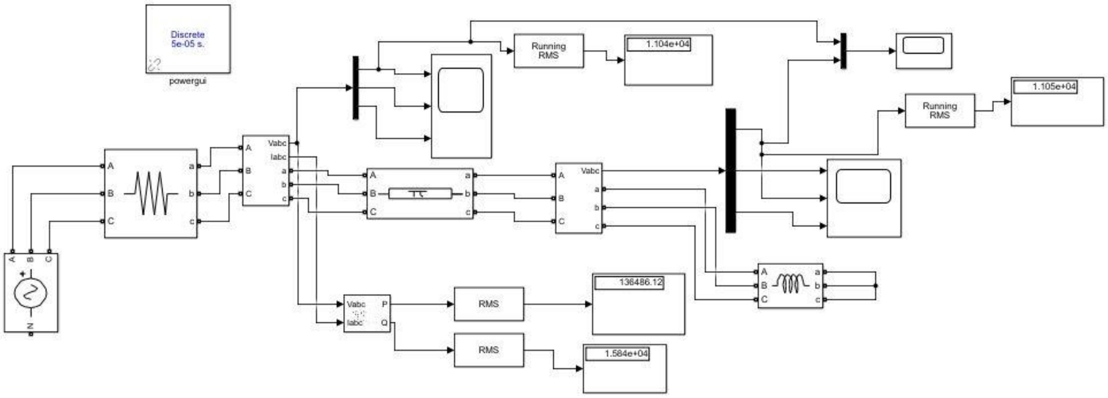


Figure 4. 7:Compensation by using shunt Reactor at bus Two

Discussion on results: After connecting the shunt reactor for consuming the reactive power and the inductor connected, as result the voltage at the receiving end is 11.05kv and sending end voltage is 11.04 kv, here the losses are reduced, and voltage are minimized.

For the analysis done , there is some small deviation and to solve this problem accurately consider the TCR is connected in the simulation diagram shown on Figure 4.8.

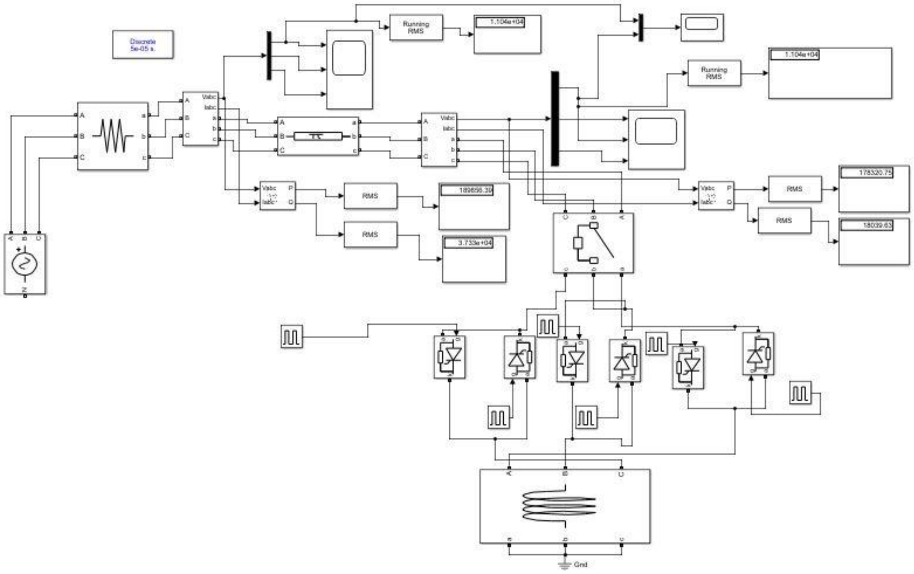


Figure 4. 8:Compensation by using TCR

	P(MW)	Q(Mvar)
Total generation	0.000267	-0.00451
Total PQ load	0.000146	-0.00247
Total Z shunt	0.000121	-6E-07
Total ASM	0	0
Total losses	1.05E-09	-0.00204

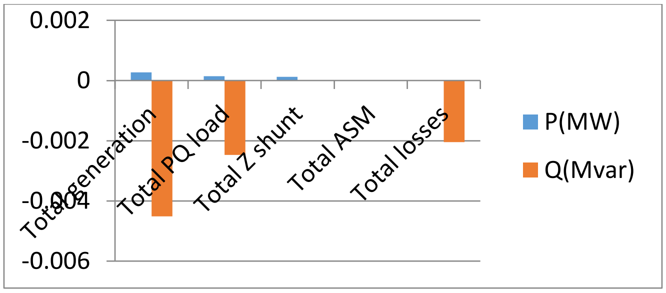


Figure 4. 9: Losses after connecting TCR

Discussion: Since the TCR is power electronic based controller can control the reactive power so that the sending end and receiving end are the same 11.04 kv. The three-phase circuit breaker can be closed or opened according to the status of the electrical network. The total generation are due to the transmission line and generator parameters.

4.2 GENERAL DESIGN AND SIMULATION

After visiting different substations, I have decided to select single line diagram of six busbar system and FACTS Device connected either on bus 5 or 4.
specifically, SVC, UPF and STATCOM will be simulated

The simulated diagram below is for five busbar, generator sources, transmission lines and other parameters like transformer, only two ends are considered for electrical network analysis.

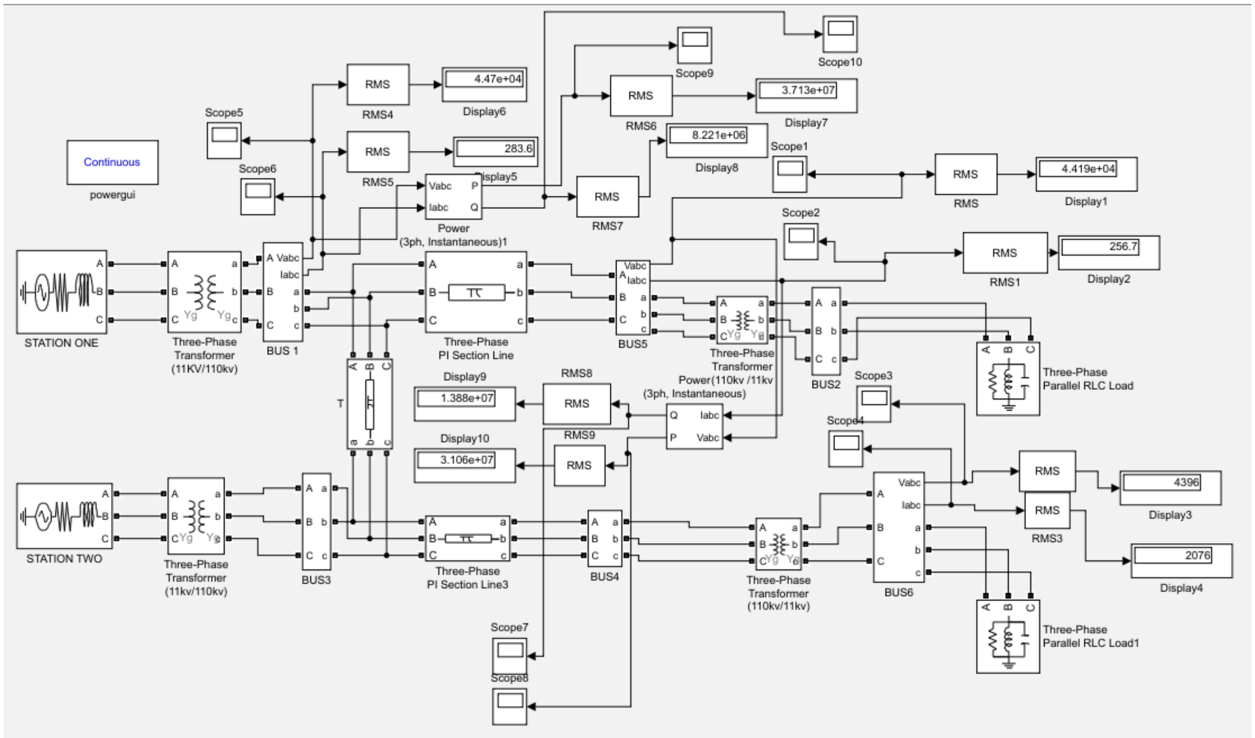
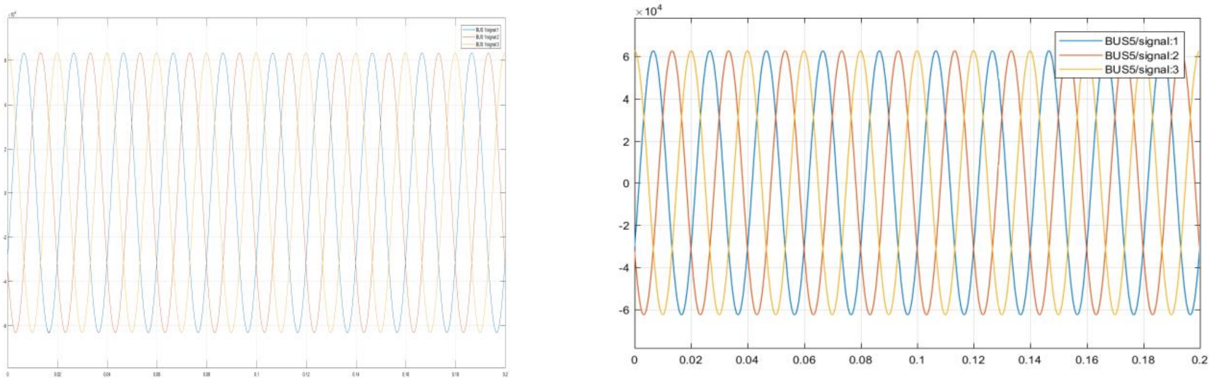


Figure 4. 10:Power System Network with Six Buses

Due to more reactive power, there is voltage drop according to the displayed data VS=44.7kv and VR=44.19 kv and their corresponding signal from scope is shown Figure 4.11.

The sending end voltage and receiving end voltage is simulated with accurate parameters and the results is given as below :



(a)Receiving end voltage (b)Sending voltage

Figure 4. 11:Sending End voltage and Receiving end voltage

Due to the variation at the receiving, different FACTS Device is going to be connected so that it can consume or generate reactive power in network. In The circuit below, STATCOM is connected in parallel for compensation of reactive power.

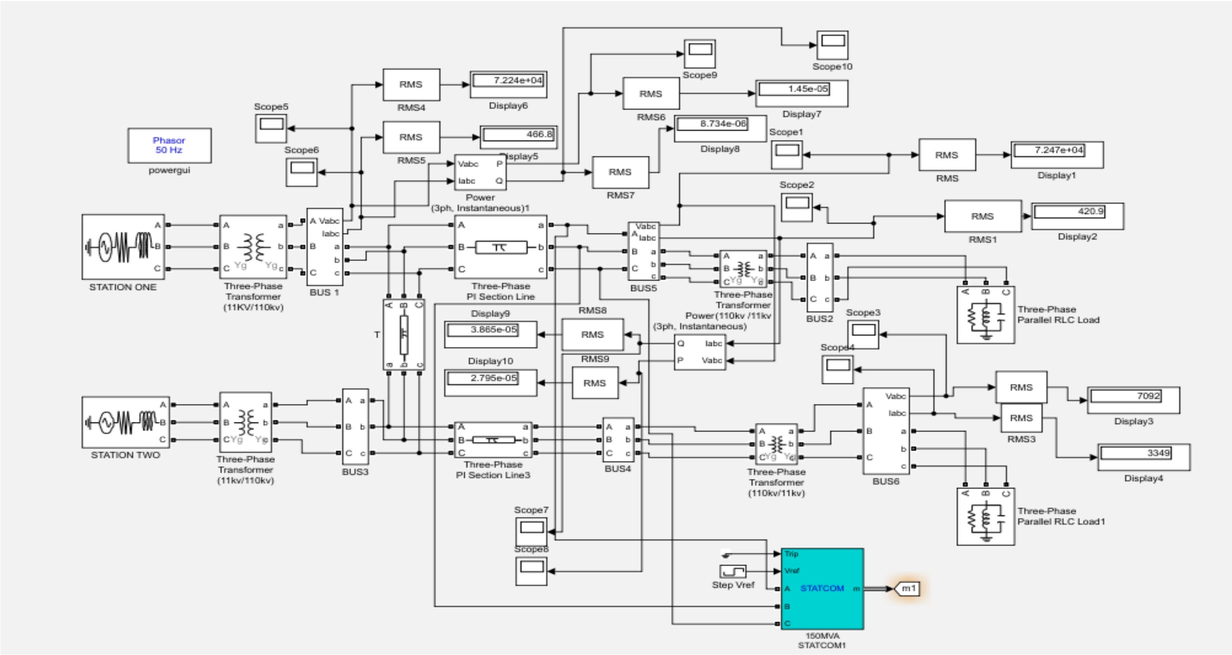


Figure 4. 12:Compensation with STATCOM connected

After Controller

With the FACTS device connected on the bus number five and solving the load flow for STATCOM, SVC, SSC and UPFC connected. The simulation model are shown in appendix C and the results are tabulated in Table 4.1

Table 4. 1:The recorded Real power for all different Busbars

BUS NO	SVC	UPFC	SSS	STATCOM
1	20	40	60	80
2	40	20	60	80
3	40	20	60	80
4	40	20	60	60
5	20	40	80	80
6	37.1	31	60	80

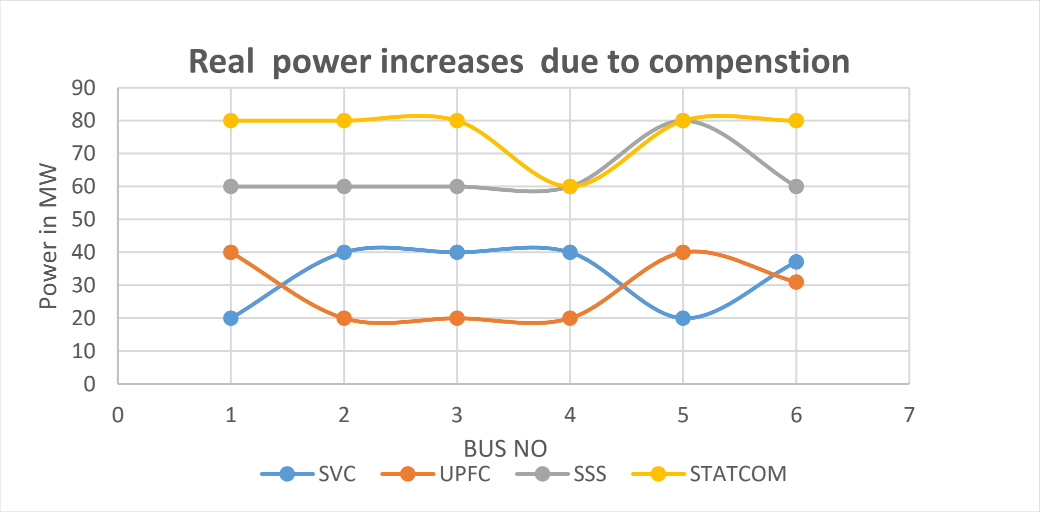


Figure 4. 13:Increase of power for different FACTS Devices

Table 4. 2:The record for reactive power in different busbars

BUS	SVC	UPFC	SSS	STATCOM
1	100	190	210	80
2	100	190	210	80
3	110	200	210	75
4	90	180	200	85
5	115	205	300	85
6	100	203	305	88

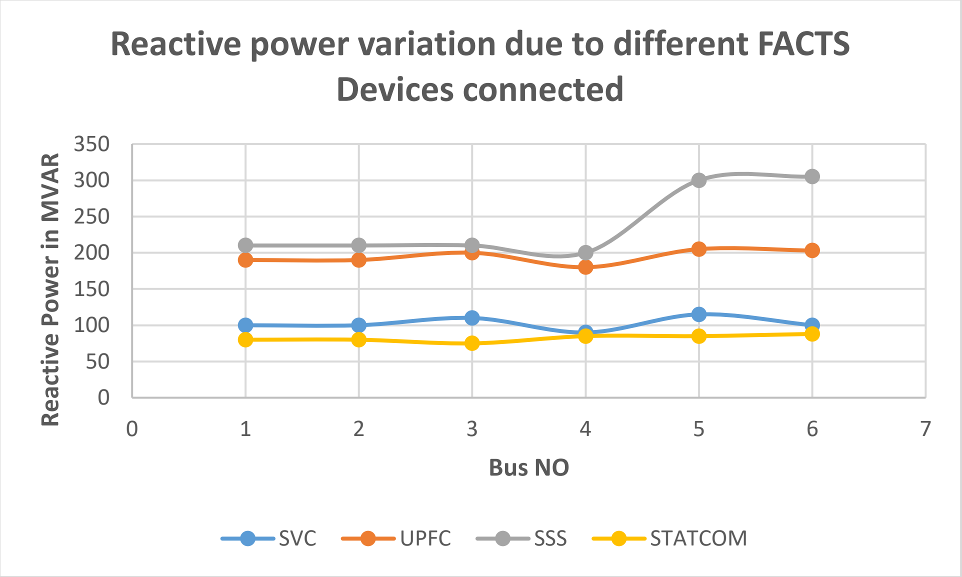


Figure 4. 14:Decrease in reactive power for different FACTS devices

As a result, the STATCOM generates good results because the real power is good for the real power and for the variation of reactive power, it is clear that the reactive power on busbars is not very high based on the analysis for load flow.

Chapter V. RESULTS AND CONCLUSION

5.1 LOAD FLOW

The results obtained in different simulations were displayed, most of them were based on load flow for given network. The load flow analysis was considered in power system and any operation based on planning requires the above tools for analysis of the system performance in terms of stability. The main objectives of load flow analysis are to provide the load power used at all buses of any electrical network and of course its active and reactive power.

5.2 Behavior of existing Electrical network in terms of Load flow

This part will compare the results with network of Rwanda. For the network analysis behavior for how it behaves in different daily hours as from in appendix A and at the end i will consider the results obtained after simulation to advise any electrical network owners how the system perform well. With specific objective of reactive power control and power loss reduction, the following Case were identified:

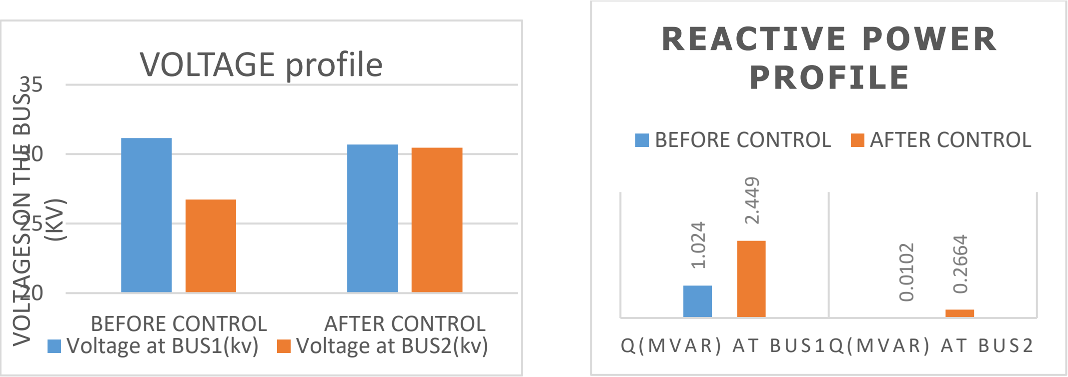
(i) Transmission line with two bus bars (with and without controller).
(ii) Interconnected network of six busbars and only two busbars are selected for analysis of reactive power controlled and uncontrolled.

(i)Transmission line with two bus bars (with and without controller)

Two cases were identified **(Undervoltage and overvoltage)**

Case one (undervoltage)

After filling different parameter in transmission line according to the model figure4.2. The simulation shows the different bus voltage total losses power generation active and reactive. Before any controller and after control the profile for voltage and reactive power is given below



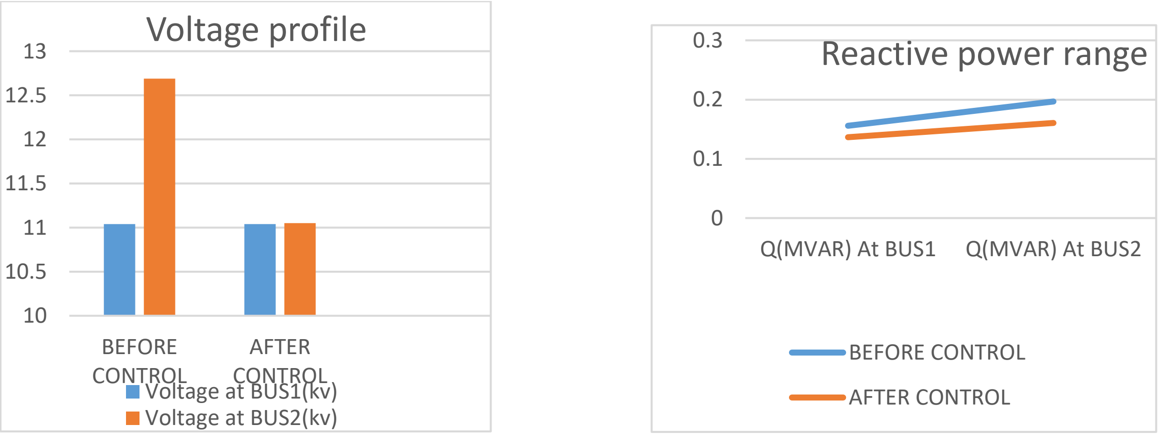
(a)voltage magnitude before controller (b)Losses after control

Figure 5. 1:Voltage magnitude and losses before and after control

Reactive power is required to maintain the voltage for delivering active power through transmission line. When it is low there is a huge voltage drop as we can see on the above diagram according to simulated results. Then the shunt capacitor should be switched at the receiving end to inject the reactive power, and this reduces the voltage drop as well as real power loss at 1.5kw to 0.213kw. In the preceding case, voltage is controlled by providing enough reactive power control margin to amplify and supply needs via shunt reactor and shunt capacitor for compensation, and voltages are then controlled by estimating and correcting reactive power demand via different loads.

Case two Overvoltage (Ferranti effect).

After filling the required parameters in software and running the simulation then the problem of overvoltage have been raised due to more reactive power and it is associated with high losses



(a)Voltage before and after controller (b)Losses before and after controller

Figure 5. 2:Voltage and losses before and after Controller

The above results shows that when the reactive power is high in the network the problem of overvoltage rises and as control measure the shunt reactor is installed to control that reactive power, it is clear that the after connecting the shunt devices the voltage at receiving end are almost similar and the accurate control should consider the Facts devices like power electronic based controller such as Thyristor controlled reactor (TCR). Below are the results for TCR connected at the receiving end.

(a)Voltage before and after TCR connected (b)Reactive power before and after controller

Figure 5. 3:Voltage and Reactive power Before and After Controller

The Results shows after control there is no voltage drop only the sending end voltage are equal to the receiving end voltage. The power losses are minimized with thyristor controlled as possible according to the power flow and the results are plotted below

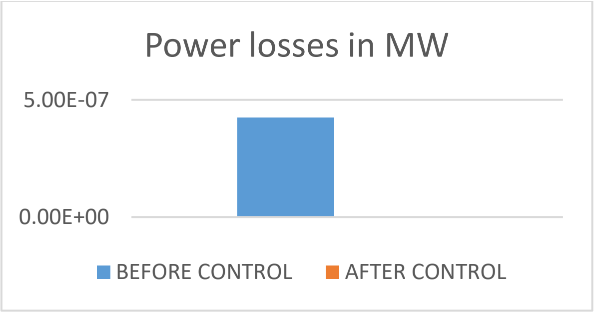
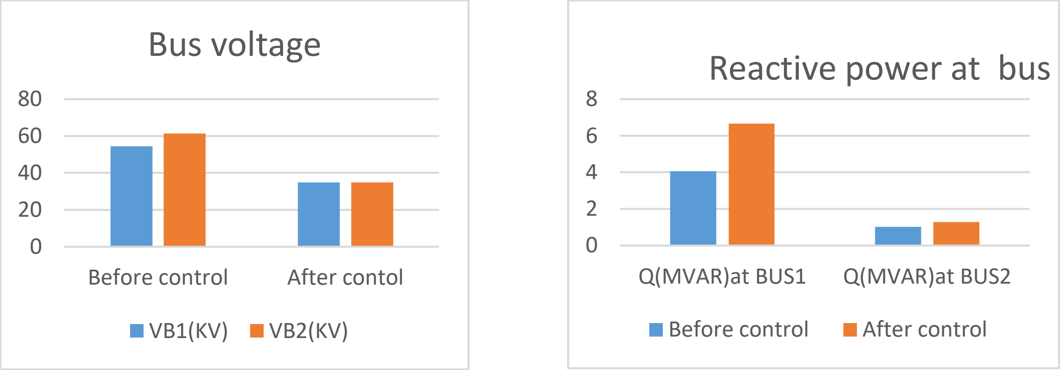


Figure 5. 4:Losses before and after Controller

(ii)Interconnected network of six busbars and only two busbars are selected for analysis of reactive power controlled and uncontrolled

Case one (Undervoltage)

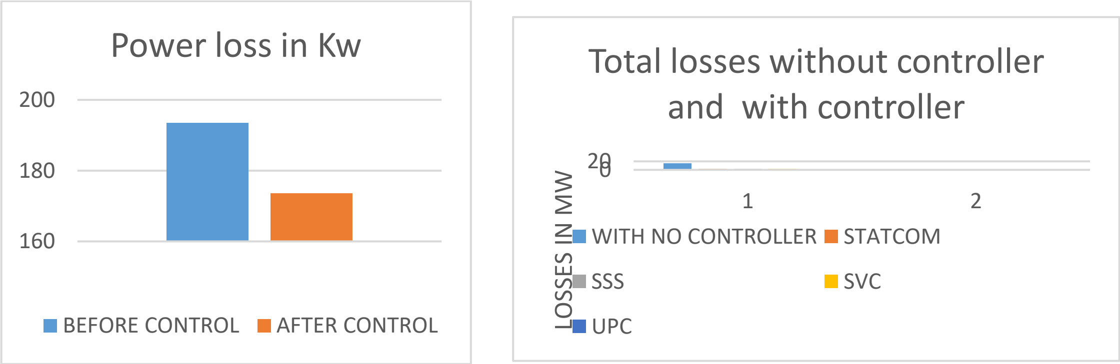
This part considers three different generating station and different transmission line however two buses have been selected for analysis on the effect of reactive power. After filling different parameter in transmission line according to the model. The simulation shows the different bus voltage total losses power generation active and reactive. Before any controller after control, the profile for voltage and reactive power as well as power losses is given below:



(a)Voltage Before and after controller (b)Figure5. 1:Reactive Power Before and after control

Figure 5. 5 :Voltage and Reactive before and after using all Controllers

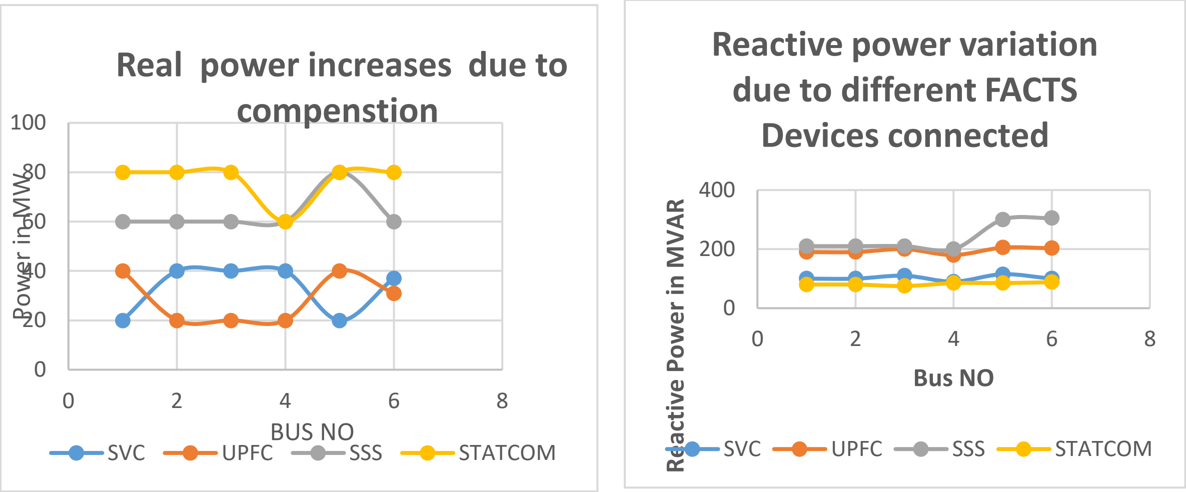
As analysis the before any controller there is voltage mismatched due to the more reactive power in network after the controller connected the voltage profile is now improved and the power loss is reduced as seen bellow



(a)Losses before and after control (b)Total losses without and with controller

Figure 5. 6 :Total losses and Losses without any control and with controller.

The real power losses need to be minimized and the FACTS devices which is power electronic based should be installed. The upcoming results from simulation will provide the contribution of Static synchronous compensator (STATCOM)connected at bus number 5, Static VAR compensator (SVC),static synchronous series compensator(SSS) connected at same place and Unified Power flow controller (UPFC) also connected at same place and their contribution on different busbar in terms of real power losses and reactive power. The results are shown below:



*(a)*The Real power on different bus (b) The reactive power at on different bus

Figure 5. 7:Real power and Reactive Power on different bus for each Connected FACT Device

The STATCOM provide the best results because the reactive power is low on different busbar in the interconnected network. Also, according to the Figure 5:7 the real power is very high compared with other devices connected. Also, it has the two-control mode either voltage control mode or reactive power mode and both cases were considered during simulation.

CHAPITERVI: CONCLUSION, RECOMMENDATION AND FUTURE WORK

6.1 CONCLUSION

The project deals with reactive power control and power loss minimization in electrical network by using FACTS Devices. The voltage drop due to uncontrolled reactive power and power losses are analyzed in this project with and without shunt Reactor, shunt capacitor, thyristor-controlled reactor, STATCOM, UPFC, SSSC and SVC. Also, for interconnected network of six busbars the increases of real power were analyzed and the decrease of reactive power on different busbars according to Figure 4:16 and Figure 4:17 respectively.

Referring to the data collected, in Rwanda Network only the shunt reactor is connected at shango substation and Brembo. But according to the simulated results, the TCR should be very accurate since there is no voltage drop with TCR as well as losses are minimized from 4.24E-07MW to 4.05E-09 MW Also for interconnected network total losses are minimized from 15Mw to 1.6424 Mw by average. Because the capacitor is there, and not working SVC with control system should be considered but for proper reactive control the STATCOM gives best results.

6.2 RECOMMENDATION

Any electrical network especially the RWANDA Network instead of connecting shunt Reactor, the Facts based controller like TCR, SVC with its control system, UPFC, and STATCOM Should be connected. Based on this project, any company can select STATCOM controller for proper reactive management in optimal location as simulated.

6.3 FUTURE WORK

All the FACTS device used in this thesis should be extended for more than six busbars in interconnected network of same parameters to evaluate their control of real power and reactive power in transmission line.

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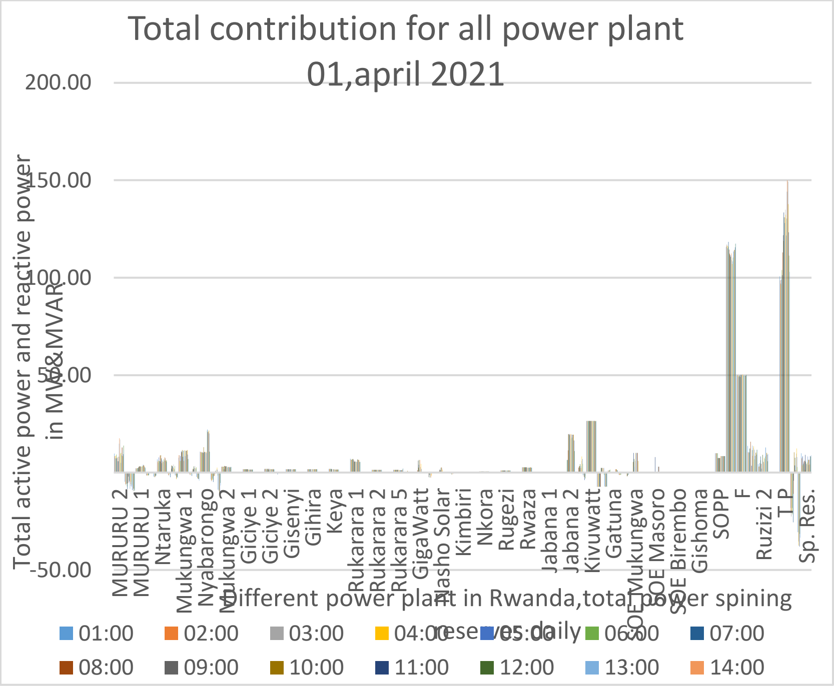
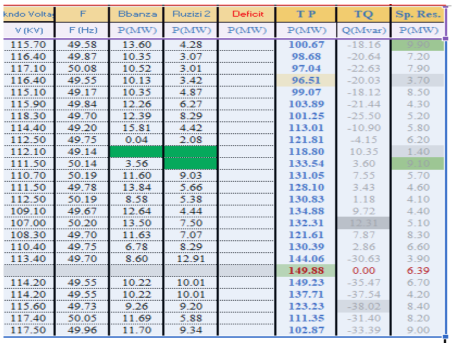
APPENDIX

APPENDIX A

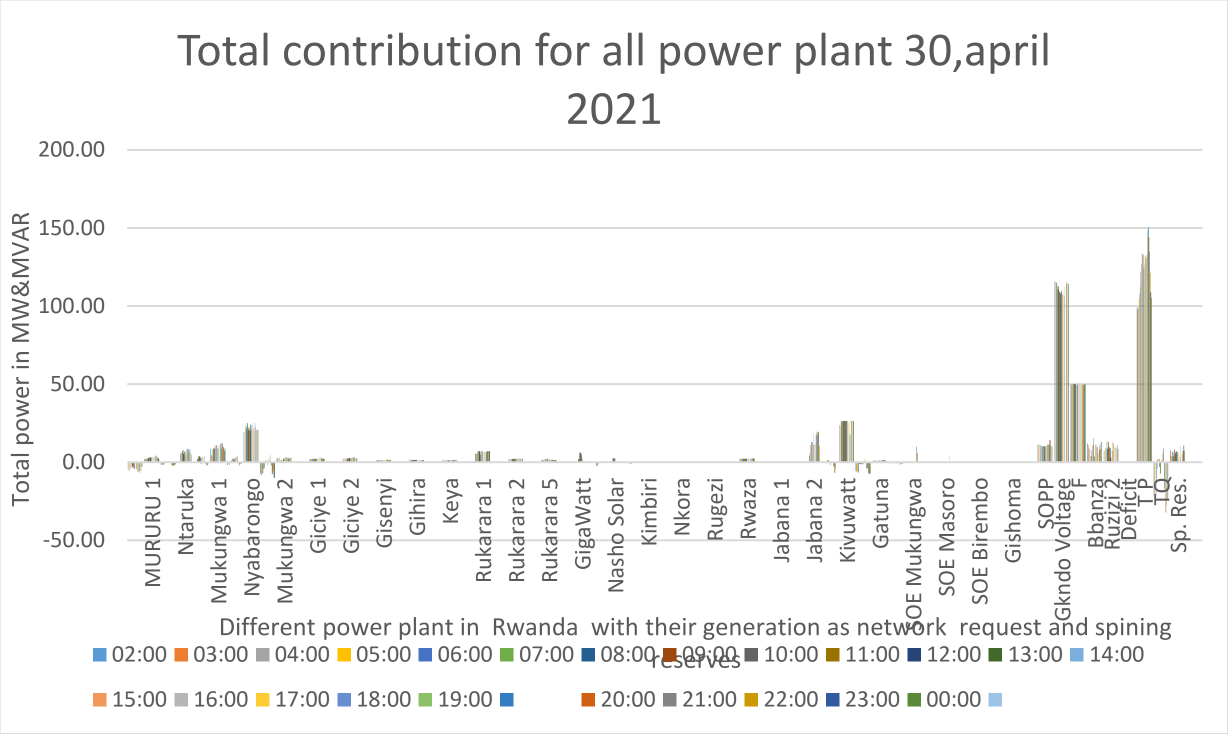
Data for the first and the last day of April 2021

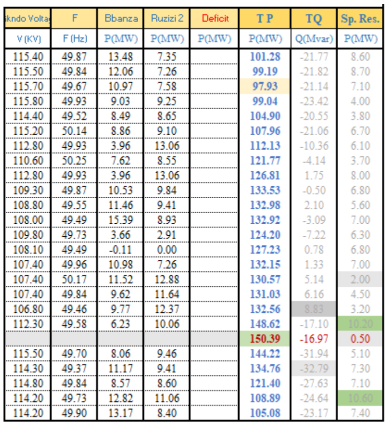




kndo Volta	F	Bbanza	Ruzizi 2	Deficit	T P	TQ	Sp. Res.
V (KV)	F (Hz)	P(MW)	P(MW)	P(MW)	P(MW)	Q(Mvar)	P(MW)
115.70	49.58	13.60	4.28		100.67	-18.16	9.90
116.40	49.87	10.35	3.07		98.68	-20.64	7.20
117.10	50.08	10.52	3.01		97.04	-22.63	7.90
116.40	49.55	10.13	3.42		96.51	-20.03	3.70
115.10	49.17	10.35	4.87		99.07	-18.12	8.50
115.90	49.84	12.26	6.27		103.89	-21.44	4.30
118.30	49.70	12.39	8.29		101.25	-25.50	5.20
114.40	49.20	15.81	4.42		113.01	-10.90	5.80
112.50	49.75	0.04	2.08		121.81	-4.15	6.20
112.10	49.14	🟩	🟩		118.80	10.35	1.40
111.50	50.14	3.56	🟩		133.54	3.60	9.10
110.70	50.19	11.60	9.03		131.05	7.55	5.70
111.50	49.78	13.84	5.66		128.10	3.43	4.60
112.50	50.19	8.58	5.38		130.83	1.18	4.10
109.10	49.67	12.64	4.44		134.88	9.72	4.40
107.00	50.20	13.50	7.50		132.31	12.31	5.10
108.30	49.70	11.63	7.07		121.61	7.87	8.30
110.40	49.75	6.78	8.29		130.39	2.86	6.60
113.40	49.70	8.60	12.91		144.06	-30.63	3.90
					149.88	0.00	6.39
114.20	49.55	10.22	10.01		149.23	-35.47	6.70
114.20	49.55	10.22	10.01		137.71	-37.54	4.20
115.60	49.73	9.26	9.20		123.23	-38.02	8.40
117.40	50.05	11.69	5.88		111.35	-31.40	8.20
117.50	49.96	11.70	9.34		102.87	-33.39	9.00

The peak load is 149.88MW

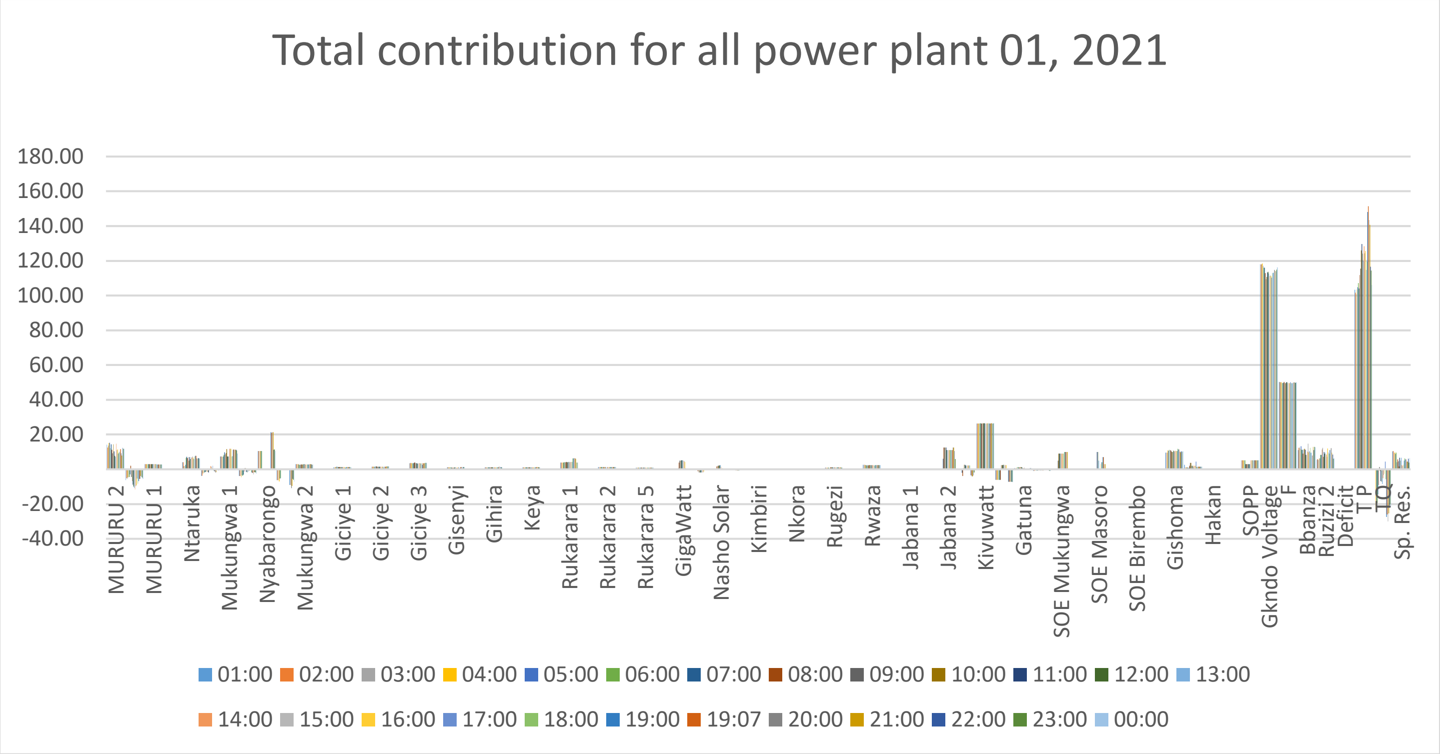


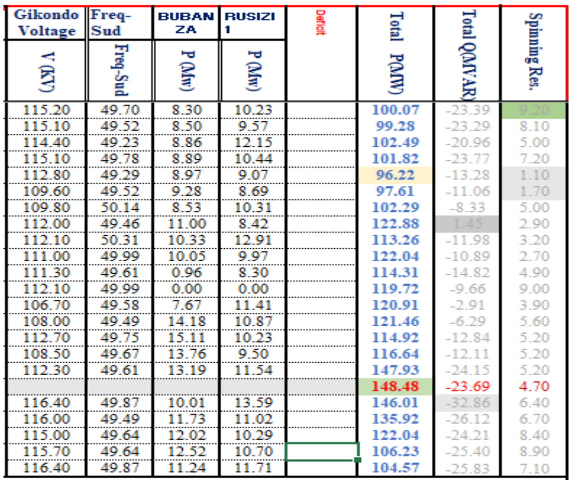


kndo Volta	F	Bbanza	Ruzizi 2	Deficit	T P	TQ	Sp. Res.
V (KV)	F (Hz)	P(MW)	P(MW)	P(MW)	P(MW)	Q(Mvar)	P(MW)
115.40	49.87	13.48	7.35		101.28	-21.77	8.60
115.50	49.84	12.06	7.26		99.19	-21.82	8.70
115.70	49.67	10.97	7.58		97.93	-21.14	7.10
115.80	49.93	9.03	9.25		99.04	-23.42	4.00
114.40	49.52	8.49	8.65		104.90	-20.55	3.80
115.20	50.14	8.86	9.10		107.96	-21.06	6.70
112.80	49.93	3.96	13.06		112.13	-10.36	6.10
110.60	50.25	7.62	8.55		121.77	-4.14	3.70
112.80	49.93	3.96	13.06		126.81	1.75	8.00
109.30	49.87	10.53	9.84		133.53	-0.50	6.80
108.80	49.55	11.46	9.41		132.98	2.10	5.60
108.00	49.49	15.39	8.93		132.92	-3.09	7.00
109.80	49.73	3.66	2.91		124.20	-7.22	6.30
108.10	49.49	-0.11	0.00		127.23	0.78	6.80
107.40	49.96	10.98	7.26		132.15	1.33	7.00
107.40	50.17	11.52	12.88		130.57	5.14	2.00
107.40	49.84	9.62	11.64		131.03	6.16	4.50
106.80	49.46	9.77	12.37		132.56	8.83	3.20
112.30	49.58	6.23	10.06		148.62	-17.10	10.20
					150.39	-16.97	0.50
115.50	49.70	8.06	9.46		144.22	-31.94	5.10
114.30	49.37	11.17	9.41		134.76	-32.79	7.30
114.80	49.84	8.57	8.60		121.40	-27.63	7.10
114.20	49.73	12.82	11.06		108.89	-24.64	10.60
114.20	49.90	13.17	8.40		105.08	-23.17	7.40

Peak load is 150.39MW

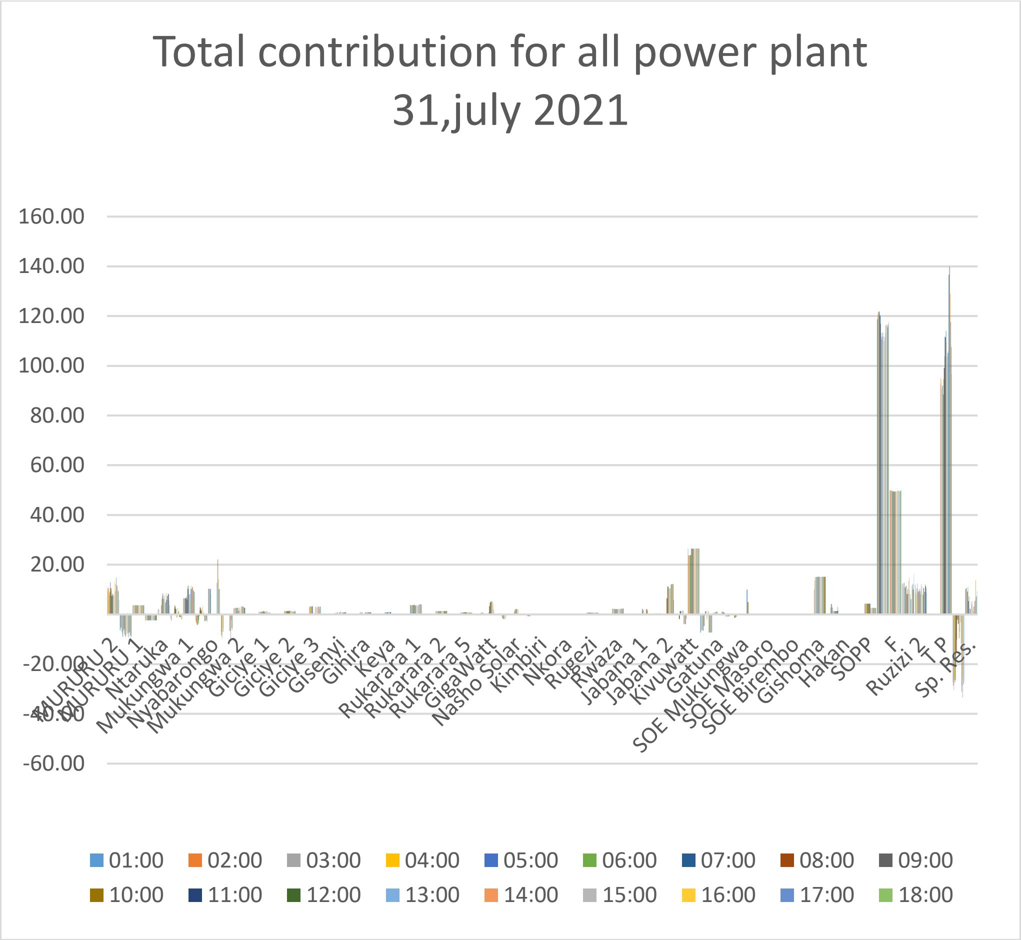
Data for the first and the last day of July 2021

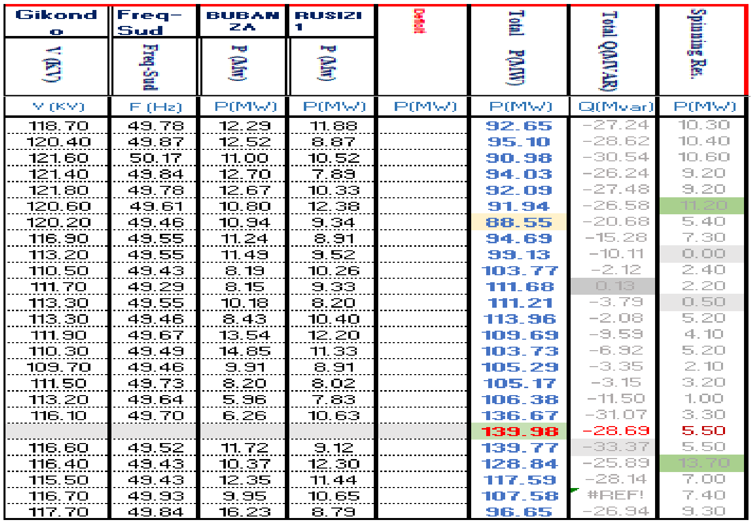




Gikondo Voltage	Freq-Sud	BUBANZA	RUSIZI 1	Deficit	Total	Total Q(MVAR)	Spinning Res.
V (KV)	Freq-Sud	P (Mw)	P (Mw)		P(MW)		
115.20	49.70	8.30	10.23		100.07	-23.39	9.20
115.10	49.52	8.50	9.57		99.28	-23.29	8.10
114.40	49.23	8.86	12.15		102.49	-20.96	5.00
115.10	49.78	8.89	10.44		101.82	-23.77	7.20
112.80	49.29	8.97	9.07		96.22	-13.28	1.10
109.60	49.52	9.28	8.69		97.61	-11.06	1.70
109.80	50.14	8.53	10.31		102.29	-8.33	5.00
112.00	49.46	11.00	8.42		122.88	1.45	2.90
112.10	50.31	10.33	12.91		113.26	-11.98	3.20
111.00	49.99	10.05	9.97		122.04	-10.89	2.70
111.30	49.61	0.96	8.30		114.31	-14.82	4.90
112.10	49.99	0.00	0.00		119.72	-9.66	9.00
106.70	49.58	7.67	11.41		120.91	-2.91	3.90
108.00	49.49	14.18	10.87		121.46	-6.29	5.60
112.70	49.75	15.11	10.23		114.92	-12.84	5.20
108.50	49.67	13.76	9.50		116.64	-12.11	5.20
112.30	49.61	13.19	11.54		147.93	-24.15	5.20
					148.48	-23.69	4.70
116.40	49.87	10.01	13.59		146.01	-32.86	6.40
116.00	49.49	11.73	11.02		135.92	-26.12	6.70
115.00	49.64	12.02	10.29		122.04	-24.21	8.40
115.70	49.64	12.52	10.70		106.23	-25.40	8.90
116.40	49.87	11.24	11.71		104.57	-25.83	7.10

The peak load is 148.48MW

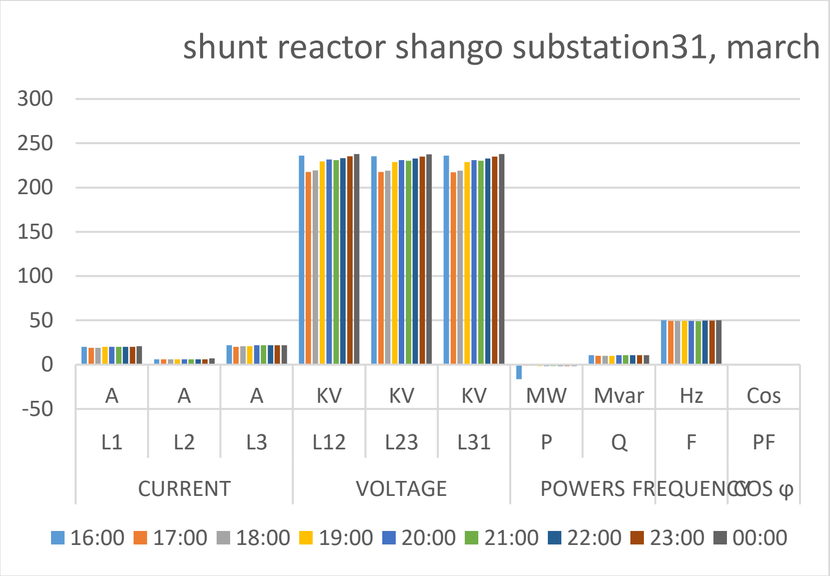


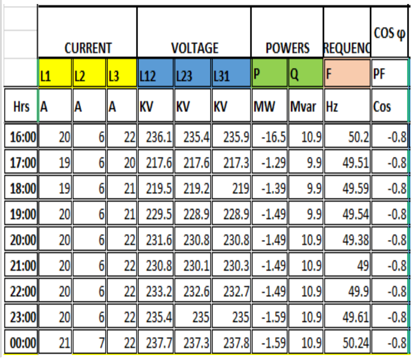


Gikondo	Freq-Sud	BUBANZA	RUSIZI 1	Deficit	Total	Total	Spinning Res.
V (KV)	Freq-Sud	P (Mw)	P (Mw)		P(MW)	Q(MVAR)	
V (KV)	F (Hz)	P(MW)	P(MW)	P(MW)	P(MW)	Q(Mvar)	P(MW)
118.70	49.78	12.29	11.88		92.65	-27.24	10.30
120.40	49.87	12.52	8.87		95.10	-28.62	10.40
121.60	50.17	11.00	10.52		90.98	-30.54	10.60
121.40	49.84	12.70	7.89		94.03	-26.24	9.20
121.80	49.78	12.67	10.33		92.09	-27.48	9.20
120.60	49.61	10.80	12.38		91.94	-26.58	11.20
120.20	49.46	10.94	9.34		88.55	-20.68	5.40
116.90	49.55	11.24	8.91		94.69	-15.28	7.30
113.20	49.55	11.49	9.52		99.13	-10.11	0.00
110.50	49.43	8.19	10.26		103.77	-2.12	2.40
111.70	49.29	8.15	9.33		111.68	0.13	2.20
113.30	49.55	10.18	8.20		111.21	-3.79	0.50
113.30	49.46	8.43	10.40		113.96	-2.08	5.20
111.90	49.67	13.54	12.20		109.69	-9.59	4.10
110.30	49.49	14.85	11.33		103.73	-6.92	5.20
109.70	49.46	9.91	8.91		105.29	-3.35	2.10
111.50	49.73	8.20	8.02		105.17	-3.15	3.20
113.20	49.64	5.96	7.83		106.38	-11.50	1.00
116.10	49.70	6.26	10.63		136.67	-31.07	3.30
					139.98	-28.69	5.50
116.60	49.52	11.72	9.12		139.77	-33.37	5.50
116.40	49.43	10.37	12.30		128.84	-25.89	13.70
115.50	49.43	12.35	11.44		117.59	-28.14	7.00
116.70	49.93	9.95	10.65		107.58	#REF!	7.40
117.70	49.84	16.23	8.79		96.65	-26.94	9.30

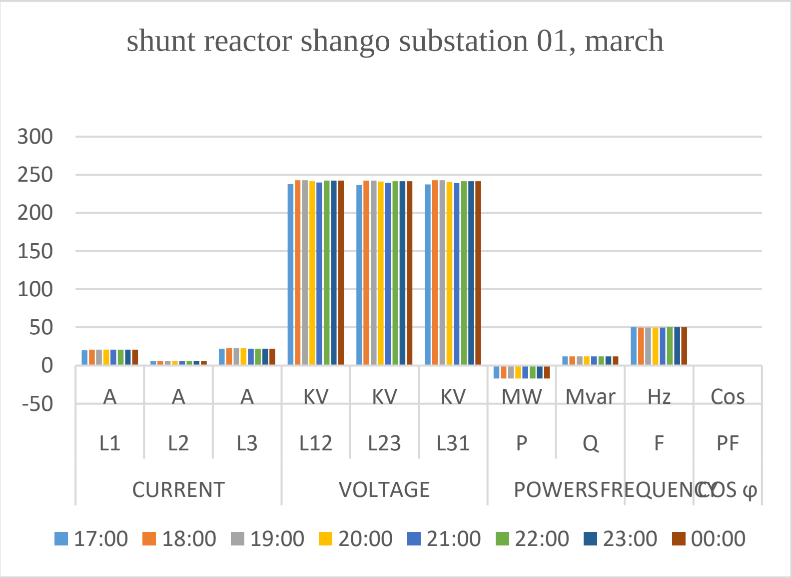
APPENDIX B

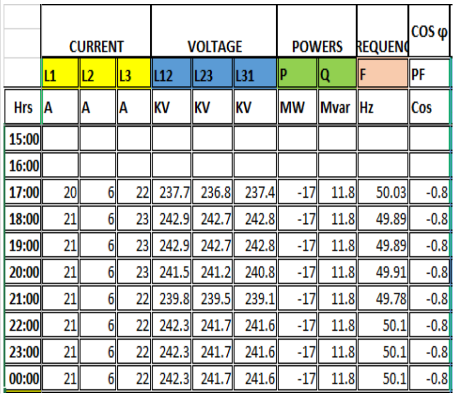
The records for the March 01,2021 and march 31,2021 Shango/mirama substation





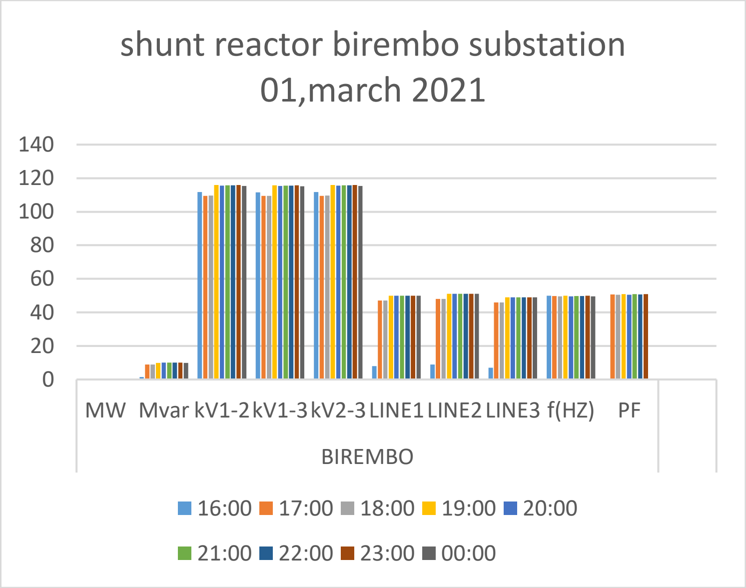
	CURRENT			VOLTAGE			POWERS		REQUENC	COS φ
	L1	L2	L3	L12	L23	L31	P	Q	F	PF
Hrs	A	A	A	KV	KV	KV	MW	Mvar	Hz	Cos
16:00	20	6	22	236.1	235.4	235.9	-16.5	10.9	50.2	-0.8
17:00	19	6	20	217.6	217.6	217.3	-1.29	9.9	49.51	-0.8
18:00	19	6	21	219.5	219.2	219	-1.39	9.9	49.59	-0.8
19:00	20	6	21	229.5	228.9	228.9	-1.49	9.9	49.54	-0.8
20:00	20	6	22	231.6	230.8	230.8	-1.49	10.9	49.38	-0.8
21:00	20	6	22	230.8	230.1	230.3	-1.49	10.9	49	-0.8
22:00	20	6	22	233.2	232.6	232.7	-1.49	10.9	49.9	-0.8
23:00	20	6	22	235.4	235	235	-1.59	10.9	49.61	-0.8
00:00	21	7	22	237.7	237.3	237.8	-1.59	10.9	50.24	-0.8

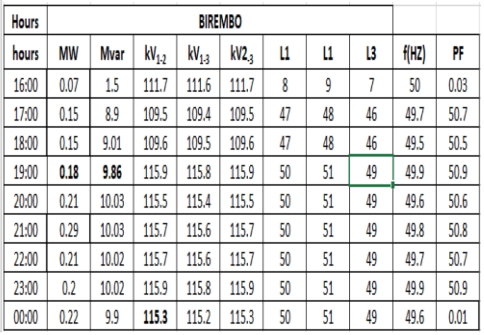




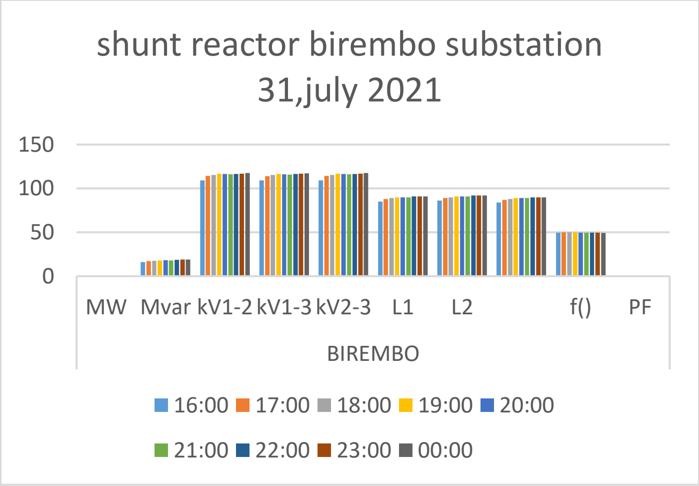
	CURRENT			VOLTAGE			POWERS		REQUENC	COS φ
	L1	L2	L3	L12	L23	L31	P	Q	F	PF
Hrs	A	A	A	KV	KV	KV	MW	Mvar	Hz	Cos
15:00										
16:00										
17:00	20	6	22	237.7	236.8	237.4	-17	11.8	50.03	-0.8
18:00	21	6	23	242.9	242.7	242.8	-17	11.8	49.89	-0.8
19:00	21	6	23	242.9	242.7	242.8	-17	11.8	49.89	-0.8
20:00	21	6	23	241.5	241.2	240.8	-17	11.8	49.91	-0.8
21:00	21	6	22	239.8	239.5	239.1	-17	11.8	49.78	-0.8
22:00	21	6	22	242.3	241.7	241.6	-17	11.8	50.1	-0.8
23:00	21	6	22	242.3	241.7	241.6	-17	11.8	50.1	-0.8
00:00	21	6	22	242.3	241.7	241.6	-17	11.8	50.1	-0.8

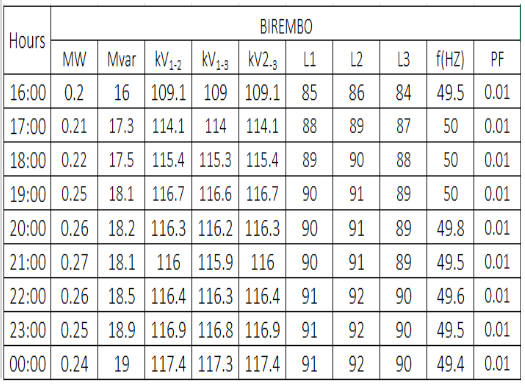
The records for the July 01,2021 and July 31,2021 BIREMBO substation





Hours	BIREMBO									
hours	MW	Mvar	kV_{1-2}	kV_{1-3}	$kV2_{-3}$	L1	L1	L3	f(HZ)	PF
16:00	0.07	1.5	111.7	111.6	111.7	8	9	7	50	0.03
17:00	0.15	8.9	109.5	109.4	109.5	47	48	46	49.7	50.7
18:00	0.15	9.01	109.6	109.5	109.6	47	48	46	49.5	50.5
19:00	**0.18**	**9.86**	115.9	115.8	115.9	50	51	49	49.9	50.9
20:00	0.21	10.03	115.5	115.4	115.5	50	51	49	49.6	50.6
21:00	0.29	10.03	115.7	115.6	115.7	50	51	49	49.8	50.8
22:00	0.21	10.02	115.7	115.6	115.7	50	51	49	49.7	50.7
23:00	0.2	10.02	115.9	115.8	115.9	50	51	49	49.9	50.9
00:00	0.22	9.9	**115.3**	115.2	115.3	50	51	49	49.6	0.01





Hours	BIREMBO									
	MW	Mvar	kV_{1-2}	kV_{1-3}	$kV2_{-3}$	L1	L2	L3	f(HZ)	PF
16:00	0.2	16	109.1	109	109.1	85	86	84	49.5	0.01
17:00	0.21	17.3	114.1	114	114.1	88	89	87	50	0.01
18:00	0.22	17.5	115.4	115.3	115.4	89	90	88	50	0.01
19:00	0.25	18.1	116.7	116.6	116.7	90	91	89	50	0.01
20:00	0.26	18.2	116.3	116.2	116.3	90	91	89	49.8	0.01
21:00	0.27	18.1	116	115.9	116	90	91	89	49.5	0.01
22:00	0.26	18.5	116.4	116.3	116.4	91	92	90	49.6	0.01
23:00	0.25	18.9	116.9	116.8	116.9	91	92	90	49.5	0.01
00:00	0.24	19	117.4	117.3	117.4	91	92	90	49.4	0.01

Data for capacitor bank are given bellow but are not working. They are there as reserve

BIREMBO :4.500MVAR

JABANA: 4.5 MVAR.

APPENDICE C

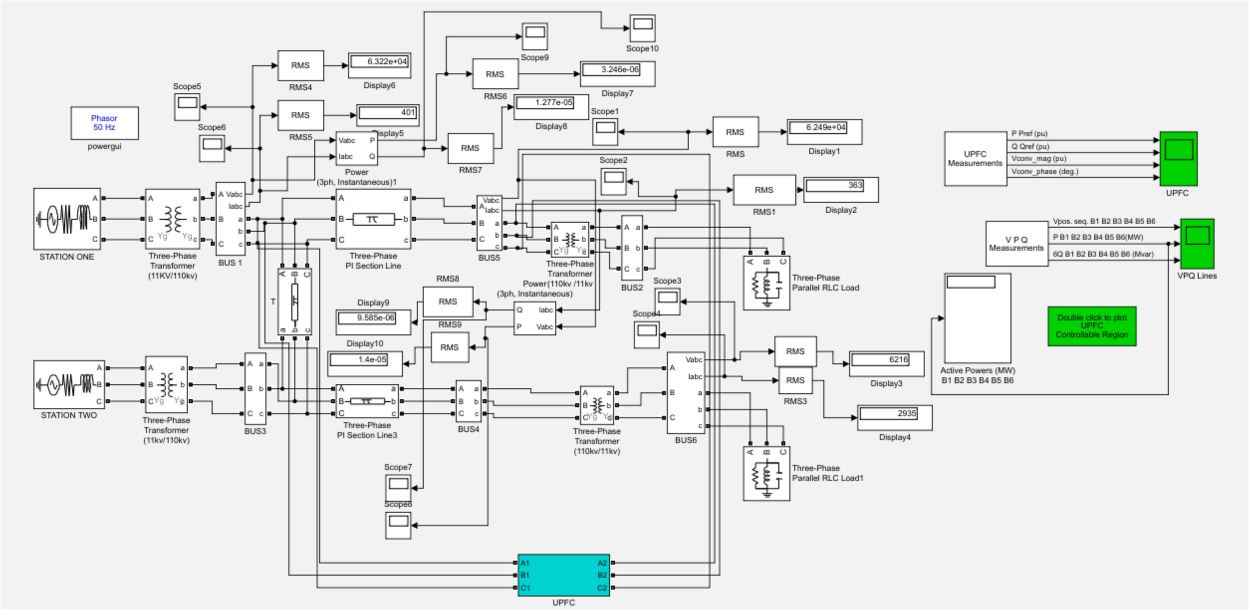


Figure4. 1:Simulation with Unified power flow controller

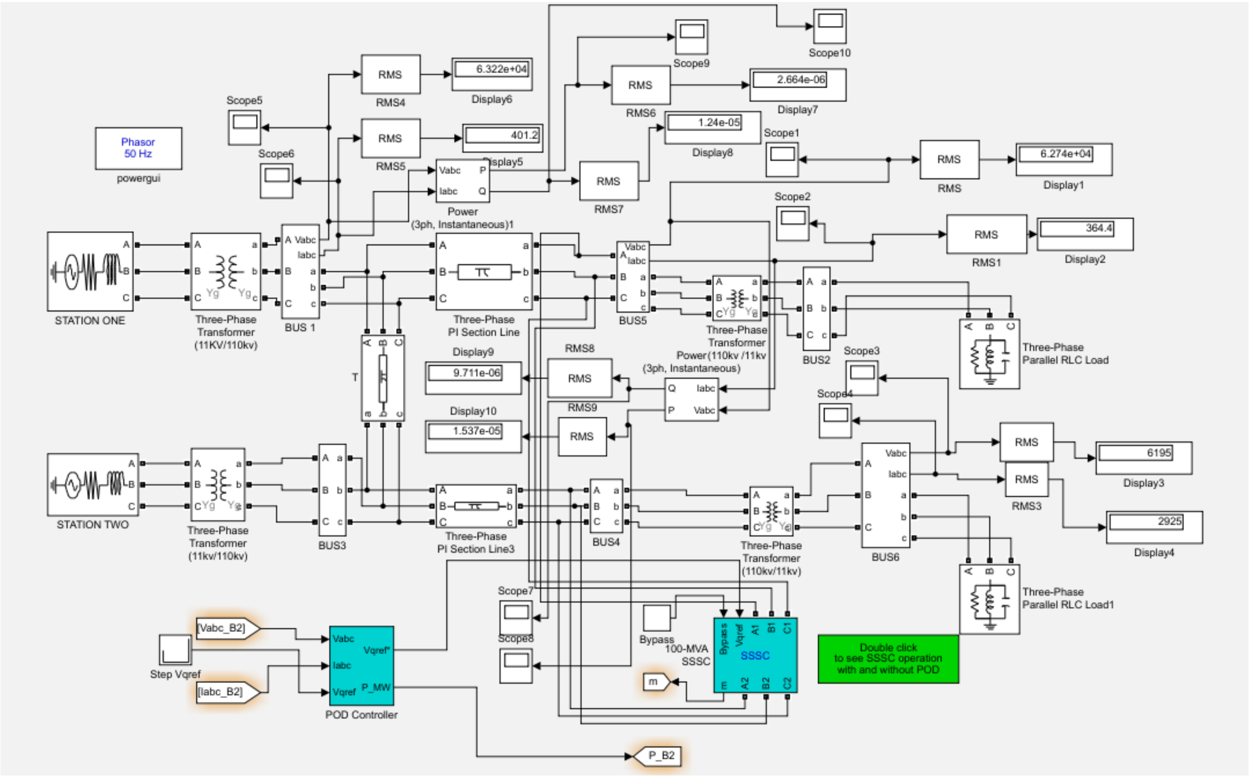


Figure 4. 2: simulation with static synchronous Series compensator

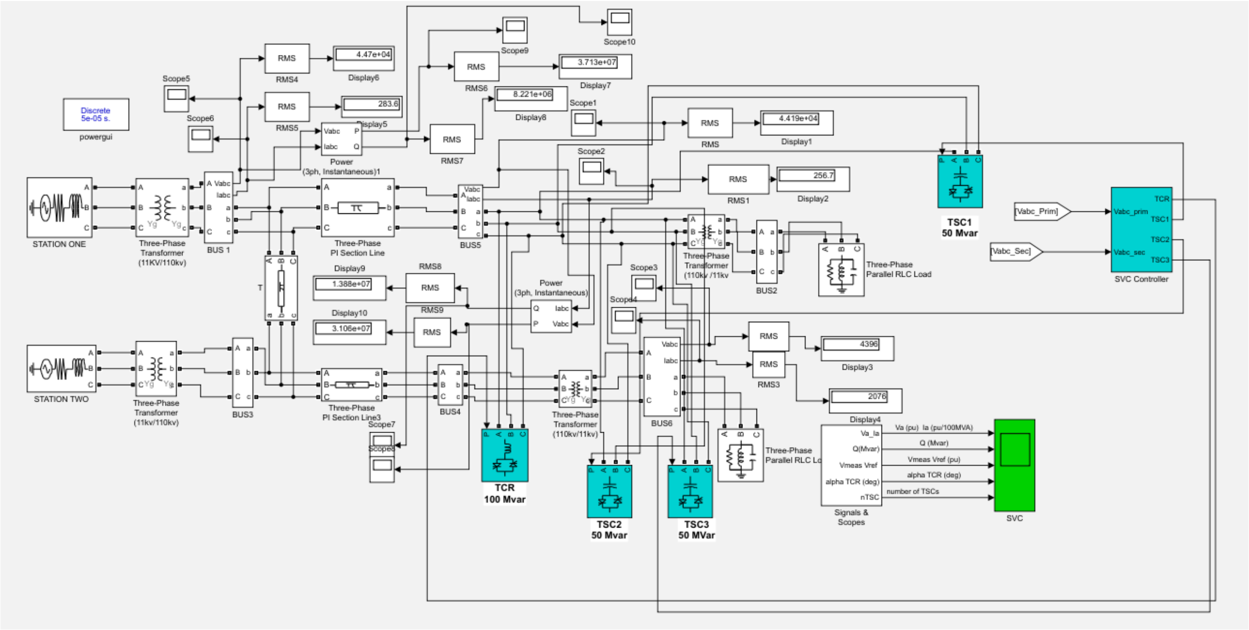


Figure4. 3:Simulation with Static VAR Compensator