UNIVERSITY of RWANDA COLLEGE OF SCIENCE AND TECHNOLOGY ACE-ESD AFRICAN CENTER OF EXCELLENCE IN ENERGY FOR SUSTAINABLE DEVELOPMENT

# Title: Comparison of integration of Phase Shift Transformer (PST) and Flexible Alternative Current Transmission Systems (FACTS) devices in the power system network. Case study Rwanda power transmission network.

**By**

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## DECLARATION

I, **Dative NYIRANTEGEYIMANA** a student from the African Center of Excellence in Energy for Sustainable Development (ACEESD), College of Science and Technology, the University of Rwanda under the master of electrical power system with the reference number 220020642. I hereby declare that this thesis entitled" **Comparison of integration of Phase Shift Transformer (PST) and Flexible Alternative Current Transmission Systems (FACTs) devices in the power system network. Case study Rwanda power transmission line"** supervised by **Dr. BIKORIMANA JMV** is my personal work from my effort and no longer has been submitted for any other Degree or Diploma at the African Center of Excellence in Energy for Sustainable Development, College of Science and Technology, University of Rwanda or any other institution.

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This thesis has been submitted for examination with Supervisor as my approval.

Supervisor: **BIKORIMANA JMV**

Bik JMV

## DEDICATION

I dedicate this thesis to:

- The almighty God;
- My Supervisor;
- My Husband and my Children;
- My relatives;
- My friends and classmates;

The Staff of the African Center of Excellence in Energy for Sustainable Development, College of Science and Technology, the University of Rwanda for providing support, guidance, and advice.

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# ABSTRACT

FACTS devices are used to compensate reactive power on a transmission line, distribution, and generation; this study presents the comparison of the integration of PST, UPFC, and STATCOM in Rwanda’s 110 kV north hub transmission line for reactive power compensation. The study utilizes MATLAB/SIMULINK (2013a) to mode the Rwanda 110 kV north hub transmission line without compensation, with PST, UPFC, and STATCOM that consists of two-generation NTARUKA and MUKUNGWA, and four buses: NTARUKA bus, MUKUNGWA bus, GIFURWE bus, and RULINDO bus. A power flow study was carried out without compensation to determine weak buses and the problem of instability; it showed that the GIFURWE bus has higher reactive power than other buses. Mathematical modeling was done and this study indicated power flow analysis for each model design. After compensation using PST, STATCOM, and UPFC, the operating per unit voltage at buses was found to be within the minimum limit of 0. 9 P.U. the design without compensation showed the voltage magnitude of buses at 0. 8 P. U; with PST, the voltage per unit of buses varies between 0.988 P.U and 0.997 P.U; with STATCOM, the voltage per unit of buses varies between 0.9 P. U and 1.1P. U; with UPFC, the voltage per unit of buses varies between 0.9 P. U and 1.1 P. U. The findings of real and reactive power showed that the real power of the model with PST and STATCOM was reduced at all buses. This means that the operation of PST and STATCOM causes the losses of real power. The real power of UPFC increased at all buses. This means that UPFC can adjust the transmission of power flow and decrease the real power losses. The result of this study after comparison indicated that UPFC performs better and controls the real and reactive power more than STATCOM and PST, and STATCOM compensates reactive power more than PST. Finally, UPFC improves the voltage stability more than PST and STATCOM.

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## LIST OF ABBREVIATIONS

**FACTS:** Flexible Alternative Current Transmission Systems

**PST:** Phase Shift Transformer

**TCSC:** Thyristor-Controlled Series Capacitor

**SSSC:** Static Synchronous Series Compensator

**STATCOM:** Static Synchronous Compensator

**SVC:** Static VAr Compensator

**UPFC:** Unified Power Flow Controller

**IPFC:** Interline Power Flow Controller

**LFOs**: low-frequency oscillations

**REG:** Rwanda Energy Group

**APSTs:** asymmetrical phase-shifting transformers

**KV**: kilovolts

**VAR:** Volt-Ampere Reactive

**V:** voltage

**I:** electrical current

**H/km**: Henry per kilometer

**X:** Reactance

**C:** Capacitance

**B:** Susceptance

**L:** Inductance

**P:** real power

**Q:** Reactive power

**X:** Impedance

**PWM:** Pulse Width Modulation

**SMES:** Superconducting Magnetic Energy Storage

**ACSR**: Aluminium Conductor Steel Reinforce

**DFC**: Dynamic Flow Controller

**DPFC**: Dynamic Power Flow Controller

**FC:** Fixed Capacitor

**HV:** High Voltage

**TCR**: Thyristor Controlled Reactor

**TSR**: Thyristor Switched Reactor

**P.U:** Per Unit

**AC:** Alternative Current

**TSC:** Thyristor Switched Capacitor

**VSC:** Voltage Source Converter

**ACPST:** Asymmetrical Controllable Phase Shifting Transformers

# 1. INTRODUCTION

## 1.1 Background

The biggest and most intricate dynamic systems created by humans are power systems. The power system continually encounters disturbances and oscillations as it changes from one operating condition to another, just like any dynamic system does[1]. The oscillations must be reduced as a basic need for the power system to remain stable. In the 1920s, power system stability was initially identified by engineers as a serious issue. Early stability issues were linked to the load Centre being fed by distant power sources through lengthy transmission lines[2]. High efficiency, reliability maximum, and protection (safety) are more critical than ever before in the power systems network operation. Because of the difficulty of establishing new transmission lines caused by path rights boundaries, current bulk transmission lines must be used to their full capacity[3]. Power systems have been strictly stressed because of electricity market activities and increasing demand. This necessitates network operations closer to their stability limitations [2]. Stability issues disturb power system operation, resulting in unpredictable system performance. Several key topics linked to the sector of power are currently being discussed around the world. Power quality, transmission overload, loss reduction of power, and voltage stability are only a few of the severe challenges [3]. The majority of blackouts of bulk power systems in the previous two decades have been produced by substantially stressed systems with high real reactive and real power demand and conditions of low voltage. When the voltages on the system buses are low, the losses are augmented as well. Voltage drops occur between the places of generation and consumption as power is sent over a transmission network.

Electrical power systems are made by power transformers, autotransformers, and, distribution transformers to deliver electricity to end users[4]. In addition to transformers, an electrical power system includes a complex web of other elements related to generation, transmission lines, and distribution networks, among others[5]. The power system is shown in figure1.1 below:

Figure 1.1: Power system components[5]

Figure1.1 represents components of the power system as discussed in the above paragraph. The power system has the parameters, such as current, voltage, impedance, frequency, active and reactive power, and power direction remains within acceptable bounds in dividing dependable and consistent energy consumption for good operation for power stability[6]. Power system operation is shown in figure1.2:

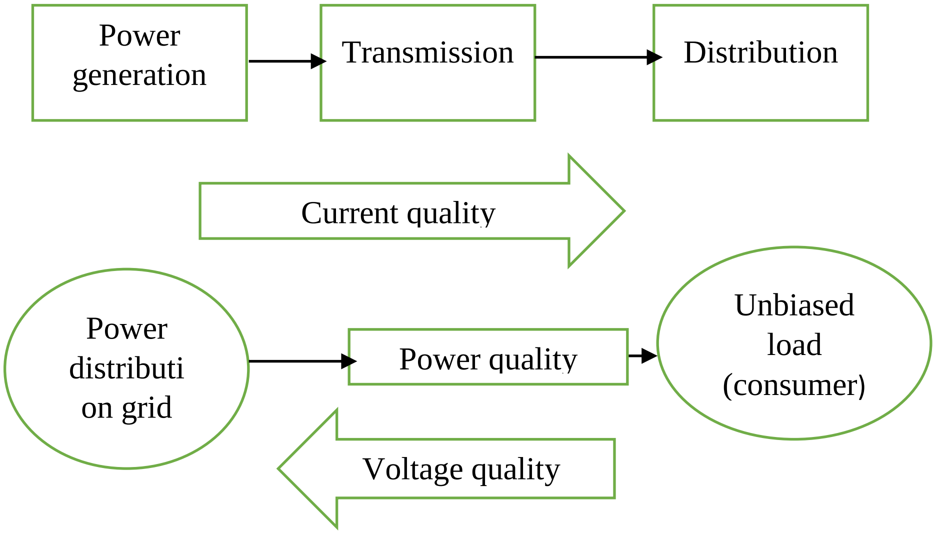


Figure 1.2: Power system operation

Figure 1.2 shows the operation of the power system, the current quality is found from generation to distribution through the transmission line while from consumer to power distribution grid represents voltage quality but bad operation causes power quality problems.

Some of these power quality problems are associated with voltage quality such as “voltage sags, voltage swells, blackouts, voltage transients, frequency deviations. Insufficient control of reactive power causes a lack of VAR support in the system and leads the system voltage instability and increased losses in the system. Installing additional transmission lines or enhancing the transmission line's capacity for electricity transfer can meet this rise in demand[7]. The most practical and cost-efficient option is to boost the transmission line's transfer capacity while focusing on increased usage. By leveraging cutting-edge research and development in power electronics technology, regulating actions should be done quickly to run the power system flexibly. To overcome the issues of the instability of power system, Flexible Alternative Current Transmission system (FACTS) devices and phase shift transformers (PSTs) have used[8]. The use of FACTS Devices and PST not only compensate for reactive power but they provide sufficient VAR power to the modeled system and also reduces the system losses[9].

All over the world, many countries faced the problem of power network instability including Rwanda. Rwanda’s network instability appears on different levels as Rwanda is a developing nation, yet despite this, its economy is expanding[10]. This entails several tasks that call for a reliable electrical network in addition to sufficient power generation[11]. The Rwandan electrical grid now relies on internal generation, which involves regional or internal energy commerce with neighboring nations. The country of Rwanda has a significant need for energy due to the country's growing population[12], the incorporation of big enterprises and farms, massive structures, and expanding mining operations. But in addition to this, these cause the Rwanda grid network to have grid sub-network imbalance, issues controlling power flow, and power losses that directly result in the waste of grid power generated[13]. These circumstances point to the Rwanda grid network's power instability.

Aside from that, Rwanda's grid network suffers from outdated infrastructure, inefficiencies, and high technical and power losses, all of which necessitate immediate and timely intervention to meet the country’s stated energy goals. The integration of phase shifting transformers (PSTs) and FACTS devices will ease some of the network's load-bearing issues like overloading and power instability to improve power flow in the transmission line.

## 1.2 Problem statement

The higher power quality of demand is necessary for a power system that is of utmost significance as power usage is growing year by year. Electrical power systems are facing instability and challenges such as:

- Load demand is increasing.
- Inadequate control of reactive power
- A power system fault
- The ageing of the transmission line infrastructure
- Insecurity of the power system

The above challenges are all over the world, including Rwanda's transmission and distribution lines. Rwanda's transmission line losses were estimated to be 22% in 2018 and the goal of the Rwanda energy group (REG) is to reduce them by up to 15% by 2024[10]. To attend to their goal, Rwanda's Transmission network needs general improvement. Therefore, [14] a provisional measure of REG, a reactive power compensation capacitor bank was installed. For example, they were installed at GIKONDO 110 kV bus bars; the implementation of capacitor banks in substations in the Kigali area improved the voltage profile. But there are problems associated with capacitor banks such as when there are voltage violations in the system or loads fluctuation, capacitor banks can deliver the required level of compensation producing either under or overcompensation, for a specific capacity, it may harm the designed device(equipment) or even it can lead to the outages in the system[9]. This study is to analyze power flow in Rwanda's power transmission network by comparing the effects of the integration of the phase-shift transformer (PST) and FACTS devices for reactive power compensation instead of using capacitor banks.

## 1.3 Objectives of the research

The present thesis has main objective and specific objectives.

### 1.3.1 Main objective of the research

The main objective of this thesis is to compare the effects of the integration of phase shift transformer (PST) and FACTS devices in Rwanda's power transmission networks for reactive power compensation to increase power transfer capability, stability, power quality of bulk transmission systems and show which FACTS device that is useful in the Rwandan power network instead of using capacitor bank.

### 1.3.2 Specific objectives of the research

To reach the intended aim, the following objectives need be attained:

i) Review phase shift transformer (PST) and FACTS technologies.
ii) Modeling of power transmission network with PST and FACTS (UPFC and STATCOM) integration.
iii) Design and Simulation of 110 kV north hub of Rwandan power transmission network with UPFC, STATCOM and PST integration.
iv) Comparison of results of UPFC, STATCOM and PST's simulation.

## 1.4 Scope of the study

Due to time and financial restrictions, the research has only targeted at simulating the 110 kV north hub of Rwanda's transmission line with PST and FACTS devices like UPFC and STATCOM in transmission power system networks and demonstrating which FACTS devices have high efficient in Rwanda's power transmission network for reactive power compensation to enhance the power quality and power transfer capability. Matlab/Simulink software is used to simulate the grid with PST, UPFC, and STATCOM.

## 1.5 Significance of the study

The increasing power demand that is followed by insufficient control of reactive power leads the system to the instability of voltage and power losses increase. FACT devices and PST have been developed for reactive power compensation and loss reduction. This thesis aims to compare the effects of the integration of PST and FACTS devices on the power transmission network and to show which FACTS devices are efficient in Rwanda's power transmission network for reactive power compensation to improve the power quality and power transfer capability. As a result of the integration of PST and FACTS devices (UPFC, STATCOM) into the power network, in Rwanda, except capacitor banks installed in the GIKONDO, BIREMBO,SHANGO and BUGESERA Substations, other substation will use FACTS devices for reactive power compensation.

### 1.6 Research questions

During this research following questions were answered:

- Why do we need to control the reactive power by using FACTS devices and PST?
- How can we develop control of real and reactive power flow in the power system network?
- What software does use in this research?
- What problem does this research intend to solve?
- What are the beneficiaries of the research?

### 1.7 Thesis outline

This thesis is organized as follows:

**Chapter 1: Introduction:** this part focuses on the background of the project, the problem statement, main objectives, specific objectives, research questions, methodologies, the framework, scope, and thesis outline.

**Chapter 2: Literature review:** this chapter summarizes the different published papers to present a literature survey on the integration of PST and FACTS devices into power system networks, a research gap, and an overview of PST, STATCOM, and UPFC.

**Chapter 3: Methodology:** this part focuses on an overview, data collection, documentation, mathematical model, simulation using software and the thesis framework.

**Chapter 4: Data collection results:** this chapter presents general data on the Rwanda transmission line as well as case study-specific data.

**Chapter 5: Modeling of power flow of Rwanda power network:** this chapter provides modeling of, PST, STATCOM, and UPFC in the power transmission network.

**Chapter 6: Design and Simulation**: This part focuses on the design of the Rwanda 110KV north hub transmission line without compensation, with PST, UPFC, and STATCOM and analysis of their simulation and compares the simulation results.

**Chapter 7: Conclusion and recommendation:** this chapter summarizes the thesis and shows the future work

# 2. LITERATURE REVIEW

## 2.1 Introduction

There are numerous researchers in the literature that had worked on the use of FACTS devices and PST in power system networks. The different published papers are summarized to present a literature survey on the integration of PST and FACTS devices in power system networks. FACTS devices overview and their principle operation are discussed in this chapter.

## 2.2 Related work

This section provides a quick overview of previous work in the integration of PST and FACTS devices in power system networks to put this study in context.

**Ananda M.H. et al study from 2021[9]** for Operational Performance evaluation of Phase Shifting Transformer and Unified Power Flow Controller in Power System found that the voltage and current are distorted when the PST is used in a power system transmission as a result of the PST's switching behavior. The quality of the power system is diminished as a result of the tap switching's high spikes. On the other hand, with a UPFC, the voltage and current are in phase, and the controller also has control over the power. The UPFC balances the power system more rapidly and smoothly than the PST because the currents and voltages are not distorted as they are in the PST. The optimal controllers between PST and UPFC are demonstrated by this study. To control real and reactive power transmission systems, UPFC performs better, with small losses, and voltage and current are in phase. However, the failure of this research compared only 2 controllers only while we have many controllers used in the power system. Other it does not specify the optimal location to present the best benefits on power flow loss reduction for UPFC.

**From the study examined by Bukola Babatunde Adetokun et al (2021)** [6] "A complete evaluation of the application and control of flexible alternating current transmission system devices for voltage stability enhancement of renewable energy grids" This paper analyzed in detail the usage of FACTS devices to enhance the voltage stability of a RE-integrated power system. Devices like SVC and STATCOM attracted a lot of interest. It has been discovered that STATCOM offers more voltage support than SVC, albeit at a higher cost. As a result, for emerging economies, SVC could be a more affordable choice than STATCOM. This research showed the best controllers of voltage stability enhancement between SVC and STATCOM. Based on high performance, the best one is STATCOM. Based on low cost, SVC is the best one.

This research compared only two FACTS devices, not PST, and showed only one issue of voltage stability, not reactive power compensation.

**From the study carried out by Paweł Albrechtowicz et al, (2021)**[15] for the Comparative Analysis of Phase Shifting Transformers" The APSTs (asymmetrical phase-shifting transformers) are discussed. The capacity to manage power flows in transmission power lines is contrasted with traditional APST methods and the proposed asymmetrical controlled phase shifting transformer (PST). In power systems, ACPST operation produces better results than traditional asymmetrical phase-shifting transformers (APST). As a result of ACPST's more flexible control skills for modifying both output voltage and phase angle, transferred power is increased. In addition, this research shows that APST cannot be implemented in real-life systems for cases of relatively high input voltage values, the best one is PST. The study failed to compare PST and FACTS devices in reactive power compensation and the results found are not from the real situation. APST and ACPST are compared through Laboratory data.

**Aleksandra BaczyĚska et al, (2018)**[16] researched "The impact of the Phase-Shifting Transformers on the power flow in the transmission grid" According to this study, a PST deployment alters the power flow in the network. It lowers costs and eliminates the need for corrective actions to a large extent. On the other hand, network losses rose dramatically as a result of PST operation, because power can be forced to flow through the higher impedance (which generally implies longer distances), resulting in higher losses. This research shows the result given by PST when it is used in transmission systems better to use it where there is a short distance to minimize losses. Therefore, this research failed to show other devices that can be used instead of using PST in long transmission due to losses happening in it because power can be forced to flow through higher impedance and failed to show reactive power compensation using PST.

A study entitled "Comparison of Multi-Line Power Flow Control Using Unified Power Flow Controller (UPFC) and Interline Power Flow Controller (IPFC) in Power Transmission Systems" was conducted by **Sunil Kumar Jiledi et al. in 2021[13].** This study discovered that IPFC is a very efficient FACTS device in today's power system network when UPFC and IPFC are integrated in a power transmission network to regulate voltage profile, actual and reactive power flow, and losses. The research's contribution is that it compared the outcomes of UPFC and IPFC in power system networks and found that IPFC is the best application. However, this study did not contrast PST and FACTS devices. Only 2 generators are employed in the design and simulation of a few generations.

**D. Murali et al, (2014)** [8] researched “Active and Reactive Power Flow Control using FACTS”. When compared to the system without and with UPFC and the system with SSSC, this research reveals that UPFC improves the actual and reactive power flow across the transmission line. The contribution of this research is that UPFC has more performance in controlling real, reactive power flow and power angle oscillations than SSSC. However, this research took a small sample as a simple single machine infinite bus power system with UPFC/SSSC connected to a three-phase transmission system and also compared 2 FACTS devices only.

Based on the research conducted **by G. Sivagnanam et al. in 2015[6]** for Reactive Power Compensation in Power Transmission Network Using FACTS devices. Software allows for the most efficient use of the FACTS controller while also lowering system costs and raising system stability. All systems should be approached using the same methodology. The study demonstrates that FACTS devices can improve the system's transient stability and that SVC and STATCOM are associated in the transmission network at the appropriate site. This study, however, fell short since it only compared SVC and STATCOM to each other, not PST.

**In the study carried out by Jean Felix MANIRAKIZA et al (2019)**[17] ‘’Technical Losses Reduction Strategies in a Transmission Network’’ In this research, the simulation of Rwanda’s power flow was done by using PSS/E to determine line losses reduction in transmission. The study shows two identical parallel lines shows better performance when compared to the technique of building a new substation. But this research failed to use FACTS devices and PST in the reduction of transmission line losses.

## 2.3 Research gaps

FACTS devices and PST are used in power system networks, same like in industrialized nations throughout the globe. The incorporation of PST and FACTS devices into the power system network was illustrated through a survey of the literature. Many different sorts of study have been carried out in industrialized nations. Those comparisons demonstrated the better FACTS device between the two controllers in managing voltage stability, actual and reactive power flow. The effects of PST and FACTS devices when they are integrated into power transmission line systems in developing nations like Rwanda have not been compared, and it is not unknown which FACTS devices are best for reactive power compensation in developing nations like Rwanda since they still use capacitor banks. Capacitor banks can provide the necessary degree of compensation, providing either under or overcompensation for a certain capacity, even when they have issues, such as when there are voltage violations in the system or load variations. It could cause system disruptions or damage the intended equipment (device).

This thesis makes a contribution by assisting Rwandans in using PST and FACTS devices in power transmission networks for compensating reactive power, hence improving power quality and transfer capacity. Additionally, it demonstrates which FACTS equipment is superior in Rwanda's electricity transmission system.

## 2.4 FACTS devices overview

### 2.4.1 Introduction

A new integrated theory called **Flexible Alternating Current Transmission Systems (FACTS)** was built on switching converters of power electronics and dynamic controllers to improve a system's utilization, capacity of power transfer, security, stability, and reliability of its connection to alternative current[18].

A group of controllers known as FACTS technology can be used alone or in conjunction with other controllers to manage variables like shunt and series impedances, current, voltage, and oscillation damping.

The FACTS devices are categorized into three kinds based on the connection type: The power circuit is connected in series with the first category; devices that control voltage and reactive power are found in parallel in the second category; and devices that control voltage and active power simultaneously are found in series-parallel connections with the power system in the third category[19].The below figure represent example of each category**.**

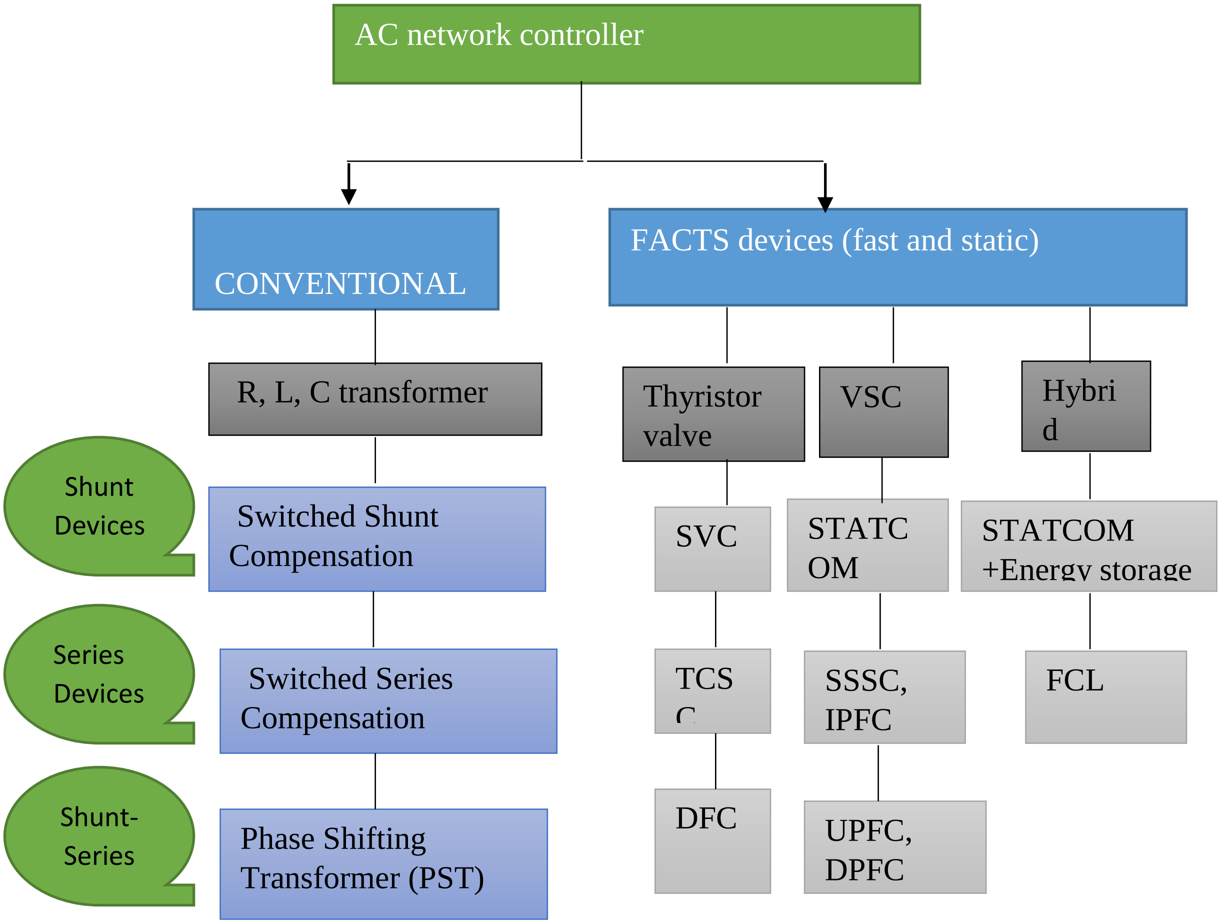


Figure 2.1: Classification AC network controllers[18].

Figure 2.1 indicates the classification of alternative current (AC) controllers that are categorized into two, such as FACTS devices and conventional switches, and each class has its own subclasses as shown.

The numbers of FACTS devices are many as shown in figure2.1. The discussion of a few of them, including SVC, SSSC, STATCOM, and UPFC, is shown below.

### 2.4.2 Static Var Compensator (SVC)

An electrical component of a flexible alternating current (AC) power transmission system is called a static VAR compensator (SVC). An SVC is said to as "static" if it has no moving components.

SVC is a static, parallel-connected VAR absorber or generator whose output is adjusted to replace inductive or capacitive current and which controls or regulates relevant current factors, primarily the bus voltage factor. The absence of gate switching off capability in thyristors is a prerequisite for a static VAR compensator[20]. The SVC adjustable reactive impedance is understood by the thyristors' properties and operation. The TCR and TSR, which are a Thyristor-Controlled Capacitor and Thyristor-Suitched Reactor, are the device's most important components[21] as shown in figure 2.2:

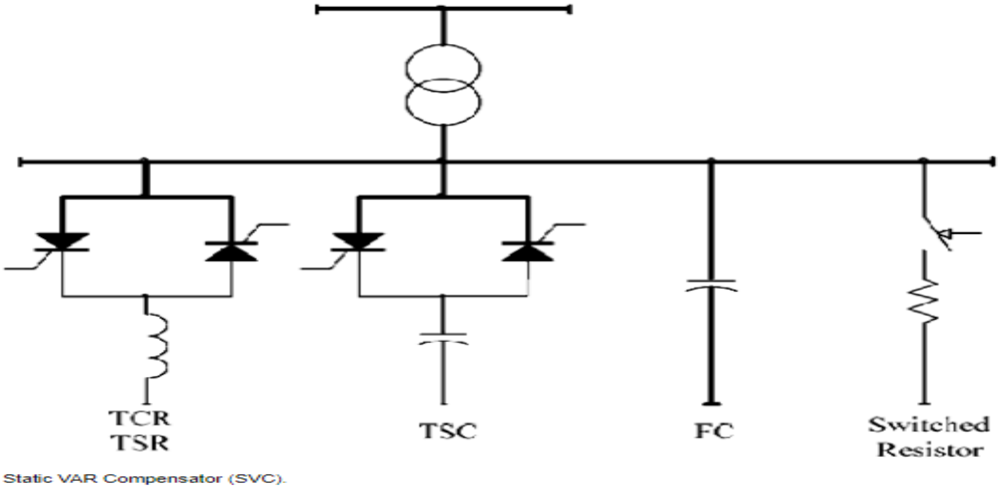


Figure 2.2: Static Var Compensator[20]

Figure2.2 depicts the static Var Compensator (SVC) components, which include the Thyristor Controlled Reactor (TCR), Thyristor Switched Capacitor (TCs), fixed capacitor (FC), and suitched resistor.

When dealing with electrical transmission systems that use excessive voltage, the gadget also offers rapid functional reactive power. SVCs fall under the categories of voltage control, system stability, and adaptive AC transmission networks[1].

### 2.4.3 Static Synchronous Series Compensator (SSSC)

A voltage source converter is used by the synchronous series compensator (SSSC), a contemporary power quality FACTS device, to link in series to a transmission line through a transformer[22]. The SSSC functions as a series capacitor and inductor with variable capacitance. SSSC functions similarly to STATCOM with the exception that it is linked serially rather than shunt. It can provide the system with both active and reactive power, enabling it to make up for resistive and reactive voltage losses while maintaining a high effective X/R that is independent of the level of series compensation[20]. However, this is expensive because a sizable energy source is needed.

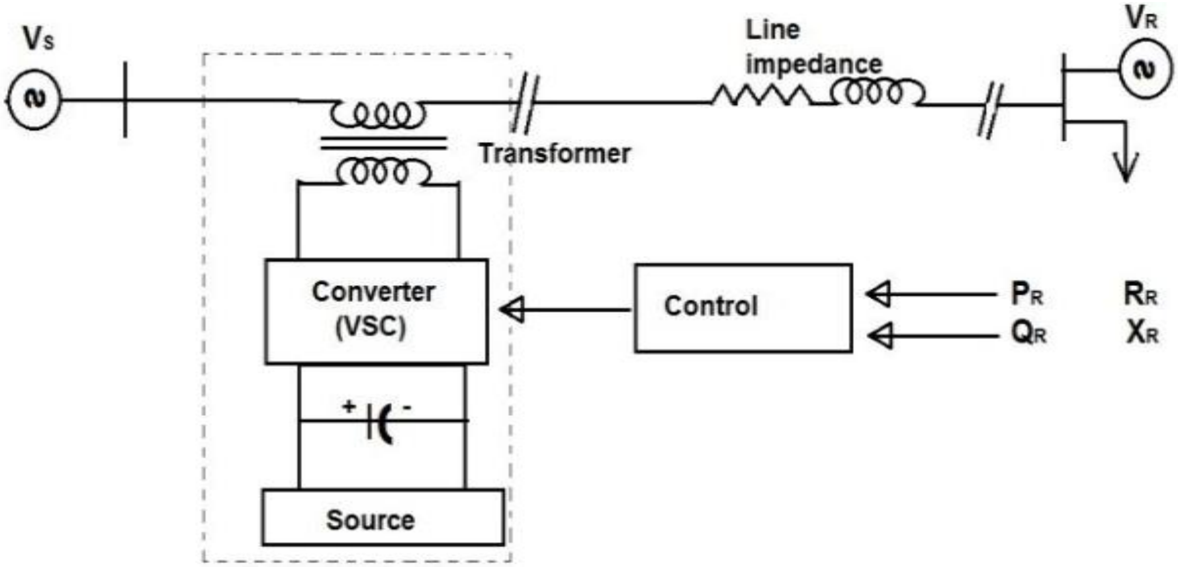


Figure 2.3: configuration of SSSC[22]

Figure 2.3 shows the configuration of SSSC. It indicates that SSSC is installed in series with the power transmission line between the sending voltage (Vs) and receiving voltage (Vr). Figure 2.3 shows how SSSC is coupled to the electrical system; the SSSC is made up of a coupling transformer, converter/inverter circuit, and a DC capacitor and its control.

### 2.4.4 Static Synchronous Compensator (STATCOM)

STATCOM, or Static Synchronous Compensator, is a power electronic device that controls the reactive power flow over a power network and so improves the stability of the power network by employing force commutated devices like IGBT, GTO, etc [23]. STATCOM is a shunt device, which means that it is shunt linked to the line. Another name for a static synchronized compensator (STATCOM) is a static synchronized condenser (STATCON)[24]. It belongs to the FACTS (Flexible AC Transmission System) family of electronics.

### 1. Principal operation of Static Synchronous Compensator (STATCOM)

Fundamentally, a static synchronous compensator (STATCOM) is a voltage source converter (VSC) connected to the grid and the earth through an inductance connection. The STATCOM functions as an AC voltage source and resembles a synchronous condenser in terms of its properties (a synchronous generator that is running lazy and used for reactive compensation)[4]. STATCOM injects an AC current that is either leading or lagging the grid voltage in quadrature, copying the capacitive or inductive impedance at the connection point. If the voltage produced by the STATCOM is lower than the grid voltage, the STATCOM behaves as an inductive device and uses reactive power from the system[3]. On the other hand, it behaves as a capacitive load when its voltage is higher than the voltage load of the grid and contributes reactive power to the grid.

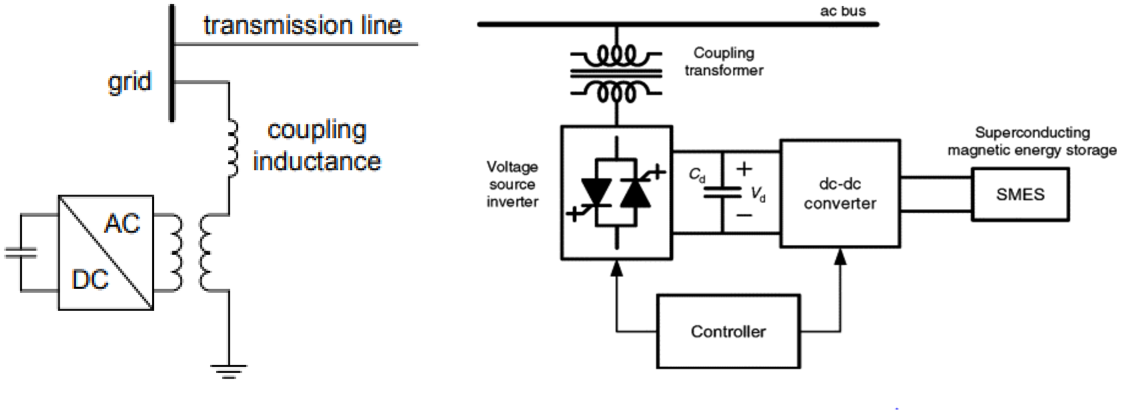


Figure 2.4: Simple configuration of STATCOM(G) [4]

The STATCOM tie on to a transmission line through a transformer coupling, the power system is connected to STATCOM. Figure 2.4 shows how STATCOM is coupled to the electrical system; the STATCOM is made up of a coupling transformer, converter/inverter circuit, and a DC capacitor and some have superconducting magnetic energy storage ,it changes a direct current to dc voltage of the superconductor magnet on the STATCOM dc side and vice versa. The ideal steady-state analysis for such a design assumed that just the exchange of reactive power could occur between the STATCOM and the AC system, leaving out the interchange of active power. When the output voltage exceeds the system voltage, the inverter pulls capacitive power for the AC grid connection and current flows through reactance from the inverter to the AC system[19]. On the other hand, if the output power's amplitude is reduced below that of the AC grid, reactive current will flow from the AC system to the inverter, which will then generate inductive power. Additionally, when the output voltage amplitude to the AC grid is balanced the voltage, the reactive power becomes zero[25]. The firing angle of the thyristor, which is determined by the phase difference between the STATCOM-voltage E and the bus voltage V, has a significant impact on the production of reactive current. The charging condition of the dc- capacitor varies in response to this firing angle, which also affects the amplitude of the STATCOM bus voltage E. The amount of reactive current that is injected into the power system is given by the equation and is determined by the magnitude of the differential between the grid voltage and the STATCOM bus voltage as well as the transformer leakage reactance XT[26].

$$I = \frac{V-E}{X_T} \qquad (2.1)$$

With: I: current injected into the power system, V: bus voltage, E: the STATCOM voltage

$X_T$: Transformer leakage reactance

Similar exchanges occur between the reactive power of the inverter and the AC system, which may be managed by changing the output voltage's magnitude. The usage of a STATCOM in real life, it may be applied to control one of the following Parameters[27][28]:

- The local bus's local voltage magnitude, to which the STATCOM is linked
- Reactive power injection to the STATCOM's local bus, which is coupled to it.
- The STATCOM's impedance.
- Voltage Injection
- The size of the voltage at a distant bus.
- Power movement
- Control of an apparent power or current on a local or distant transmission line

The most well-known control function among these control possibilities is control of the voltage of the local bus to which the STATCOM is attached. In power flow analysis, the various control options have not been properly examined[1].

## 2. Modes of operation

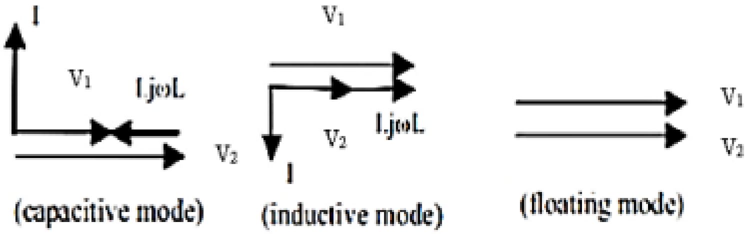


Figure 2.5 : Mode of operation[23]

In STATCOM, there are three operational modes as shown in figure2.5:

- Whether the STATCOM functions as a capacitor when$V_1 > V_2$.

- If the STATCOM functions as an inductor when $V_1 < V_2$.
- Since there is no exchange of reactive power between the two nodes, the STATCOM will float in this mode when$V_1 = V_2$.

With:

$V_1$ : System Voltage. $V_2$: Voltage Source Converter (VSC) output voltage [4]

### 3. V- I characteristics of STATCOM

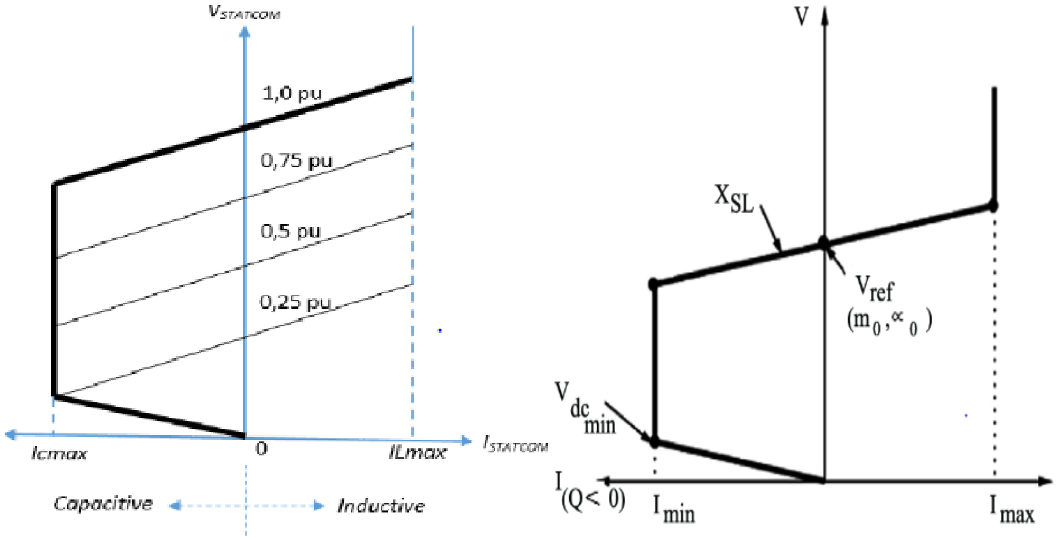


Figure 2.6 : V I characteristics of STATCOM[9]

The maximum voltage and current ratings of the converter are the sole factors limiting the STATCOM's operational range or operating region (V-I characteristics are depicted in Figure 2.6).

STATCOM's V-I characteristics are influenced by the source voltage. STATCOM is not only capable of operating at low voltage while preserving the voltage independence of the maximum current but is also able to provide more robust reactive support even at low voltage. By changing the modulation index or the DC bus voltage, you may obtain the regulated response that the STATCOM has selected[29].

### 2.4.5 Unified Power Flow Controller (UPFC)

Unified Power Flow Controller (UPFC) is the Combining of a static series compensator (SSSC) and a static synchronous compensator (STATCOM), which is connected by a single dc connection, to enable real/reactive power to flow back and forth between their respective series output terminals and shunt output terminals[30].

### 1. Principal operation of Unified Power Flow Controller (UPFC)

Two voltage-source converters (VSCs) with semiconductors that can have the capacity to switch off, sharing a common dc capacitor, and coupled to a power supply through coupling transformers make up the UPFC[27].

The transmission voltage, impedance, and phase angle of the transmission line may all be controlled simultaneously by the UPFC.it comprises two switching converters. A d. c. storage capacitor serves as the common d.c connection that powers these converters[31]. By injecting a c voltage with a configurable magnitude and phase angle in series with the transmission line through a series transformer, Converter 2 manages the power flow of the UPFC. The true power demand from converter 2 is to be absorbed or supplied by converter 1 at the shared d.c connection. Additionally, it can compensate for shunt reactive power and absorb or produce regulated reactive power[21].

The Unified Power Flow Controller (UPFC) consists of a STATCOM and an SSSC that are connected by a shared DC connection to allow active power to flow in both directions between the SSSC's shunt output terminals and the STATCOM's series output terminals. Reactive power can be provided (or consumed) by each converter at its own AC terminal. A DC storage capacitor provides a DC connection that powers the two converters[16].

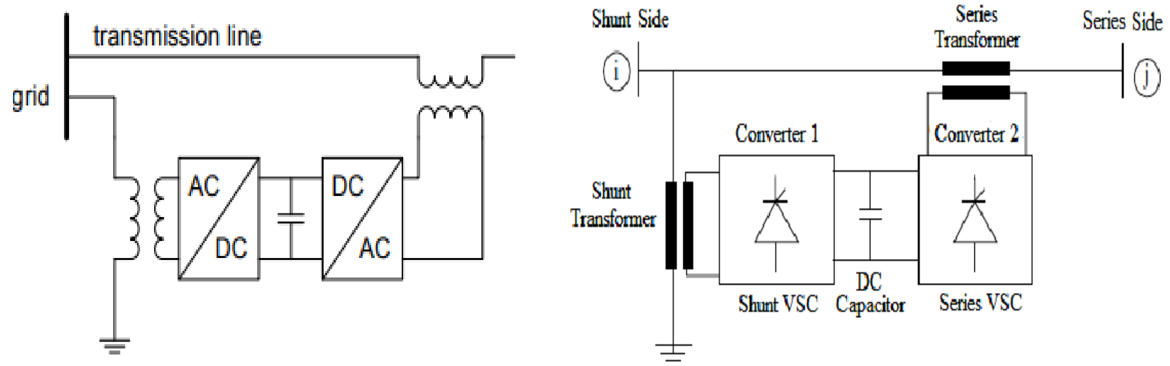


Figure 2.7 : Configuration of UPFC[27]

Figure 2.7 shows how UPFC is coupled to the electrical system, two voltage-source converters (VSCs) with semiconductors that can have the capacity to switch off, sharing a common dc capacitor, and coupled to a power supply through coupling transformers make up the UPFC.The left and the right figures represent converters symbols and inside of converters respectively. By enabling the independent management of both the real and reactive power flow and, as a result, the maximizing of real power transfer at the lowest possible line losses, the UPFC idea offers a potent instrument for the cost-effective exploitation of individual transmission lines [21].

### 2. Modes of operation of UPFC

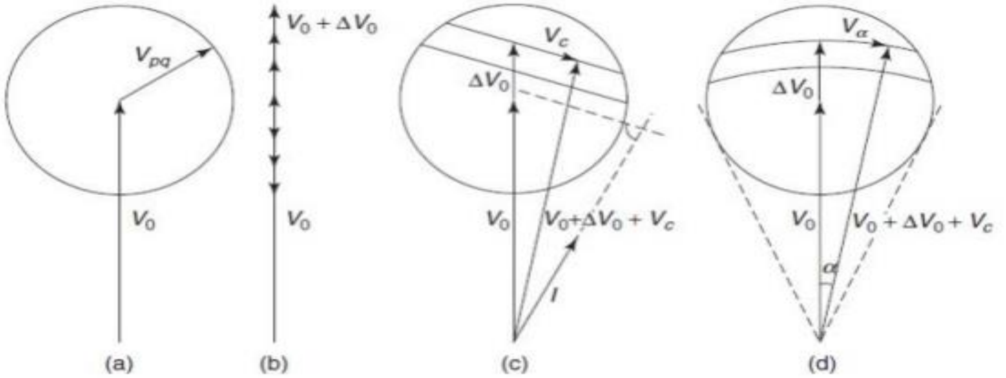


Figure 2.8:The principles of different power-flow control functions using the UPFC phasors diagram[32]

a) injection of Series-voltage; b) regulation of Terminal-voltage; c) regulation of Terminal-voltage and line-impedance; and d) regulation of Terminal-voltage and phase-angle are shown in the phasor diagram, which also shows the overall idea of series-voltage injection and achievable power flow control functions[32].

In earlier Figure 2.8, the principles of different power-flow control functions using the UPFC are shown from (a) to (d). The addition of the general voltage phasor Vpq to the already-existing bus voltage, V0, is shown in Part (a) for an angle ranging from $0^0$ to $360^0$ degrees. If Vpq = V0 is created in phase with V0, as indicated in part, voltage control is achieved (b)[33]. Part (c) implements a mixture of voltage regulation and series compensation, where Vpq is the total of a voltage regulating component (V0) and a voltage component (Vc) that provides series compensation and lags the line current by $90^0$. The UPFC-generated voltage Vpq in the phase-shifting process depicted in section (d) is made up of the voltage-regulating component V0 and the phase-shifting voltage component Va [30]. The purpose of Va is to add or subtract an angle to the phase angle of the regulated voltage phasor, V0 + V. Figure 2.8 shows the simultaneous achievement of all three of the aforementioned power-flow control tasks. Depending on the needs of the system, the UPFC controller may choose one or a mixture of the three functions as its control target[30].

## 2.5 Phase Shifting Transformer (PST)

### 2.5.1 Introduction

To regulate the active power flow on 3-phase transmission networks, a specific class of transformers called a PST, or phase shifting transformer, is utilized. This may be accomplished by altering the voltage phase angle differences between system nodes[34].

### 2.5.2 Principal operation of Phase Shift Transformer (PST)

The Phase Shifting Transformer (PST), a kind of transformer, controls the transmission line's active and reactive power flow. A PST frequently consists of a series transformer and a shunt transformer with a tap changer. PST's function is to enable the other phases of the shunt transformer to reach the voltage that the series transformer inserts[16]. The injected voltage, which is in quadrature with the phase voltage and alters the phase angle across the transformer, changes the transmission angle. By altering the shunt transformer's taps, it is possible to control the magnitude of the quadrature voltage and, therefore, the voltage phase changes across the PST. The graphic below depicts how a simple PST is set up[15].

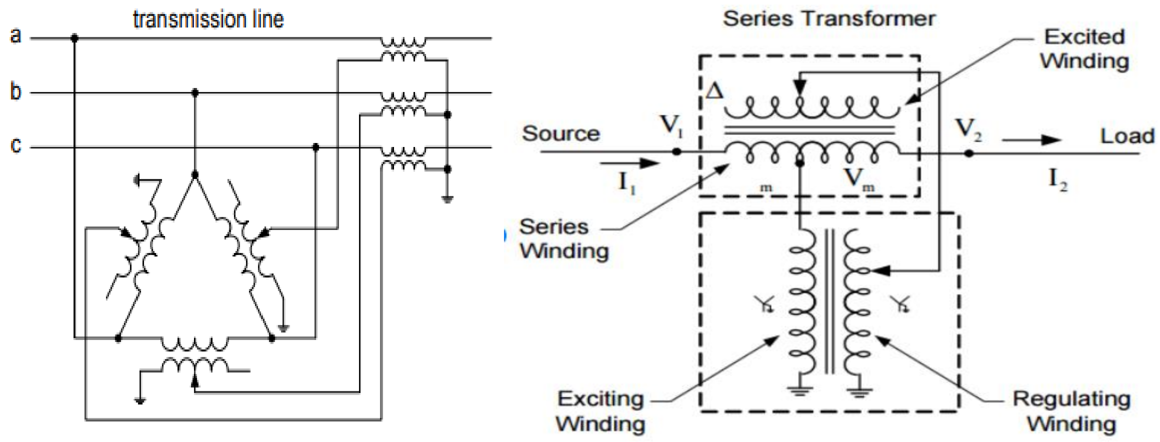


Figure 2.9 :Simple block diagram of Phase Shift Transformer (PST)[16],[15].

Figure 2.9 depicts how PST is coupled to the electrical system. It is made by three winding coupled to transformer connected in series with transmission line

### 2.5.3 Modes of operation

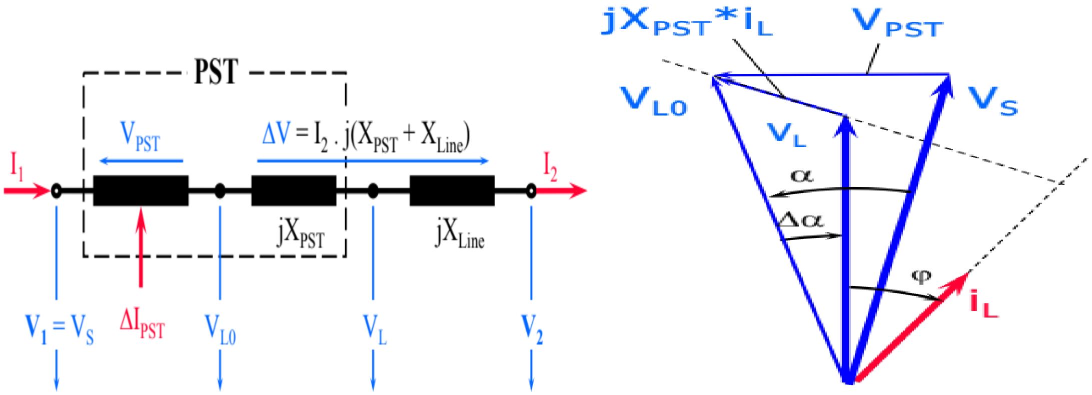


Figure 2.10 circuit of PST two system nodes and phasor diagram of change voltage[34]

Figure 2.10 shows Phase Shifting Transformer two system nodes on left side and variation of load voltage due to load current to right side. When PST is installed in transmission line, it controls the power flow as seen in the below formula.

$$P = \frac{V_1 V_2 Sin(\varphi + \Delta\alpha)}{X + X_{PST}} \quad (2.2)$$

$$V_S = V_L + (jX_{PST} * i_L) - V_{PST} \quad (2.3)$$

$$V_L = V_{L0} - (jX_{PST} * i_L) \quad (2.4)$$

With: $X_{PST}$: phase shifting transformer reactance

P: real power flow, $V_1 = V_S$: sending voltage, $V_2$: receiving voltage

$V_L$: Load voltage, $V_{PST}$: phase shifting transformer,

$i_L$ : Load current $\varphi$: load angle , $\Delta\alpha$: Phase shift angle

### 2.5.4 Types of Phase Shifting Transformers (PST)

Phase Shifting Transformers (PST) may be divided into four groups based on how they were built and how they were designed. The quadrature voltage is generated by only two additional phases at an exciting winding difference in each design, with the transmitting and receiving ends only connected to the series winding[16].The figure below shows different types of PST by taking into account of their design and construction[15].

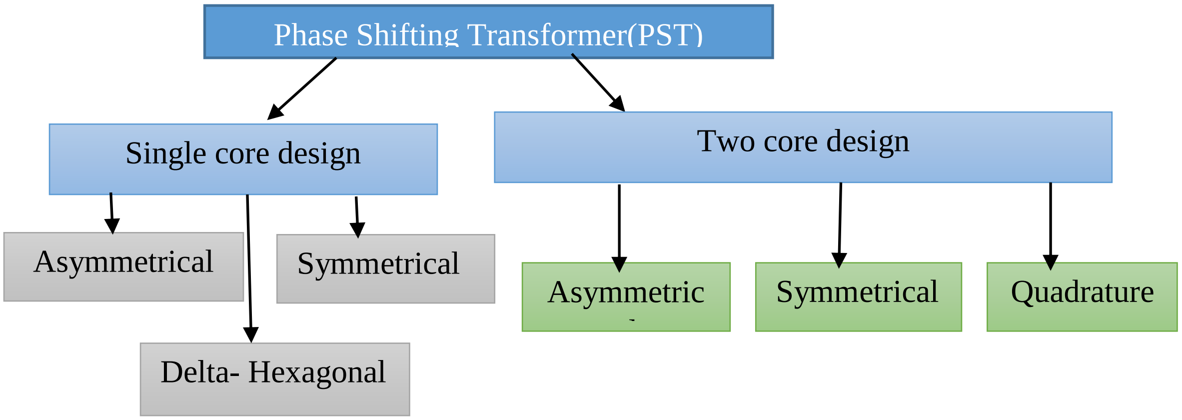


Figure 2.11 : Different types of PST[15]

- **Asymmetrical PST:** To produce an output voltage, asymmetrical phase-shifting transformers vary the amplitude and phase angle in relation to the input voltage.
- In contrast to the input voltage, **symmetrical phase-shifting transformers** provide an output voltage with a different phase angle but same amplitude[34].

# 3. METHODOLOGY

## 3.1 Introduction

The goals of this research can be achieved via the use of several steps. The FACTS devices and PST are applied where there is a problem of power system instability to get power quality. Integration of STATCOM, UPFC, and PST in the 110 kV northern Hub of Rwandan's transmission was designed using a site visits to the selected case study. Data gathering on the chosen location, documentation, mathematical modeling, and simulation can all be used to get the necessary information.

## 3.2 Documentation

Documentation of related books and observation of selected data sites for case studies were done. Many researchers investigated power system quality issues by integrating FACTS devices and PST in power systems to control real and reactive power. A study entitled "Power Flow Analysis Using Unified Power Flow Controller" was conducted by **Anil Kumar Bonela et al.** [35]**.** In this study, the effectiveness of UPFC in managing the flow of electricity across the transmission line was examined. The model's usefulness in terms of computational efficiency, precision, and resource requirements is confirmed by numerical results. It was discovered that the UPFC controls the buses' voltage as well as their active and reactive power. Some information is required during the design of STATCOM, UPFC, and PST in the 110 kV northern Hub of Rwandan transmissions to ensure that the power transmission line does not have power quality problems.

## 3.3 Data collection

The process of gathering information for use in a certain activity or for another reason is known as data collection. Through interviews, surveys, documentation, or observation, it is the process of obtaining, quantifying, and evaluating precise data from a range of areas in accordance with the goal. Some data was needed to simulate the design. Data for this thesis was gathered during site visits to the NTARUKA and MUKUNGWA power stations, the GIFURWE Substation, and the RULINDO Substation, where observations and documentation were made in order to obtain data used in design and simulation.

## 3.4 Mathematical modeling of power transmission line

In order to efficiently transport huge amounts of energy at high voltage without loss, power transmission lines are used to link power plants and substations as well as for connections between substations [5]. They therefore play a significant part in the provision of electricity.

The technique of presenting a situation in the real world using mathematical equations, graphs, or diagrams is known as a mathematical model. During the design, some formulas were needed to get the final results and graph. The mathematical models used in this study are length between buses, real power and reactive power generated by NTARUKA and MUKUNGWA generation, real power and reactive power at GIFURWE and RULINDO substations, and power flow for each bus of the Rwanda 110 kV north hub transmission line. Those parameters were modeled with PST, STATCOM, and UPFC in the transmission line.

## 3.5 Simulation using MATLAB/Simulink

The world's leading businesses and academic institutions utilize MATLAB as a development environment for numerical computation, statistical analysis, and simulation. Simulink is a graphical platform for model-based design and multi-domain simulation that is integrated with MATLAB [36].

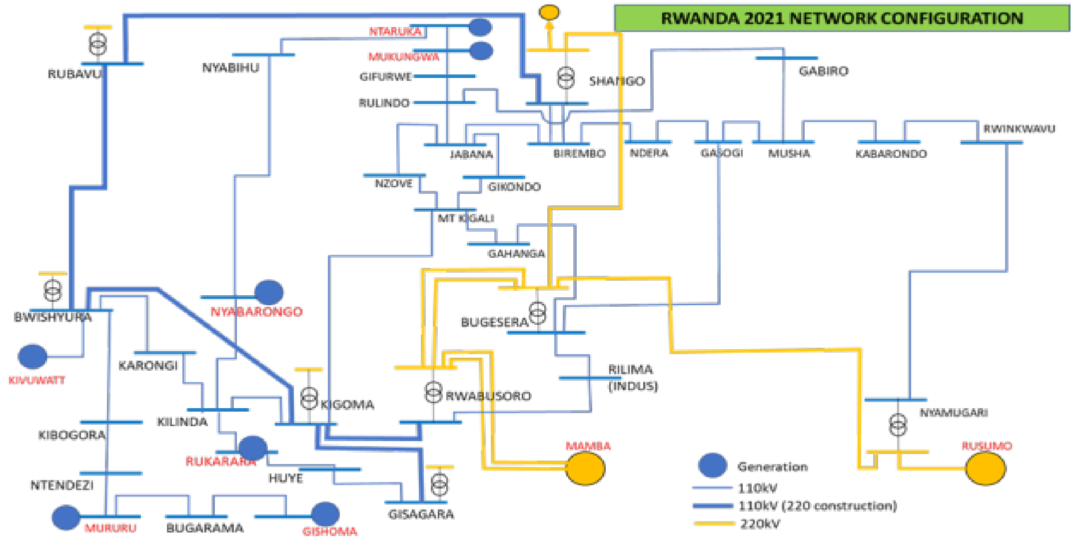
The matrix laboratory tool called MATLAB/Simulink was used in this study. Reactive power compensation of Rwanda's 110 kV north Hub of Rwanda’s transmission network with STATCOM, UPFC, and PST has been observed by using MATLAB/SIMULINK. And analyzing results from MATLAB/SIMULINK and indicating which device is efficient for the Rwandan power transmission network.

# 4. DATA COLLECTION

## 4.1 General data of Rwanda transmission Network

The transmission system in Rwanda consists of three primary voltage profile levels: 70 kV, 110 kV, and 220 kV. The overall length of the country's transmission network, comprising 220 kV and 110 KV lines, was 944.39 km as of the end of June 2021[35]. Three (3) high-voltage substations—Mamba, Rwabusoro, and Bugesera—along the transmission line Mamba-Rwabusoro-Bugesera-Gahanga, as well as the temporary 110/30 kV Rubavu substation along the Mukungwa-Nyabihu transmission line, were finished and put into service by the end of June 2021. This brought the total number of substations—including five switchyards[35].

2021 Rwanda network configuration[14].



**Source: EDCL transmission masterplan July,2018**

Figure 4.1 : Rwanda network configuration[14]

Figure 4.1 represents the 2021 Rwanda power system network configuration. The blue circle shows the generation of 110 kV, the yellow circle shows the generation of 220 kV, the two circles show transformers, and the blue and yellow lines show transmission lines.

The table below represents 110 kV High voltage(HV) transmission of Rwanda transmission network[35][13].

## Table 4.1 : 110 kV High voltage(HV) transmission of Rwanda transmission[13]

| NO | Line (kV) | Description | Length(km) |
|---|---|---|---|
| **1** | 110 | Birembo – Gasogi | 8.67 |
| **2** | 110 | Birembo-Shango | 9.59 |
| **3** | 110 | Bugarama-Gishoma | 12.27 |
| **4** | 110 | Bugesera - Bugesera IP | 23.10 |
| **5** | 110 | Gabiro-Musha | 45.96 |
| **6** | 110 | Gahanga-Bugesera | 17.31 |
| **7** | 110 | Gasogi-Musha | 17.48 |
| **8** | 110 | Gifurwe-Mukungwa (Double Circuit) | 18.46 |
| **9** | 110 | Gikondo-MountKigali | 5.22 |
| **10** | 110 | Gikondo - Jabana I | 8.36 |
| **11** | 110 | Jabana I-Birembo | 6.97 |
| **12** | 110 | Jabana I-Jabana II | 1.29 |
| **13** | 110 | JabanaI-Rulindo | 25.73 |
| **14** | 110 | Kabarondo-Rwinkwavu | 7.25 |
| **15** | 110 | Karongi-Kibuye | 12.41 |
| **16** | 110 | Karongi –Kibogora | 39.20 |
| **17** | 110 | Kibogora-Ntendezi | 18.46 |
| **18** | 110 | Kibuye-KivuWatt | 1.21 |
| **19** | 110 | Kigoma-Kilinda | 27.45 |
| **20** | 110 | Kilinda-Karongi | 25.11 |
| **21** | 110 | Kilinda-Nyabarongo | 27.85 |
| **22** | 110 | Kilinda-Rukarara | 31.29 |
| **23** | 110 | Mamba-Rwabusoro | 21.54 |
| **24** | 110 | MontKigai-Kigoma | 40.33 |
| **25** | 110 | MontKigali-Gahanga | 9.64 |
| **26** | 110 | MontKigali-Jabana | 17.25 |
| **27** | 110 | Mururu II-Mururu I | 0.37 |

|  |  |  |  |
|---|---|---|---|
| **28** | 110 | Musha-Kabarondo | 23.35 |
| **29** | 110 | Ndera cut-In cut-out | 2.14 |
| **30** | 110 | Ntaruka-Gifurwe | 8.51 |
| **31** | 110 | Ntendezi-Bugarama | 17.62 |
| **32** | 110 | Ntendezi-Mururu II | 20.89 |
| **33** | 110 | Rubavu-Goma Border | 7.01 |
| **34** | 110 | Rubavu - Bwishyura/Kibuye | 57.54 |
| **35** | 110 | Rulindo-Gabiro | 63.86 |
| **36** | 110 | Rulindo-Gifurwe | 24.93 |
| **37** | 110 | Rwabusoro-Bugesera SS | 40.64 |
| **38** | 110 | Shango – Rubavu | 106.11 |
| **39** | 110 | Shango –Mirama (Up to Uganda Border) | 92.01 |
|  |  | Total | 944.39 |

The load and transmission line data for the Rwanda 110 kV high voltage transmission network were obtained from Rwanda Energy Group (REG), which is a state-owned power utility company. Rwanda’s high and medium voltage transmission lines have 5 hub MV networks according to the region, such as Kigali Hub, South Hub, East Hub, North Hub, and West Hub[14][13].This thesis aims at the comparison of PST, STATCOM, and UPFC for reactive power compensation in Rwanda's transmission network to enhance the power quality. Models of Rwanda's 110 kV north transmission line network in Matlab.

## 4.2 Specific data related to case study

Rwanda's 110 kV north hub transmission line has three **substations (**NTARUKA, GIFURWE, and RULINDO), the MUKUNGWA switchyard, and two power plants (generations). All together, they made four buses. The data from two power plants (NTARUKA and MUKUNGWA) are shown below [10].

**Table 4.2: Data of NTARUKA and MUKUNGWA hydropower plant**

| Data | NTARUKA | MUKUNGWA |
|---|---|---|
| **Location** | Installed at Lake BURERA, Northern Province | installed Lake Ruhondo, Northern Province |
| **Coordinates** | GQF2+34Ruhondo, Rwanda | CM93+8X Nyakinama, Rwanda |
| **Installed capacity** | 11.5 MW | 12 MW |
| **Operational capacity** | 2.6 MW | 6 MW |
| **Date of installation** | 1959 | 1982 |

The below table 4.3 shows the data of the north hub transmission line network [37].

**Table 4.3 : Data of the north hub transmission line network**

| N0 | substations | Line HV(Side) | Line LV(Side) | MVA Rated | Generator | | | Loads | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | P(MW) | Q(Max) | Q(min) | P(MW) | Q(Mvar) |
| **1.** | NTARUKA | 110 kV | 6.6/30 kV | 10/15 | 11.5 | inf | Inf | 1.014 | 0.7 |
| **2.** | MUKUNGA | 110 kV | 6.6/30 kV | 15 | 12 | inf | Inf | 1.577 | 0.8 |
| **3.** | GIFURWE | 110 kV | 30 kV | 6 | - | - | - | 1.178 | 0.9 |
| **4.** | RULINDO | 110 kV | 30 kV | 20 | - | - | - | 6.642 | 3 |

The table below presents 110 kV High voltage(HV)North hub transmission of Rwanda transmission network[35] .

**Table 4.4: 110 kV High voltage(HV)north hub transmission of Rwanda transmission network and length between buses**[35]

| no | Line HV(kV) | Description | Length(km) |
|---|---|---|---|
| **1** | 110 | Ntaruka- Mukungwa | 9.95 |
| **2** | 110 | Mukungwa-Gifurwe | 18.46 |
| **3** | 110 | Gifurwe-Rulindo | 24.93 |

# 5. MATHEMATICAL MODELING WITHOUT AND WITH PST, UPFC AND STATCOM

## 5.1 Introduction

This study analyzed Rwanda's power network with two generations, four buses, four transmission lines, and loads connected to each bus. Rwanda’s power systems face power quality issues caused by any faults that happen in transmission lines.

## 5.2 General power flow model of power system network

To analyze the power flow of a selected site system, the necessary tool to use is load flow analysis. Since the real power system is made up of a non–linear system, studies of load flow consist of a set of non–linear equations to analyze different parameters of the power system network[1].

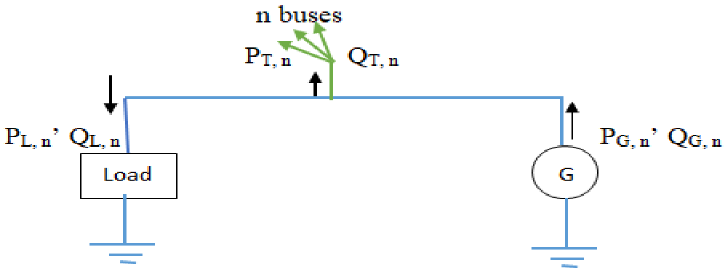


Figure 5.1: Power flow of any given system[5].

Figure 5.1 indicates any given system where G, $P_G$, and $Q_G$ are generation with it real and reactive power respectively; $P_T$, QT, $P_L$, and $Q_L$ are the real and reactive power of the transmission line and load of the selected site respectively

The equations of reactive and real power flow at bus n may be expressed as given in Figure 5.1 above in accordance with Kirchhoff Law (KCL)[5]. Equations:

$$P_{G,n} = P_{L,n} + P_{T,n} \tag{5.1}$$

$$Q_{G,n} = Q_{L,n} + Q_{T,n} \tag{5.2}$$

With: $P_{G,n}$ : real power .To relate to it the selected site is real power of NTARUKA or MUKUNGWA generation.

n: any bus among four buses of selected site(GIFURWE,RULINDO,MUKUNGWA and NTARUKA)

$Q_{G,n}$: Reactive power. It is reactive power of NTARUKA or MUKUNGWA (generation).

$P_{L,n}$ , $P_{T,n}$: Real power of load and transmission line at any bus among four of the selected site respectively.

$Q_{L,n}$ , $Q_{T,n}$: Reactive power of load and transmission line at any bus among four of the selected site respectively. The equations (5.3) and (5.4) show real power and Reactive power of all M buses (four buses as selected site)

$$P_{T,n} = \sum_{i=1}^{M} V_n V_i \; Y_{n,i} \cos(\beta_n - \beta_i - \vartheta_{n,i}) \tag{5.3}$$

$$Q_{T,n} = \sum_{i=1}^{M} V_n V_i \; Y_{n,i} \sin(\beta_n - \beta_i - \vartheta_{n,i}) \tag{5.4 }$$

n=1, 2, 3, 4, 5………...M, where M is the number of buses (M is four for the selected site)

$Y_{n,i}$: Admittance between n$^{th}$& i$^{th}$ bus

$\vartheta_{n,i}$ : Angle on $Y_{n,i}$ admittance: to find the admittances Newton Raphson method must be used

Total real power flow generation at any **bus** n is obtained by substituting equation (5.3) in (5.1)

$$P_{G,n} = P_{L,n} + \sum_{i=1}^{M} V_n V_i \; Y_{n,i} \cos(\beta_n - \beta_i - \vartheta_{n,i}) \tag{5.5}$$

$$P_{G,n} - P_{L,n} - \sum_{i=1}^{M} V_n V_i \; Y_{n,i} \cos(\beta_n - \beta_i - \vartheta_{n,i}) = P_n(V,\beta) = P_n = 0$$
(5.6)

Total reactive power flow at each bus **n** is obtained by- substituting equation (5.4) in (5.2)

$$Q_{G,n} = Q_{L,n} + \sum_{i=1}^{M} V_n V_i \; Y_{n,i} \sin(\beta_n - \beta_i - \vartheta_{n,i}) \tag{5.7}$$

$$\mathrm{Q_{G,n}} - \mathrm{Q_{L,n}} - \sum_{i=1}^{M} \mathrm{V_n V_i \; Y_{n,i}} \sin(\beta_n - \beta_i - \vartheta_{n,i}) = \mathrm{Q_n}(V,\beta) = \mathrm{Q_n} = 0 \tag{5.8}$$

### 5.3 Power system model with Phase Shift Transformer (PST)

A PST may have a modeling with a series reactance of line and PST(X, $X_{PST}$) for phase shift α. Equation becomes:

$$P = \frac{V_1 V_2 Sin(\delta+\alpha)}{X+X_{PST}} \tag{5.9}$$

Where, the equation (5.9) represents the relationship the active power with different parameters of transmitting electricity over long lines and phase shift angle. Thus, once the variation of α applied, such changes influence slightly δ and provides much contribution to the active power P. Thus, once the action control done, the active power allows a constant δ curve.

Phase shift transformer circuit in transmission line is shown in figure5.2 below:

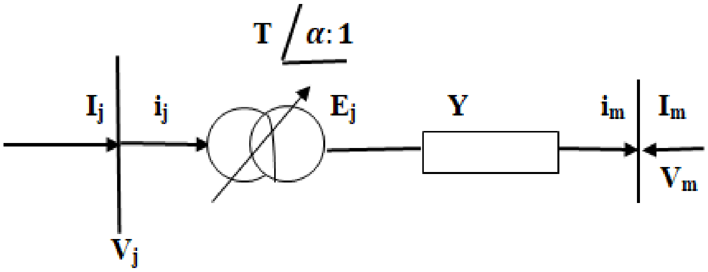


Figure 5.2: Equivalent circuit of phase shift transformer in transmission line (PST)[15]

The equivalent circuit of the phase shift transformer (PST) is presented in Figure5.2. Show that the line admittance is in series with the PST.PST shifts the phase angle of the voltage and the current to arranged value and control the power flow in the line that inserted in by changing the phase angle between the two buses of the line[28]. PST are connected in Series with transmission line between bus I(GIFURWE bus as the site selected shown in figure 6.7) and m(RULINDO bus as the site selected shown in figure 6.7) as shown in figure 5.2 for the purpose of load flow solutions form the Y –bus matrix[34].

The real power flow in a transmission line connected between any two buses in power system depends on voltage phase angle difference between the 2 buses

Assume a PST connected between bus j and bus m with series transformer admittance as shown in figure 5.2.

PST, the MVA ($S_j$) is:

$$S_j = P_{j+i}Q_j \tag{5.10}$$

$$V_j = |V_j|\angle\delta$$

The following equations show the power flow:

$$\Delta P_j = P_j{}^S + P_{j,c} \tag{5.11}$$

$$\Delta Q_j = Q_j{}^S + Q_{j,c} \tag{5.12}$$

$$P_{j,c} = \sum_{i=1}^{n} V_j V_m \; Y_{jm} \, cos(\mu_{jm} + \delta_m - \delta_j); \; \mu_{jm}\text{: Admittance angle for bus j and m} \tag{5.13}$$

$$Q_{j,c} = \sum_{i=1}^{n} V_j V_m \; Y_{jm} \, sin(\mu_{jm} + \delta_m - \delta_j) \tag{5.14}$$

$$P_j{}^S = P_{j,gen} - \; P_{j,load} \tag{5.15}$$

$$Q_j{}^S = Q_{j,gen} - \; Q_{j,load} \tag{5.16}$$

With: $\delta_m$, $\delta_j$: Voltage phase angle at bus m and j respectively

$\Delta P_j$: Change of real power at bus j; $\Delta Q_j$: Change of reactive power at bus j

$V_m$ , $V_j$, $Y_{jm}$: Voltage at m and j buses and admittance of j m buses

$P_{j,c}$ , $Q_{j,c}$: Real power calculated value and calculated reactive power at bus j respectively.

$P_j{}^S$, $Q_j{}^S$ : specified value of real power and specified reactive power at bus j respectively.

$P_{j,gen}$ , $P_{j,load}$: Real power of generation and load respectively

### 5.4 Modeling of Unified Power Flow Controller (UPFC)

It is simple to connect the UPFC injection model with a load flow program. A reactance between nodes j and m that is similar to an **X** series is added to the admittance matrix if a UPFC is situated between nodes **j** and **m** in a power system[36].relate to the design of this study UPFC is installed between GIFURWE bus (bus j) and RULINDO bus(bus m).

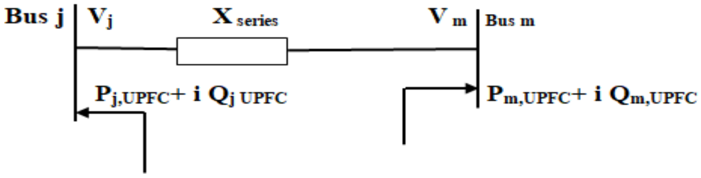


Figure 5.3: Circuit of mathematical model of UPFC[36]

A UPFC mathematical model can be built by linking the series and shunt power injections at both bus j (GIFURWE bus) and bus m (RULINDO bus). The elements of equivalent power injections in the figure 5.3 above are:

$$P_{j,UPFC} = xkb_{series}{V_j}^2 sin\alpha - ykb_{series}V_jV_m sin(\vartheta_j - \vartheta_m + \alpha) \quad (5.17)$$

$$P_{m,UPFC} = kb_{series}V_jV_m sin(\vartheta_j - \vartheta_m + \alpha) \quad (5.18)$$

$$Q_{j,UPFC} = -kb_{series}{V_j}^2 cos\ \alpha \quad (5.19)$$

$$Q_{m,UPFC} = kb_{series}V_jV_m cos(\vartheta_j - \vartheta_m + \alpha) \quad (5.20)$$

Where x: is the total switching losses of the two converters that can be estimated to be about 2%=0.02 of the power transferred for thyristor based PWM converters [6].

k: the per unit magnitude of voltage source, α: the phase angle of voltage source.

The limit of phase angle and per unit magnitude respectively is: $-\pi \leq \alpha \leq \pi$; $0 \leq k \leq k_{max}$

$b_{series} = \frac{1}{X_{series}}$ : Admittance

$X_{series}$: Series impedance

$V_j$: Voltage source at bus j (GIFURWE bus), $V_m$: Voltage source at bus m (RULINDO bus); $\vartheta_j$: The angle at bus j (GIFURWE bus);$\vartheta_m$: Angle at bus m (RULINDO bus)

$P_{j,UPFC}$, $P_{m,UPFC}$: Injected Real power of UPFC at bus j (GIFURWE bus) and m (RULINDO bus) respectively

$Q_{j,UPFC}$, $Q_{m,UPFC}$: Injected Reactive power (consumed) of UPFC at bus j and m respectively

Y: times of the injected series real power in order to get real power shunt

The equation of power when UPFC is combined with the power system transmission line equation

$$P_j + iQ_j = \sum_{j=1}^{n} V_jV_mY_{jm}\angle(\vartheta_m - \vartheta_j + \alpha_{jm}) + P_j' + iQ_j'$$
(5.21)

With: $P_j$, $Q_j$: real power and reactive power at $j^{th}$bus respectively.

$P_j'$, $Q_j'$: Active and reactive power flow from UPFC between the buses j and m respectively.

$Y_{jm}$: Admittance of j m buses

$\alpha_{jm}$: α: The phase angle of voltage source of j m buses

### 5.5 Modeling of Static Synchronous Compensator (STATCOM)

The below figure5.4 is general design of STATCOM connected on bus i of transmission line, this study i bus is represented by GIFURWE BUS where STATCOM is connected.

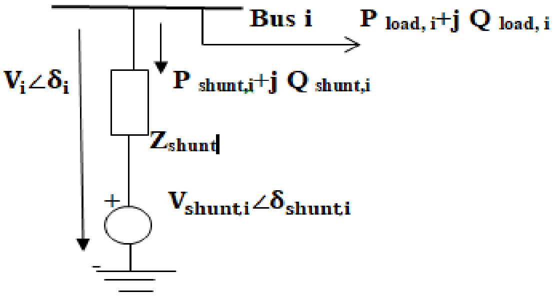


Figure 5.4 Equivalent circuit of STATCOM[37]

The Figure 5.4 represents equivalent circuit with STATCOM connected to bus i. It is capable to regulate the bus voltage magnitude by absorbing or injecting reactive power from or to bus is connected. The equation of i bus with STATCOM[37]:

$$S_i = (P_{load,i} + jQ_{load,i}) + (P_{shunt,i} + jQ_{shunt,i}) \tag{5.22}$$

$$P_i = P_{load,i} + P_{shunt,i} \tag{5.23}$$

$$Q_i = Q_{load,i} + Q_{shunt,i} \tag{5.24}$$

$$I_{shunt,i} = \frac{P_{shunt,i} - jQ_{shunt,i}}{V_i} \tag{5.25}$$

$$V_{shunt,i} = V_{i} \_\ I_{shunt,i}\, Z_{shunt,i} \tag{5.26}$$

The STATCOM equivalent circuit shown in figure5.5 constrains power of STATCOM are:

$$P_{shunt,i} = |V_i|^2 * c_{shunt,i} - |V_i||V_{shunt,i}| * \left[c_{shunt,i}cos(\delta_i - \delta_{shunt,i}) + s_{shunt,i}Sin(\delta_i - \delta_{shunt,i})\right]$$

(5.27)

$$Q_{shunt,i} = -|V_i|^2 * s_{shunt,i} + |V_i||V_{shunt,i}| * [-s_{shunt,i} Sin(\delta_i - \delta_{shunt,i}) + c_{shunt,i} cos(\delta_i - \delta_{shunt,i})]. \qquad (5.28)$$

These equations (5.24) and (5.25) present the active and reactive power of STATCOM.

The boundary of voltage Injection and capacity of STATCOM:

$$V_{shunt,i\,min} \leq V_{shunt,i} \leq V_{shunt,imax}\,; \quad Q_{shunt,i\,min} \leq Q_{shunt,i} \leq Q_{shunt,imax} \qquad (5.29)$$

With: voltage, Q: reactive power, P: real power, S: apparent power, I: current

## 5.6 Newton Raphson method in power system

### 5.6.1 Introduction

The power flow equation has been solved using a variety of methods over the years[36]. Early in the 1970s, the Newton-Raphson technique and its derivations were created to address the other methods' subpar convergence capabilities when used to solve networks[38].It uses the matrix of Jacobian.The matrix of Jacobian is improved by the addition of appropriate injection powers. If we consider the linearized model of load flow[36]as:

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} \Delta \vartheta \\ \Delta V \end{bmatrix}$$

where the elements of matrix of Jacobian are A, B, C, and D, the size of the matrix of Jacobian having a system with the total number of buses n, the first selected bus as a slack bus, m buses as PV buses.

$$A_{jn} = \frac{\delta P_j}{\delta \vartheta_n}; B_{jn} = \frac{\delta P_j}{\delta V_n};\ C_{jn} = \frac{\delta Q_j}{\delta \vartheta_n};\ D_{jn} = \frac{\delta Q_j}{\delta V_n} \qquad (5.30)$$

J = 1, 2, 3……...n, n: number of buses

$\delta$: derivative; $\Delta$Q: change in reactive power; $\Delta$P: change in real power; $\Delta$V: change in voltage between sending and receiving buses.

$\Delta\vartheta$: Phase angle difference between sending and receiving buses, the elements of the Improved matrix are $\Delta\vartheta$ and $\Delta$V and the elements of mismatch matrix are $\Delta$P and $\Delta$Q

### 5.6.2 Power flow by Newton-Raphson with UPFC controller

Utilizing MATLAB programming, the algorithm for a power flow issue integrated with UPFC is constructed. The following stages illustrate how the UPFC is included into the load flow algorithm of Newton Raphson[39].

- Read the input data of the system
- Formulation of admittance matrix: Y
- Linking the power equations of UPFC with equations of the system, the power flow equation is shown in equation( 5.21):
- Formulation of the improved Jacobian matrix” A, B, C, D” and mismatching the power equations.
- Modernize the bus voltage and Check the convergence
- Calculate load flow output and if yes achieved, if no return to step four.

### 5.6.3 Power flow by Newton-Raphson with STATCOM Controller

Utilizing MATLAB programming, the algorithm for a power flow issue integrated with STATCOM is constructed. The following stages illustrate how the STATCOM is included into the Newton Raphson load flow algorithm[38]. Equations (5.24) and (5.25) are used to compute the power at the buses where STATCOM is attached.

- System bus types, voltages, angles, actual power, reactive power, l data of line, etc. that are contained in files are read for the first time.
- A flat voltage profile is taken into account.
- The polar form is used to compute the Y bus.
- Formulation of the improved Jacobian matrix” A, B, C, D” and mismatching the power equations.
- Every bus must be examined to determine the STATCOM's position.
- Calculating the voltage at that bus is based on STATCOM's position.
- If yes achieved, if no return to step four.

# 6. DESIGN AND SIMULATION

## 6.1 Introduction

This chapter presents a model of a grid electric network with help of the matrix laboratory tool called MATLAB/Simulink. It starts by illustrating the best inputs and selected areas of the project where UPFC, STATCOM, and PST are being applied by also demonstrating the technical specifications and resources or available data based on the selected model (Rwanda 110 kV North hub transmission line) and simulating it with MATLAB/Simulink and this chapter ends by providing discussion on brief comparison between results of UPFC PST, and STATCOM to compensate reactive power in Rwanda 110kv North hub transmission line. The aim of this study is to compare the effect of the integration of phase shift transformer (PST) and FACTS devices in Rwanda's power transmission networks for reactive power compensation to increase the capability of power transfer, and power quality of bulk transmission systems and evaluate and recommends if FACTS Devices can be used for the Rwandan grid network in the purpose of grid stability improvement instead of the capacitor bank.

The table below represents the parameters of Rwanda north Hub transmission line.

**Table 6.1: The parameters of Rwanda north Hub transmission line**

| No | Line HV(kv) | Description | Length(km) |
|---|---|---|---|
| **1** | 110 | Ntaruka-Mukungwa | 9.95 |
| **2** | 110 | Mukungwa-Gifurwe | 18.46 |
| **3** | 110 | Gifurwe-Rulindo | 24.93 |
| Total lines distance | | | **53.34** |
| Conductor Size | | | **ACSR/40** |
| Frequency | | | **50Hz** |
| Resistance | | | **0.1188Ω/Km** |
| Reactance | | | **0.425 Ω/Km** |

## 6.2 Model design of Rwanda 110 kV north hub transmission line without compensation

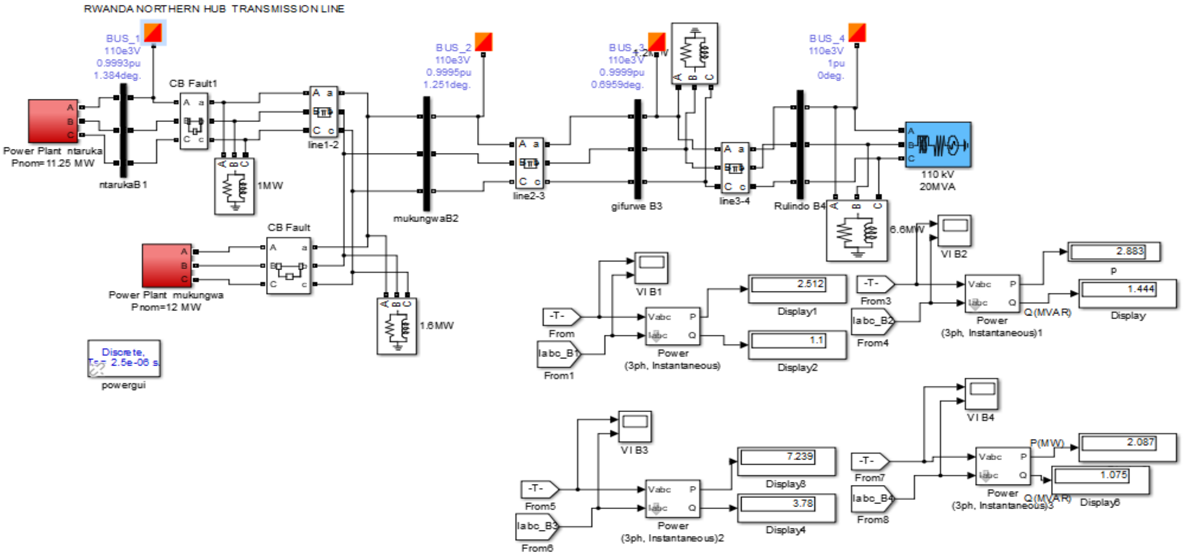
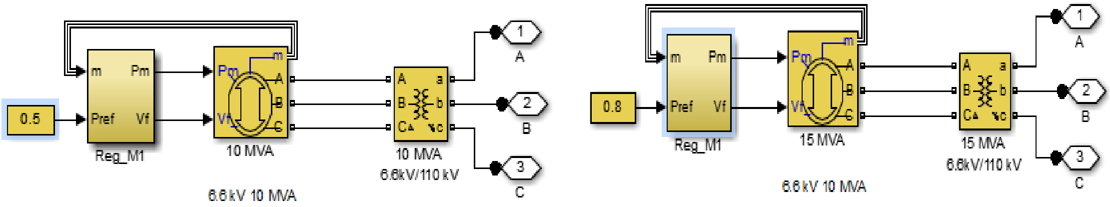


Figure 6.1: Design of Rwanda 110 kV north hub transmission line without compensation



**MUKUNGWA POWER PLANT** **NTARUKA POWER PLANT**

Figure 6.2: MUKUNGWA and NTARUKA Power Plant design

Rwanda's northern HUB transmission line consists of 4 buses **NTARUKA** bus, **MUKUNGA** bus, **GIFURWE** bus, and **RULINDO** Bus.

### 6.2.1 Reactive and real power displayed

The values of real power and reactive power are displayed in figure 6.1. All buses have positive reactive power and real power. The GIFURWE bus has higher reactive and real power than others, as shown in table 6.2.

**Table 6.2: Real and reactive power of design without compensation**

| Buses | P(MW) | Q(Mvar) |
|---|---|---|
| **NTARUKA** | 2.512 | 1.1 |
| **MUKUNGWA** | 2.883 | 1.444 |
| **GIFURWE** | 7.239 | 3.78 |
| **RULINDO** | 2.087 | 1.075 |

### 6.2.2 Signal of three-phase voltage simulation

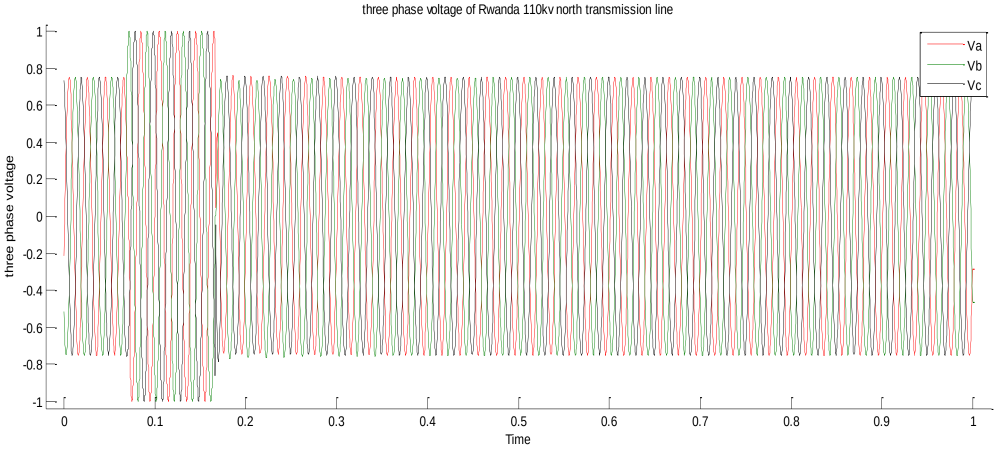


Figure 6.3: Graph of three-phase voltage

Figure6.3 shows the three-phase voltage of one of four buses, but there is a voltage swell (voltage rise) between 0.08 and 0.16 seconds from amplitude 0.8 P. U. to 1 P. U then return to 0.8 P.U in 1 sec as running time because of any fault happens in the system . Therefore, there is a need to avoid this instability of voltage in order to get the power quality.

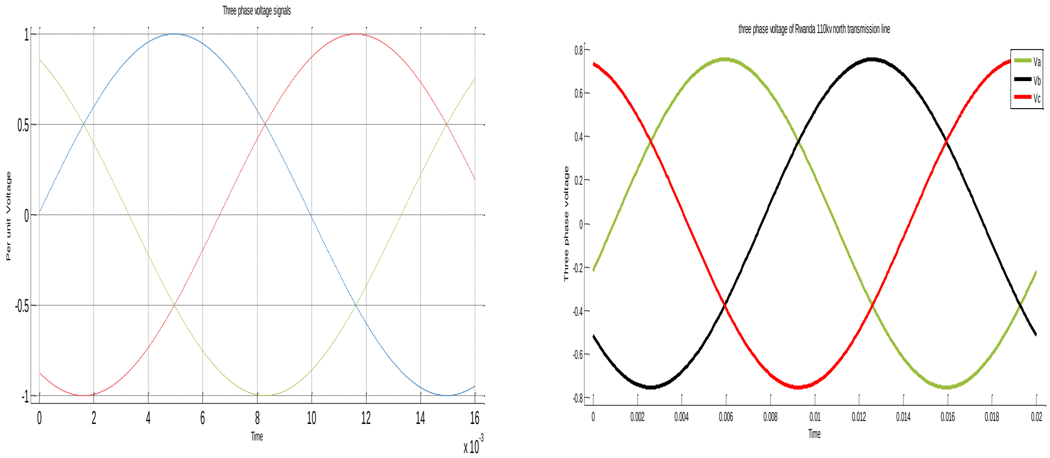
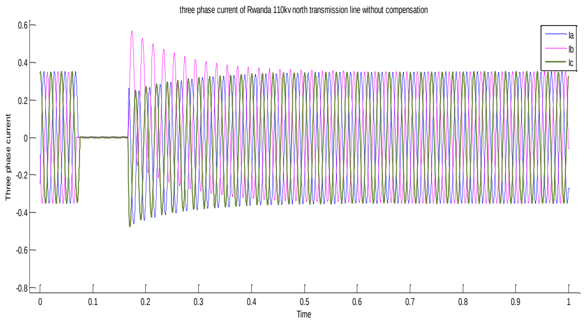


Figure 6.4: Visible graphs of three-phase voltage at difference running time

Figure 6.4 represents two visible three-phase voltages running at different time; left figure shows three voltage signals when running time is 0.016 sec with 1P.U (the per unit voltage amplitude) as shown in figure 6.3 the voltage rise up to 1P.U before 0.016sec.Right figure shows the three phase voltage signal when running time is 0.02 sec with 0.8 P.U (the per unit voltage amplitude) as shown in figure 6.3 from 0.016 sec up to 0.08 sec.the per unit voltage is not rising.

### 6.2.3 Signal of three phase current



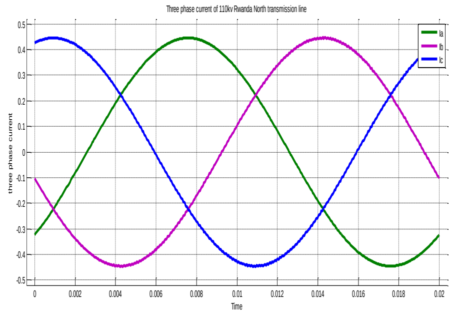


Figure 6.5: Graph of three- phase current

Figure 6.6: visible graph of three phase current

Figure 6.5 represents the graph of the three-phase current of one bus among NTARUKA BUS, MUKUNGWA, GIFURWE, and RULINDO BUS, but between 0.08 and 0.16 seconds, the amplitude reduces from 0.4 P. U. up to 0 P. U. current. Therefore, there is a need to avoid this instability of power in order to get the power quality. Figure 6.6 depicts a clear display of three-phase current from 0 to 0.02 seconds.

## 6.3 Model design of Rwanda 110 kV north hub transmission line with phase shift transformer (PST)

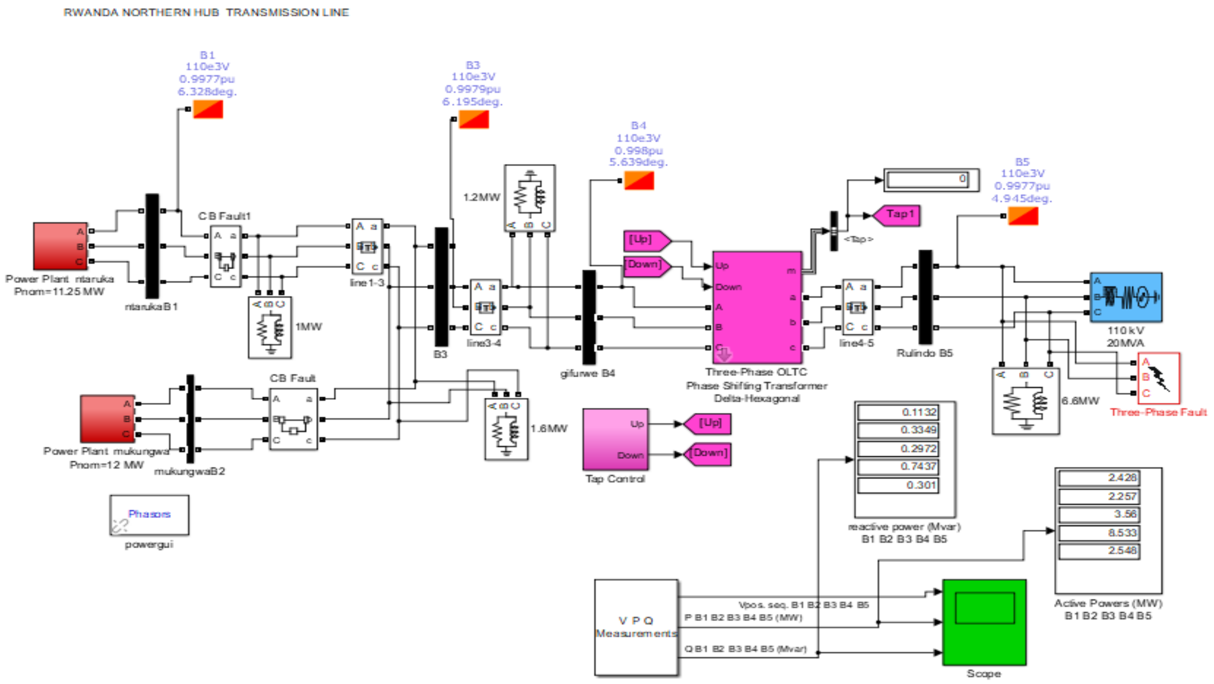


Figure 6.7: Design of Rwanda 110 kV north hub transmission line with phase shift transformer (PST)

Figure 6.7 represents Rwanda's 110 kV North Hub transmission line with three phases of OLTC Phase Shifting Transformer Delta Hexagonal and its tap control in magenta color, installed between GIFURWE bus and RILINDO bus. The bold black-colored bars are NTARUKA, MUKUNGWA, GIFURWE, and RULINDO buses. Rectangles of red are NTARUKA and MUKUNGWA power plants, and Figure 6.7 shows the circuit breaker fault, transmission line, three phase faults, load and suing bus generator.

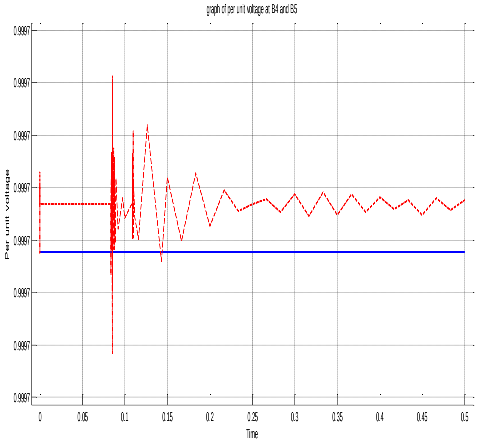
### 6.3.1 Displayed reactive and real power

The values of real power and reactive power are displayed in figure 6.7 in the display block. All buses have both positive reactive and real power. But the values of real power are reduced for buses where PST is not located; reactive power is reduced for all buses compared to the real and reactive power of the design without compensation. The values of real power and reactive power are shown in table 6.3:

**Table 6.3: Real and reactive power of design with PST**

| Buses | P(MW) | Q(Mvar) |
|---|---|---|
| **NTARUKA** | 2.428 | 0.1132 |
| **MUKUNGWA** | 2.257 | 0.3349 |
| **GIFURWE** | 7.133 | 0.7437 |
| **RULINDO** | 2.048 | 0.301 |

### 6.3.2 Graph of per unit voltage of buses with PST and Graph of phase shift of PST



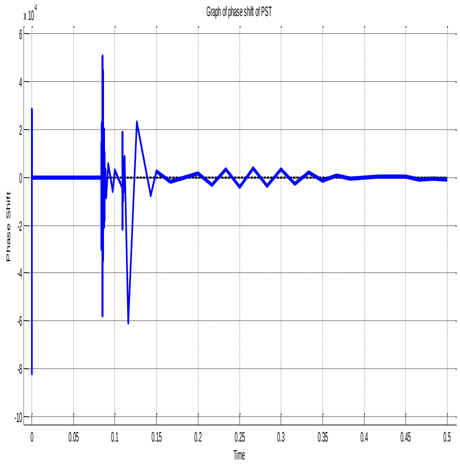


Figure 6.8: Graphs of per unit voltage of buses with PST

Figure 6.9: Graph of phase shift of PST

Figure 6.8 shows two graphs. The red-colored graph shows the per unit voltage of buses with PST varies from 0. 987 P.U to 0. 997 P.U, and the blue-colored graph is the reference graph, per unit voltage is at 0. 988 P.U. This graph shows that the per unit voltage increases compared to the per unit voltage of the design without compensation, which is 0.8 p.u. Figure 6.9 indicates the graph of how phase shift varies: between 0 sec and 0.09 s, phase shift is zero, then after it varies between -8*$10^4$ to 3*$10^4$ up to 0.15 sec, it returns to zero.

### 6.3.3 Graph of three phase power at bus with PST

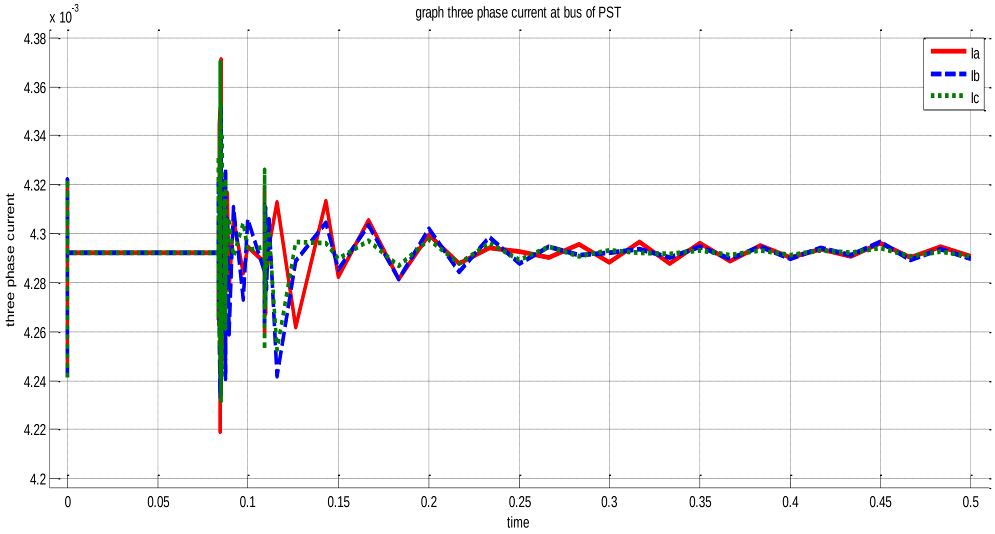


Figure 6.10: Graph of three phase power at bus with PST

Figure 6.10 displays a graph of three-phase power at the bus with PST: the red, blue, and green colors of the graph show power of phases a, b, and c, respectively. Between 0 and 0.07 sec, power is constant. After 0.07 sec, it varies up to 0.014 sec and then returns to stability.

### 6.4. Model design of Rwanda 110 kV north hub transmission line with UPFC

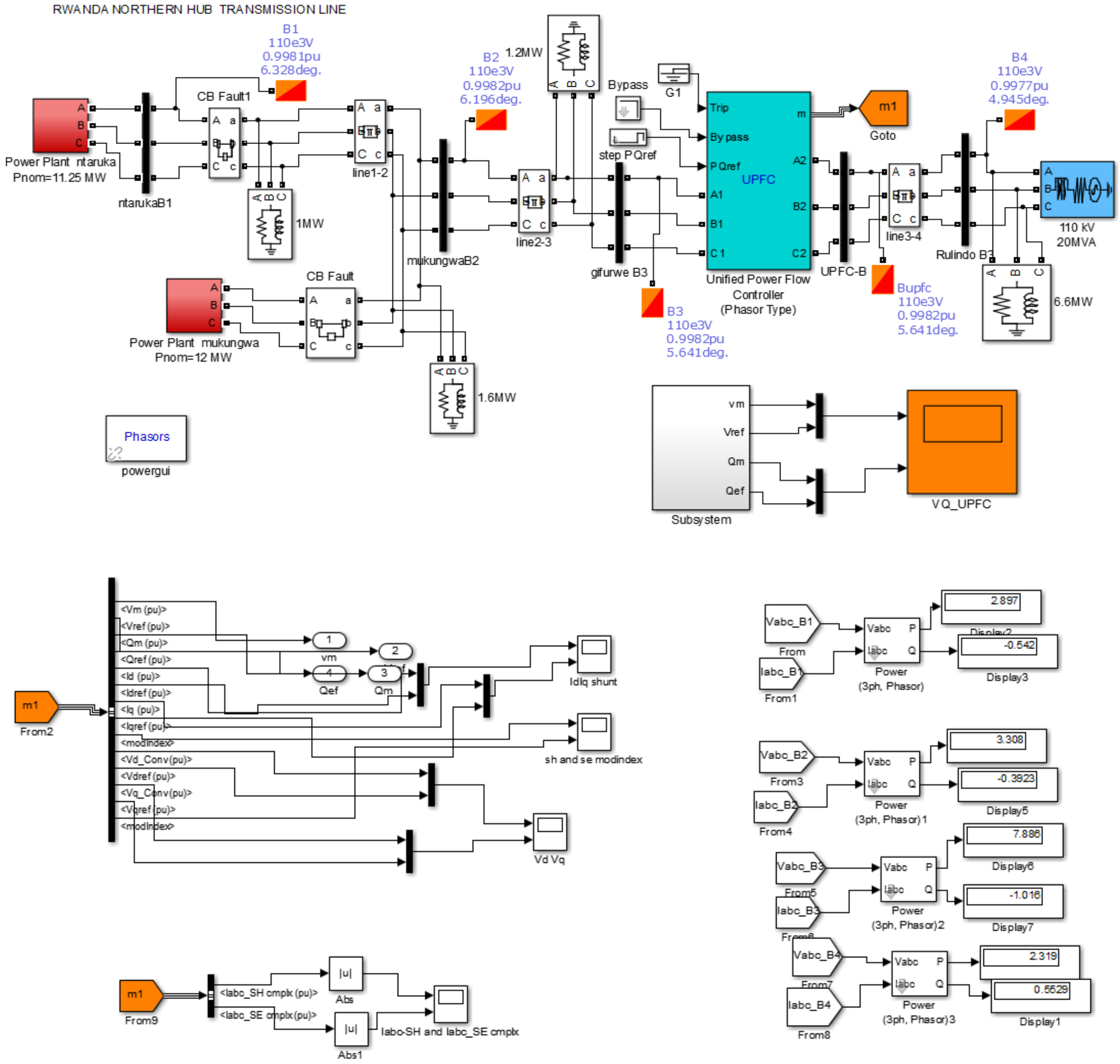


Figure 6.11: Design of Rwanda 110 kV north hub transmission line with UPFC

Figure 6.11 shows Rwanda's 110 kV North Hub transmission line with UPFC in green color, installed between GIFURWE bus and RULINDO bus with its control and display block that displays the values of real and reactive power. The black-colored bars are the NTARUKA bus, MUKUNGWA bus, GIFURWE bus, and RULINDO bus. The red rectangular blocks are NTARUKA and MUKUNGWA power plants.

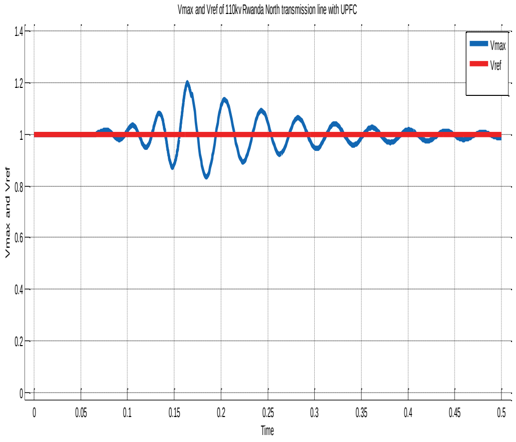
### 6.4.1 Displayed reactive and real power

The values of real power and reactive power are displayed in the display block of figure 6.11. All buses have positive real power and negative reactive power except the RULINDO bus, which has positive. But the values of real power are increased for small values and reactive power is reduced for 3 buses to negative compared to the value of real and reactive power of the design without compensation. The values of real power and reactive power are shown in table 6.4:

**Table 6.4: Real and reactive power of design with UPFC**

| **Buses** | **P(MW)** | **Q(Mvar)** |
|---|---|---|
| **NTARUKA** | 2.897 | -0.897 |
| **MUKUNGWA** | 3.308 | -0.3923 |
| **GIFURWE** | 7.886 | -1.018 |
| **RULINDO** | 2.319 | 0.5529 |

### 6.4.2Graph of per unit voltage of buses (V max and V ref) and Q max and Q ref of design model with UPFC



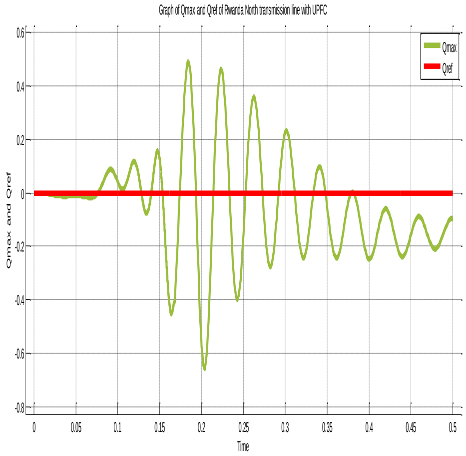


Figure 6.12: Graphs of V max and V ref with UPFC. Figure 6.13: Graph of Q max and Q ref of design with UPFC.

Figure 6.12 shows two graphs. The blue color graph shows the per unit voltage of buses (V max) with UPFC varies from 0. 9 P. U to 1.2 P.U of voltage, and the red color graph is the reference graph per unit voltage is at V ref of 1 P. U. This graph shows that the per unit voltage increases compared to the per unit voltage of the design without compensation, which is 0.8 P. U. Figure 6.13 shows a graph of the variation of reactive power maximally based on the reactive power reference. The red color graph shows Q reference and the green graph shows Q max varies between-0.8Mvar and 0.4Mvar.

### 6.4 .3 Graph of Id and I q in control of UPFC

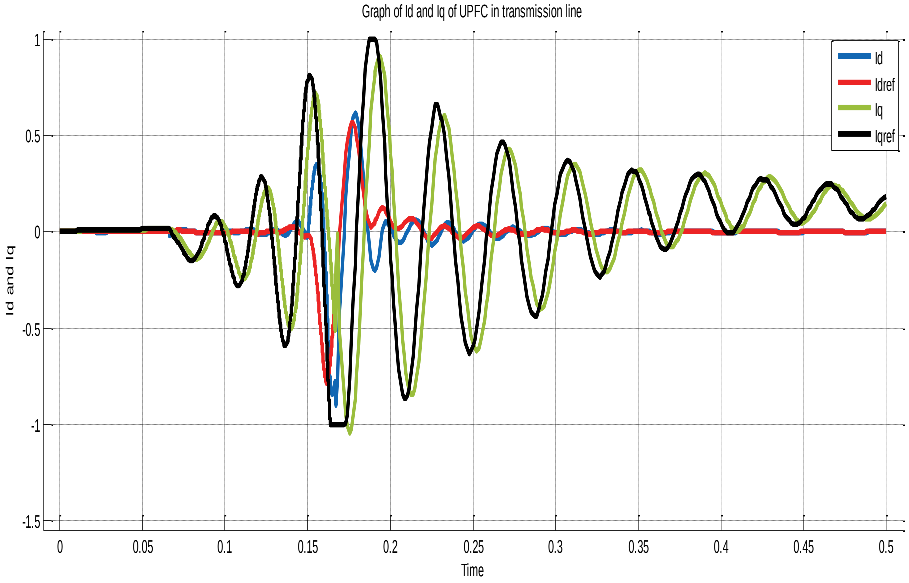


Figure 6.14: Graph of Id and Iq in control of UPFC

Figure 6.14: Id with Id ref of UPFC control that varies between-1p. u and 1p. u current between 0.15sec and 0.2 sec and I q with I q ref that is zero except between 0.15sec and 0.25sec that varies between-0.5p. u to 0.5p. u. The red color graph presents Id ref, the blue color graph presents Id, the black color graph presents I q ref, and the green color graph presents I q.

### 6.5. Model design of Rwanda 110 kV north hub transmission line with STATCOM

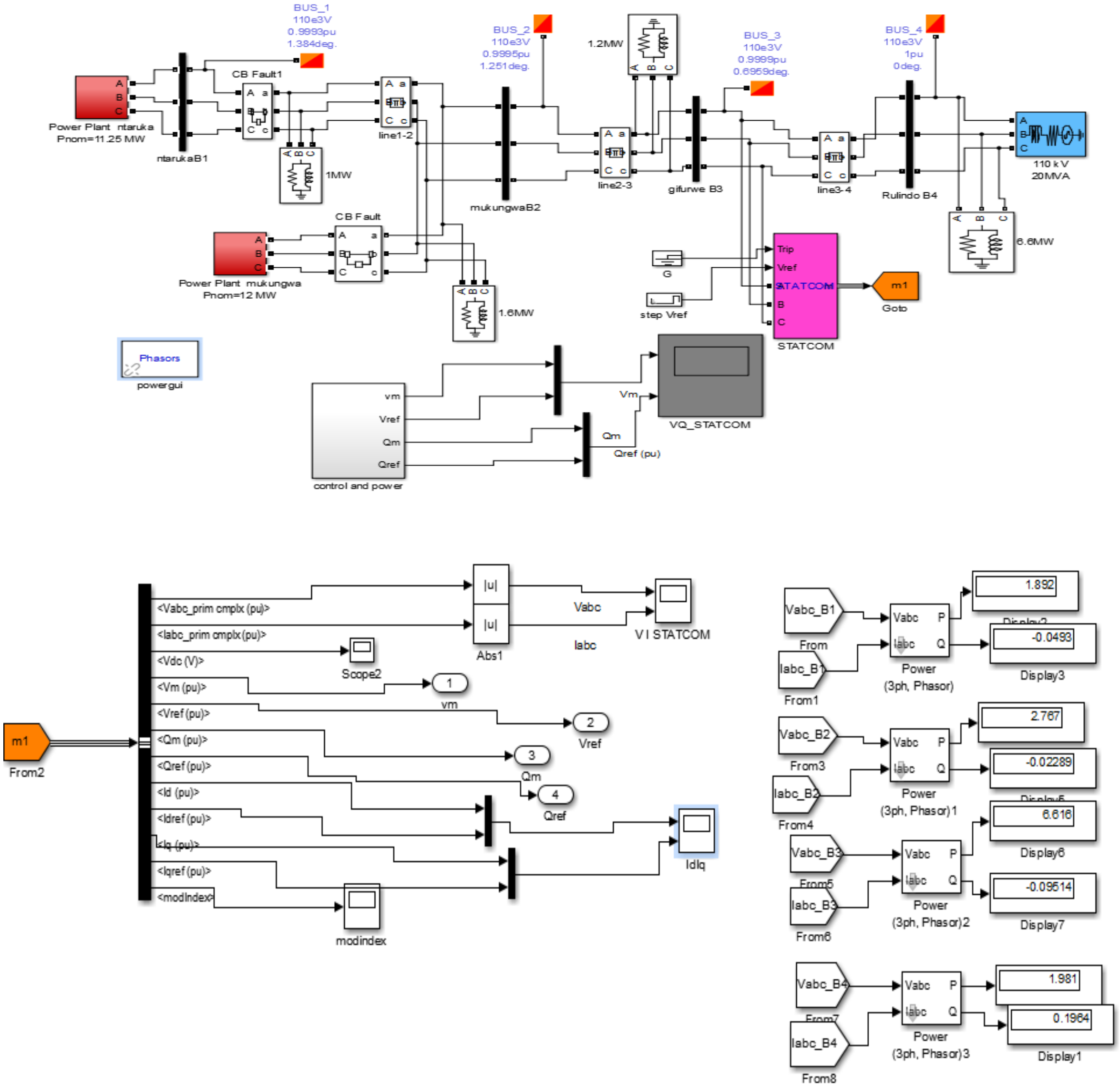


Figure 6.15: Design of Rwanda 110 kV north hub transmission line with STATCOM

Figure 6.15 depicts Rwanda's 110 kV North Hub transmission line with STATCOM in magenta, installed in parallel at the GIFURWE bus, with its control and display block displaying real and reactive power values.

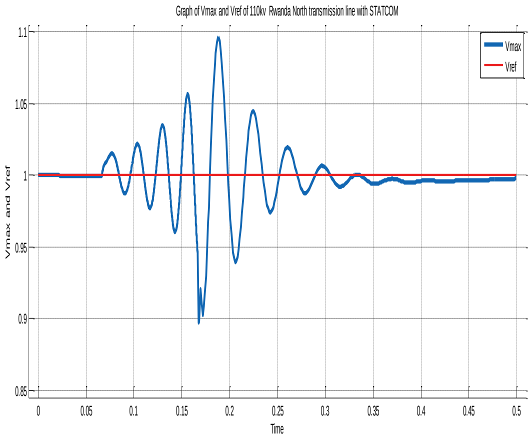
### 6.5.1 Displayed reactive and real power

The values of real power and reactive power are displayed in the above design display block. All buses have positive real power and negative reactive power except the RULINDO bus, which has positive. But the values of real power are reduced for small values; reactive power of 3 buses is reduced to a negative value when compared to the value of real and reactive power of the design without compensation. The values of real power and reactive power are shown in table 6.5:

**Table 6.5: Real and reactive power of design with STATCOM**

| Buses | P(MW) | Q(Mvar) |
|---|---|---|
| **NTARUKA** | 1.892 | -0.0493 |
| **MUKUNGWA** | 2.767 | -0.02269 |
| **GIFURWE** | 6.616 | -0.09614 |
| **RULINDO** | 1.981 | 0.1964 |

### 6.5.2 Graph of V max and V ref per unit of design with STATCOM



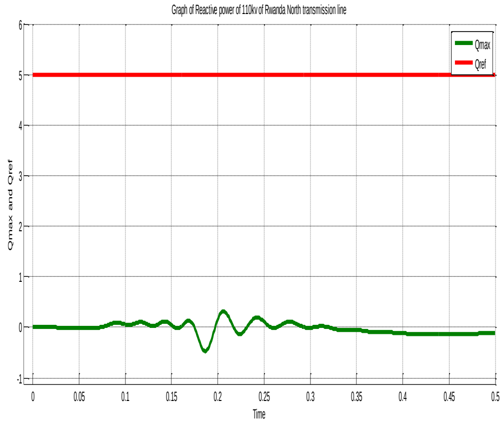
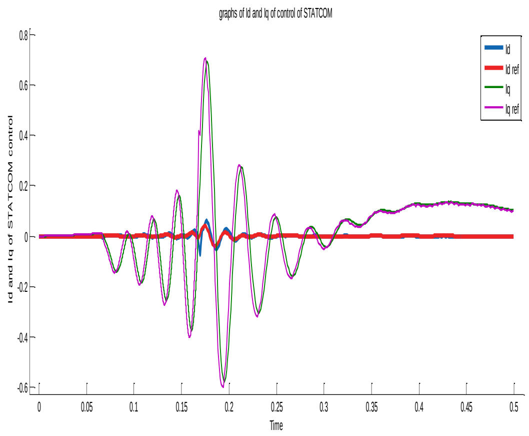


Figure 6.16: Graph of V max and V ref p.u of design with STATCOM. Figure 6.17: Graph of Q max and Q ref of design with STATCOM.

Figure 6.16 presents the graph of the voltage of the 110 kV Rwanda north hub transmission line with STATCOM and with the graph of V reference. The red color graph represents the reference of 1 P.U. While the blue color graph represents the value per unit Voltage that varies between 0.9 P. U and 1.1 P. U from 0 sec to 0.5 sec. Figure 6.17 presents the graph of reactive power (Q0 of 110 kV Rwanda north hub transmission line with STATCOM and with the graph of Q reference. The red color graph represents a reference of 5 Mvar while the green color graph represents a value of reactive power that varies between-0.022 Mvar and 0.19 Mvar.

### 6.5.3Graph of I d ,I d ref and I q, I q ref and Graph of V dc control of STATCOM



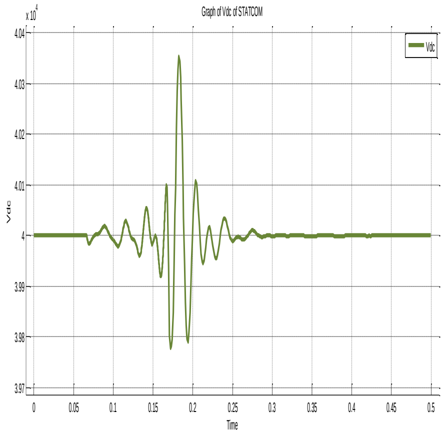


Figure 6.18: Graph of I d, I d ref, I q, I q ref of control of STATCOM. Figure 6.19: Graph of V dc control of STATCOM.

Figure 6.18 shows the graph of Id with Id ref of STATCOM control that varies between-0.6 p. u and 0.6 p. u current and I q with I q ref that is zero except between 0.15sec and 0.2sec, which varies between-0.02 P. U to 0.02 P. U. The red color graph presents Id ref, the blue color graph presents Id, the magenta color graph presents I q ref, and the green color graph presents I q. Figure 6.19 shows the graph of the DC voltage of STATCOM that is constant at a value of $4*10^4$V except the change happens between 0.07sec and 0.25sec because of the instability of the transmission line.

### 6.6 Comparison of results

1. Based on the reactive and real power present in tables 6.2, 6.3, 6.4, and 6.5 for each model design, such as design model without compensation, design model with PST, UPFC, and STATCOM as summarized in below table 6.6:

**Table 6.6: Comparison of results of real and reactive power**

| **Buses** | **Model Without compensation** | | **Model With PST** | | **Model with UPFC** | | **Model with STATCOM** | |
|---|---|---|---|---|---|---|---|---|
| | P(MW | Q(Mvar | P(MW) | Q(Mvar) | P(MW) | Q(Mvar) | P(MW) | Q(Mvar) |
| **NTARUKA** | 2.512 | 1.1 | 2.428 | 0.1132 | 2.897 | -0.897 | 1.892 | -0.0493 |
| **MUKUNGWA** | 2.883 | 1.444 | 2.257 | 0.3349 | 3.308 | -0.3923 | 2.767 | -0.02269 |
| **GIFURWE** | 7.239 | 3.78 | 7.133 | 0.7437 | 7.886 | -1.018 | 6.616 | -0.09614 |
| **RULINDO** | 2.087 | 1.075 | 2.048 | 0.301 | 2.319 | 0.5529 | 1.981 | 0.1964 |

Table 6.6 shows real and reactive power with all compensation and without compensation. The real power of the model with PST and STATCOM is reduced at all buses, indicating that the operations of PST and STATCOM cause real power losses. The real power of UPFC is increased at all buses, indicating that UPFC can adjust the transmission of power flow and reduce real power losses. Therefore, UPFC reduces losses of active power, and STATCOM increases active power losses more than PST. Reactive power of models with PST, UPFC, and STATCOM is reduced in the transmission system of the selected site, but STATCOM and UPFC reduce reactive power up to a negative value on all buses except the RULINDO, which is reduced to positive. UPFC compensates reactive power more than STATCOM and PST, and STATCOM compensates reactive power more than PST. Therefore, UPFC performs better and controls the real and reactive power more than STATCOM and PST.

2. Graph per unit voltage present on model design without compensation, with PST, UPFC, and STATCOM. Figure 6.3 and 6.4 indicate the per unit voltage of the design without compensation, which is 0.8 P.U. and has voltage swell. Figure 6.8 indicates the per unit voltage of model design with PST varies between 0.988 P.U. and 0.997 P.U. Figure 6.12 is for UPFC and Figure 6.16 is for STATCOM, varying between 0. 9 P.U to 1. 2 P.U and 0.9 P.U to 1,1 P.U, respectively. The per unit voltage of UPFC is in a better range than PST and STATCOM. Therefore, UPFC improves the voltage profile more than PST and STATCOM to provide more stability of voltage.

## 7. CONCLUSION AND RECOMMANDATION

The increase in voltage instability problems in Rwanda's electricity grid is a challenge facing the electricity supply utility. In this study, the effect of integration of PST, STATCOM, and UPFC for reactive power compensation in the electricity grid using Rwanda's 110 kV North Hub transmission line with NTARUKA bus, MUKUNGWA bus, GIFURWE bus, and RULINDO bus as a case study was examined. In this thesis, the MATLAB | SIMULINK is used to simulate Rwanda's 110 kV North Hub transmission line without compensation and with PST, UPFC, and STATCOM installed between GIFURWE and RULINDO buses, as the GIFURWE bus has higher reactive power than the others, that is 3.75 Mvar. According to the simulation results, the design without compensation has a per unit voltage magnitude of 0. 8 P.U; with PST, the per unit voltage magnitude of buses varies between 0.988 P. U and 0.997 P. U; with STATCOM, the per unit voltage magnitude of buses varies between 0.9 P. U and 1.1 P. U; and with UPFC, the per unit voltage magnitude of buses varies between 0.9 P. U and 1.1 P. U. The displayed real and reactive power results revealed that the real power of models with PST and STATCOM was reduced at all buses, indicating that the operation of PST and STATCOM causes real power losses, whereas the real power of UPFC increased at all buses, indicating that UPFC can adjust the transmission of power flow and reduce real power losses. The results of this study after comparison indicated that UPFC performs better and controls the real and reactive power more than STATCOM and PST, and STATCOM compensates for reactive power more than PST. UPFC improves the voltage profile more than PST and STATCOM to provide more stability of voltage.

Finally, I can conclude that UPFC is a solution for the improvement of the existing transmission line usage, power quality enhancement, and other related power stability issues of the transmission line. I recommend using UPFC in Rwanda's transmission line to control real and reactive power, hence power stability. Future work can be done firstly on a comparison of costs between UPFC, PST, and STATCOM. Secondly, to quantify all the required UPFC to be installed in Rwanda's power network

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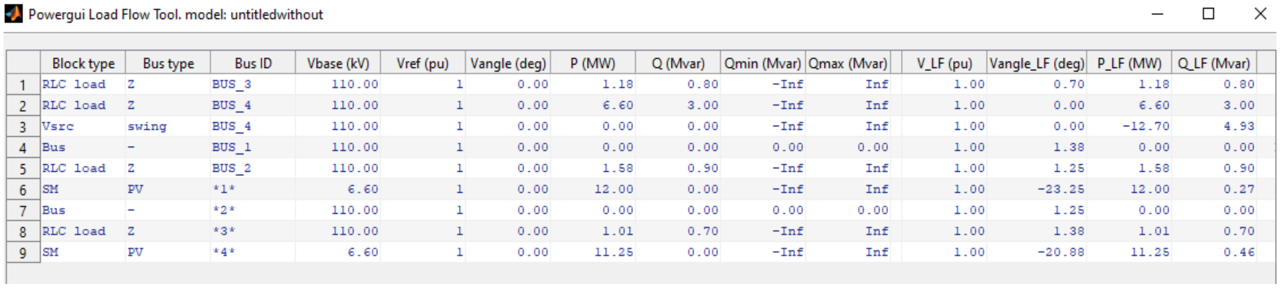
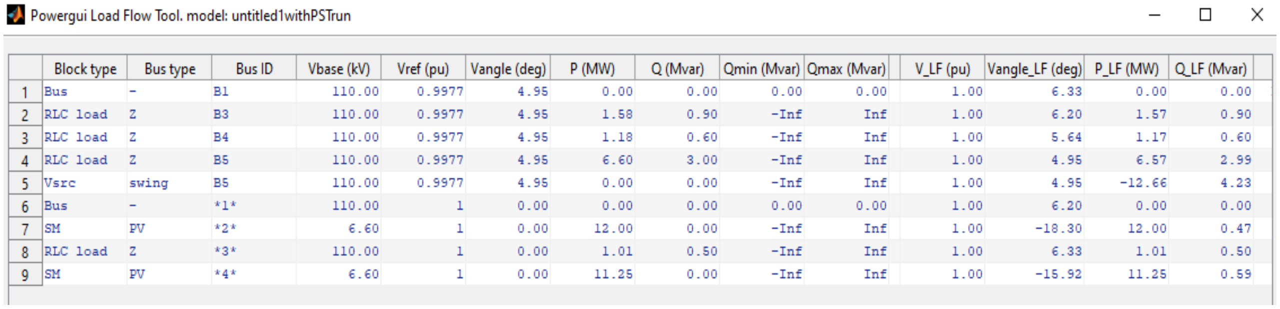
# APPENDIX

## 1. Power flow analysis of Rwanda 110KV north hub transmission line without compensation



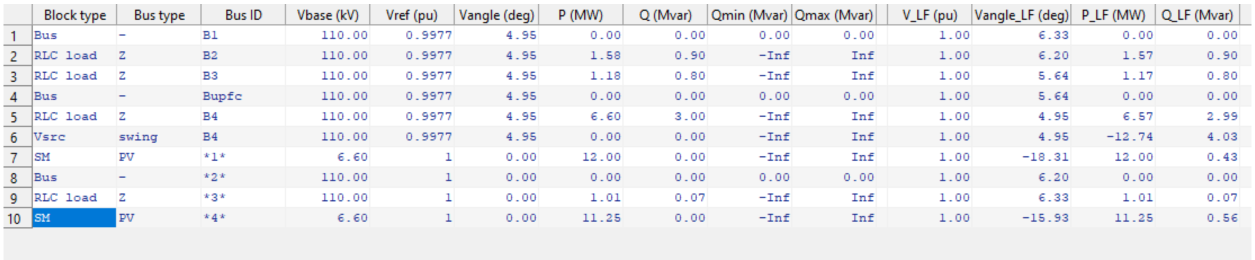
| | Block type | Bus type | Bus ID | Vbase (kV) | Vref (pu) | Vangle (deg) | P (MW) | Q (Mvar) | Qmin (Mvar) | Qmax (Mvar) | V_LF (pu) | Vangle_LF (deg) | P_LF (MW) | Q_LF (Mvar) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | RLC load | Z | BUS_3 | 110.00 | 1 | 0.00 | 1.18 | 0.80 | -Inf | Inf | 1.00 | 0.70 | 1.18 | 0.80 |
| 2 | RLC load | Z | BUS_4 | 110.00 | 1 | 0.00 | 6.60 | 3.00 | -Inf | Inf | 1.00 | 0.00 | 6.60 | 3.00 |
| 3 | Vsrc | swing | BUS_4 | 110.00 | 1 | 0.00 | 0.00 | 0.00 | -Inf | Inf | 1.00 | 0.00 | -12.70 | 4.93 |
| 4 | Bus | - | BUS_1 | 110.00 | 1 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 1.00 | 1.38 | 0.00 | 0.00 |
| 5 | RLC load | Z | BUS_2 | 110.00 | 1 | 0.00 | 1.58 | 0.90 | -Inf | Inf | 1.00 | 1.25 | 1.58 | 0.90 |
| 6 | SM | PV | *1* | 6.60 | 1 | 0.00 | 12.00 | 0.00 | -Inf | Inf | 1.00 | -23.25 | 12.00 | 0.27 |
| 7 | Bus | - | *2* | 110.00 | 1 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 1.00 | 1.25 | 0.00 | 0.00 |
| 8 | RLC load | Z | *3* | 110.00 | 1 | 0.00 | 1.01 | 0.70 | -Inf | Inf | 1.00 | 1.38 | 1.01 | 0.70 |
| 9 | SM | PV | *4* | 6.60 | 1 | 0.00 | 11.25 | 0.00 | -Inf | Inf | 1.00 | -20.88 | 11.25 | 0.46 |

## 2. Power flow analysis of Rwanda 110KV north hub transmission line PST



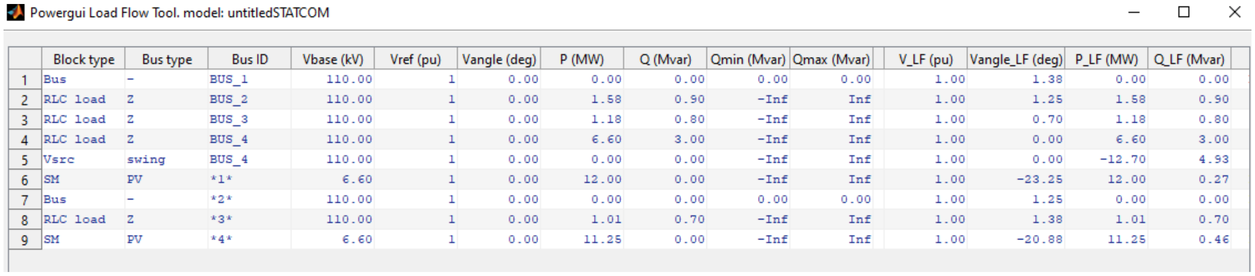
| | Block type | Bus type | Bus ID | Vbase (kV) | Vref (pu) | Vangle (deg) | P (MW) | Q (Mvar) | Qmin (Mvar) | Qmax (Mvar) | V_LF (pu) | Vangle_LF (deg) | P_LF (MW) | Q_LF (Mvar) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Bus | - | B1 | 110.00 | 0.9977 | 4.95 | 0.00 | 0.00 | 0.00 | 0.00 | 1.00 | 6.33 | 0.00 | 0.00 |
| 2 | RLC load | Z | B3 | 110.00 | 0.9977 | 4.95 | 1.58 | 0.90 | -Inf | Inf | 1.00 | 6.20 | 1.57 | 0.90 |
| 3 | RLC load | Z | B4 | 110.00 | 0.9977 | 4.95 | 1.18 | 0.60 | -Inf | Inf | 1.00 | 5.64 | 1.17 | 0.60 |
| 4 | RLC load | Z | B5 | 110.00 | 0.9977 | 4.95 | 6.60 | 3.00 | -Inf | Inf | 1.00 | 4.95 | 6.57 | 2.99 |
| 5 | Vsrc | swing | B5 | 110.00 | 0.9977 | 4.95 | 0.00 | 0.00 | -Inf | Inf | 1.00 | 4.95 | -12.66 | 4.23 |
| 6 | Bus | - | *1* | 110.00 | 1 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 1.00 | 6.20 | 0.00 | 0.00 |
| 7 | SM | PV | *2* | 6.60 | 1 | 0.00 | 12.00 | 0.00 | -Inf | Inf | 1.00 | -18.30 | 12.00 | 0.47 |
| 8 | RLC load | Z | *3* | 110.00 | 1 | 0.00 | 1.01 | 0.50 | -Inf | Inf | 1.00 | 6.33 | 1.01 | 0.50 |
| 9 | SM | PV | *4* | 6.60 | 1 | 0.00 | 11.25 | 0.00 | -Inf | Inf | 1.00 | -15.92 | 11.25 | 0.59 |

## 3. Power flow analysis of Rwanda 110KV north hub transmission line with UPFC



| | Block type | Bus type | Bus ID | Vbase (kV) | Vref (pu) | Vangle (deg) | P (MW) | Q (Mvar) | Qmin (Mvar) | Qmax (Mvar) | V_LF (pu) | Vangle_LF (deg) | P_LF (MW) | Q_LF (Mvar) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Bus | - | B1 | 110.00 | 0.9977 | 4.95 | 0.00 | 0.00 | 0.00 | 0.00 | 1.00 | 6.33 | 0.00 | 0.00 |
| 2 | RLC load | Z | B2 | 110.00 | 0.9977 | 4.95 | 1.58 | 0.90 | -Inf | Inf | 1.00 | 6.20 | 1.57 | 0.90 |
| 3 | RLC load | Z | B3 | 110.00 | 0.9977 | 4.95 | 1.18 | 0.80 | -Inf | Inf | 1.00 | 5.64 | 1.17 | 0.80 |
| 4 | Bus | - | Bupfc | 110.00 | 0.9977 | 4.95 | 0.00 | 0.00 | 0.00 | 0.00 | 1.00 | 5.64 | 0.00 | 0.00 |
| 5 | RLC load | Z | B4 | 110.00 | 0.9977 | 4.95 | 6.60 | 3.00 | -Inf | Inf | 1.00 | 4.95 | 6.57 | 2.99 |
| 6 | Vsrc | swing | B4 | 110.00 | 0.9977 | 4.95 | 0.00 | 0.00 | -Inf | Inf | 1.00 | 4.95 | -12.74 | 4.03 |
| 7 | SM | PV | *1* | 6.60 | 1 | 0.00 | 12.00 | 0.00 | -Inf | Inf | 1.00 | -18.31 | 12.00 | 0.43 |
| 8 | Bus | - | *2* | 110.00 | 1 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 1.00 | 6.20 | 0.00 | 0.00 |
| 9 | RLC load | Z | *3* | 110.00 | 1 | 0.00 | 1.01 | 0.07 | -Inf | Inf | 1.00 | 6.33 | 1.01 | 0.07 |
| 10 | SM | PV | *4* | 6.60 | 1 | 0.00 | 11.25 | 0.00 | -Inf | Inf | 1.00 | -15.93 | 11.25 | 0.56 |

## 4. Power flow analysis of Rwanda 110KV north hub transmission line with STATCOM



| | Block type | Bus type | Bus ID | Vbase (kV) | Vref (pu) | Vangle (deg) | P (MW) | Q (Mvar) | Qmin (Mvar) | Qmax (Mvar) | V_LF (pu) | Vangle_LF (deg) | P_LF (MW) | Q_LF (Mvar) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Bus | - | BUS_1 | 110.00 | 1 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 1.00 | 1.38 | 0.00 | 0.00 |
| 2 | RLC load | Z | BUS_2 | 110.00 | 1 | 0.00 | 1.58 | 0.90 | -Inf | Inf | 1.00 | 1.25 | 1.58 | 0.90 |
| 3 | RLC load | Z | BUS_3 | 110.00 | 1 | 0.00 | 1.18 | 0.80 | -Inf | Inf | 1.00 | 0.70 | 1.18 | 0.80 |
| 4 | RLC load | Z | BUS_4 | 110.00 | 1 | 0.00 | 6.60 | 3.00 | -Inf | Inf | 1.00 | 0.00 | 6.60 | 3.00 |
| 5 | Vsrc | swing | BUS_4 | 110.00 | 1 | 0.00 | 0.00 | 0.00 | -Inf | Inf | 1.00 | 0.00 | -12.70 | 4.93 |
| 6 | SM | PV | *1* | 6.60 | 1 | 0.00 | 12.00 | 0.00 | -Inf | Inf | 1.00 | -23.25 | 12.00 | 0.27 |
| 7 | Bus | - | *2* | 110.00 | 1 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 1.00 | 1.25 | 0.00 | 0.00 |
| 8 | RLC load | Z | *3* | 110.00 | 1 | 0.00 | 1.01 | 0.70 | -Inf | Inf | 1.00 | 1.38 | 1.01 | 0.70 |
| 9 | SM | PV | *4* | 6.60 | 1 | 0.00 | 11.25 | 0.00 | -Inf | Inf | 1.00 | -20.88 | 11.25 | 0.46 |