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

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College of Science and Technology

Title of the Project: Voltage profile improvement and power loss minimization using Static Var Compensator (SVC) of distribution network in Rwanda

Case Study: Southern Province Distribution Substation

A proposal submitted to the African Center of Excellence in Energy studies for sustainable development (ACE-ESD)

In partial fulfillment of the requirement for the degree of MASTERS OF SCIENCE IN ELECTRICAL POWER SYTEMS ENGINEERING)

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DECLARATION

I, the undersigned, declare that this Project is my original work, and has not been presented for a degree in University of Rwanda or any other universities. All sources of materials that will be used for the thesis work will have been fully acknowledged.

Names: NIYOBUHUNGIRO Confiance

Date of Submission: 4/12/2023______ ______

This thesis has been submitted for examination with my approval as a university advisor.

Thesis Advisor: Dr.-Ing. Getachew Biru (Associate Professor)

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Lastly, I say thank you to my family and relatives together with friends for the support and encouragement throughout my studies.

ABSTRACT

This study focuses on voltage profile improvement and power loss minimization through the implementation of a Static Var Compensator (SVC) in Rwanda distribution network system. The objective of this study is to analyze the effectiveness of SVC in addressing voltage variations and reducing power losses within the distribution network.

Voltage profile problems and power losses are common challenges in distribution networks, affecting the reliability and efficiency of electrical power supply. The introduction of SVC as a flexible reactive power compensation device offers a promising solution to mitigate these issues. SVC devices are capable of dynamically controlling the reactive power flow, thereby stabilizing voltage levels and reducing power losses.

In this case study, I will take consideration into Distribution feeder from Kigoma Substation. The voltage profile and power loss analysis are carried out, identifying critical areas experiencing voltage deviations and high power losses. The implementation of an SVC system is proposed as a potential solution to these problems.

Through the integration of an SVC device into the distribution feeder, the voltage profile is expected to be enhanced, ensuring that voltage levels remain within acceptable limits. The SVC system can rapidly respond to voltage fluctuations and maintain a stable voltage profile, thereby improving the reliability of power supply to consumers. Additionally, by effectively regulating reactive power flow, power losses in the network can be minimized, resulting in enhanced system efficiency.

The study will employ comprehensive simulation models and optimization techniques to assess the performance and benefits of the proposed SVC implementation. Parameters such as voltage deviation, power loss reduction, and system stability will be evaluated. Economic analysis will also be conducted to determine the cost-effectiveness of the proposed solution.

The outcomes of this study will provide valuable insights into the potential of SVC technology in the context of the Rwandan distribution network system. The findings can guide decision-makers

and stakeholders in the energy sector to optimize the system's performance, improve voltage profile, and minimize power losses, ultimately contributing to a more reliable and efficient power supply in Rwanda.

ABBREVIATION

SVC: Static Var Compensator

MW: Megawatt

KV: Kilovolt

V: Volt

NTL: Non-Technical losses

TL: Technical losses

FACT: Flexible AC Transmission

I: Current through the feeder

$\theta: Power\ Factor\ Angle$

R: Resistance of the Feeder

X: Reactance of the Feeder

V1: Sending End Voltage

V2: Receiving End Voltage

$Pl: Active\ Load\ Power$

$Ql: Reactive\ Power\ Power$

$\Delta v: Voltage\ Drop$

SSSC: Static Series Synchronous Compensator

TCSR: Thyristor Controlled Series Reactor

TSSC: Thyristor Switched Series Capacitor

TCSC: Thyristor Controlled Series Capacitor

TCPST: Thyristor Controlled Phase Shifting Transformer

TCPAR: Thyristor Controlled Phase Angle Regulator

REG: Rwanda Energy Group

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CHAPTER ONE

1. INTRODUCTION

Rwanda is experiencing rapid industrialization, urbanization, and economic growth, which has led to an increase in the demand for electricity. The power system in Rwanda is facing various challenges, including voltage instability and power losses. The voltage variation problem can result in equipment failure, voltage sag, and voltage swell, which affect the reliability and efficiency of the power system. Power loss is another major problem faced by the power system, which can result in economic losses and environmental issues [1].

1.1. BACKGROUND

The government of Rwanda recognizes that availability of reliable electrical energy is the most requirement for people's social prosperity, development and economic growth of the country. In order to supply all people with electricity, the government is working very hard to electrify all people 100% by 2024. Currently, the total installed capacity in Rwanda is 276.068 MW from different power plants. By generation technology mix, 51% is from thermal sources, followed by hydro sources (43.9%) and solar sources with 4.2% [2].

As part of the efforts to increase the current capacity, a number of projects to build new power plants are underway and will add more capacity on the existing national grid by the year 2024. These include among others Hakan peat to power plant which will add 80MW, Rusumo Falls Hydropower plant (26MW), Rusizi III (48.3MW), Shema (56 MW) and Nyabarongo II (43.5 MW [2].

The current Rwanda electricity distribution network is covered by a total of 10,520.1 km of Medium Voltage lines and 17,334.25 km of low voltage lines giving access to on-grid electricity to 47.6% of Rwanda households. These include the 30kV, 15kV and 400V lines [3].

1.2. PROBLEM STATEMENT

Voltage profile deviations refer to variations in voltage magnitudes and phase angles at different nodes of the distribution network. These deviations can occur due to several factors, including uneven load distribution, voltage drops along the distribution lines, and reactive power imbalances. Voltage deviations can lead to inefficient operation of electrical devices, reduced power quality, and increased system losses [4].

1.3. OBJECTIVES

The objective of this research is to investigate the effectiveness of the Static Var Compensator (SVC) in improving the voltage profile and minimizing power losses in the distribution network system in Rwanda.

1.3.1. SPECIFIC OBJECTIVE

- ✓ Assess the existing voltage profile and power losses in the distribution network in Rwanda.
- ✓ Analyze the impact of voltage fluctuations and power losses on the system performance and stability.
- ✓ Evaluate the potential benefits of implementing Static Var Compensator (SVC) in the distribution network system.
- ✓ Design an optimal SVC placement strategy considering the characteristics of the Rwandan distribution network.
- ✓ Simulate and analyze the performance of the distribution network system with SVC.
- ✓ Quantify the improvements in voltage profile and power loss reduction achieved through the deployment of SVC.
- ✓ Investigate the economic feasibility of implementing SVC in the Rwandan distribution network system.

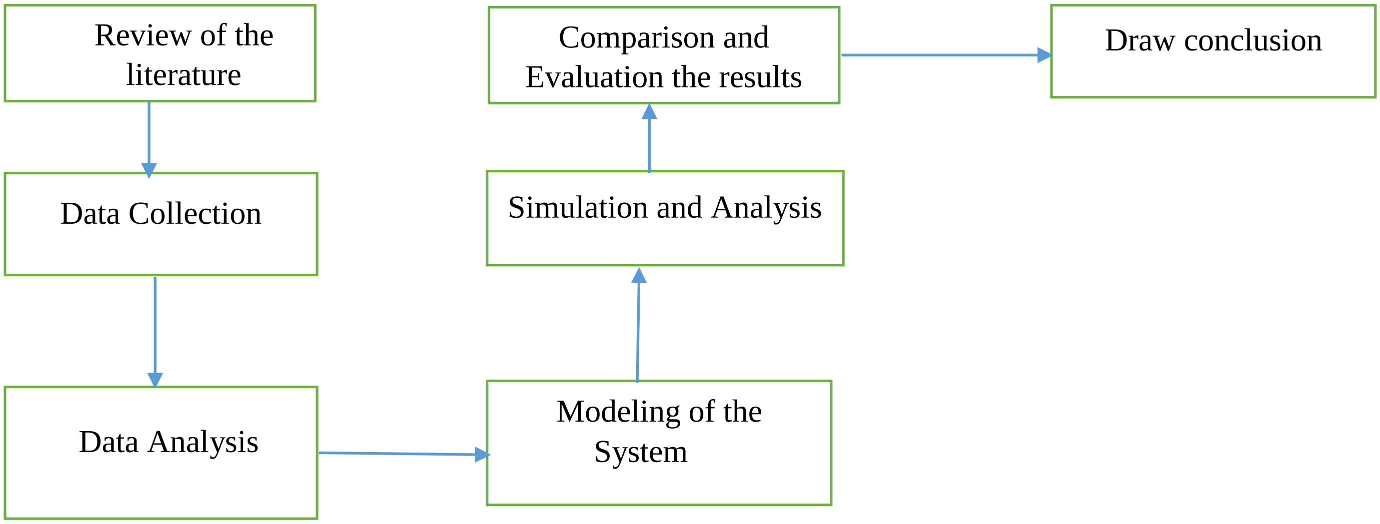
1.4. SCOPE OF THE STUDY

The study aims at evaluating the voltage variation problem and power losses in Rwanda distribution network and potential solution to the problem. The study will explore the potential benefits of integrating SVCs in the distribution network system. It will examine how SVCs can improve the voltage profile and minimize power losses using Power World Simulator and also this will involves assessing the voltage profile and power losses in the distribution network system. It includes analyzing the distribution network topology, load characteristics, and power flow patterns.

1.5. METHODOLOGY

The proposed research will be conducted in the following phases:

Table 1: Methodology



- Literature review A comprehensive review of literature related to the voltage profile improvement and power loss minimization using SVC will be conducted.
- Data Collection Data on the distribution network system in Rwanda, including load flow data, voltage profiles, and power loss data, will be collected.
- Modeling, Simulation and Analysis: Based on the data collected from site, the system is modeled and simulated using software such as Power World Simulator. The simulation will be used to analyze the effectiveness of SVC in improving the voltage profile and minimizing power losses in the distribution network system.
- Result Evaluation and Draw Conclusion: The results obtained from the simulation will be analyzed. The effectiveness of the SVC in improving the voltage profile and minimizing

power losses will be evaluated. Conclusions are drawn that will be recommended to the power utility for practical implementation.

1.6. EXPECTED OUTCOME

The research is expected to provide valuable insights on the problem of voltage variations and power losses in the Rwandan distribution system and on possible solutions. The effectiveness of SVC in improving the voltage profile and minimizing power losses in the distribution network system will be studied. The findings will be useful for improving the power system performance in the distribution network system of Rwanda.

CHAPTER TWO:

THEORETICAL BACKGROUND AND LITERATURE REVIEW

2.1. Distribution Systems Background

Electric power distribution is the final stage in the delivery of electricity. Electricity is carried from the transmission system to individual consumers. Distribution substations connect to the transmission system and lower the transmission voltage to medium voltage [5].

Electric power distribution was discovered in 1880s where electricity started being generated at power stations. Before that, electricity was usually generated where it was used [5].

Electric power distribution is the final stage in the delivery of electric power; it carries electricity from the transmission system to individual consumers. The network of lines that carries electricity from distribution substations to the homes of the consumer is called distribution lines. The distributed electricity is then used by the consumer [6].

In general, the distribution system is the electrical system between the substation fed by the transmission system and the consumer meters. It generally consists of feeders, distributors and the service mains. Figure below shows the single diagram of a typical low-tension distribution system.

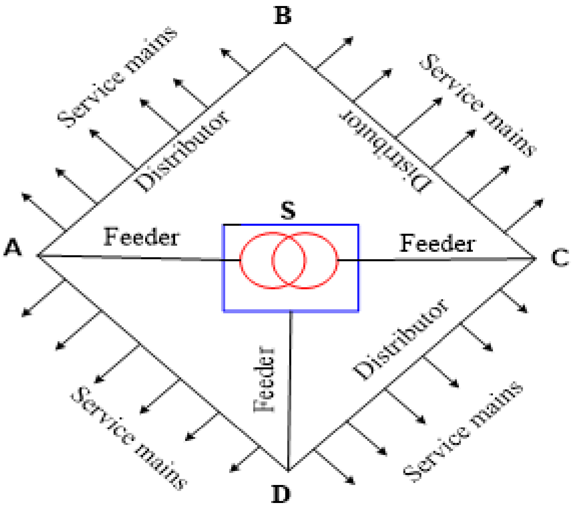


Figure 1:Single line diagram of a typical low-tension distribution system

2.2. Classification of Distribution System

A distribution system may be classified on the basis of:

A) Nature of current: According to nature of current, distribution system can be classified As:

- ✓ AC distribution system.
- ✓ DC distribution system.

B) Type of construction: According to type of construction, distribution system is classified as:

- ✓ Overhead system
- ✓ Underground system

D) Scheme of operation: According to scheme of operation, distribution system may be classified as:

- ✓ Radial delivery network
- ✓ Ring main system
- ✓ Interconnected system

2.2.1. Radial System

In this system, separate feeders radiate from a single substation and feed the distributors at one end only. Figure a: and b: shows a single line diagram of a radial system for d.c and a.c distribution respectively. This is the simplest distribution circuit and has the lowest initial cost [7].

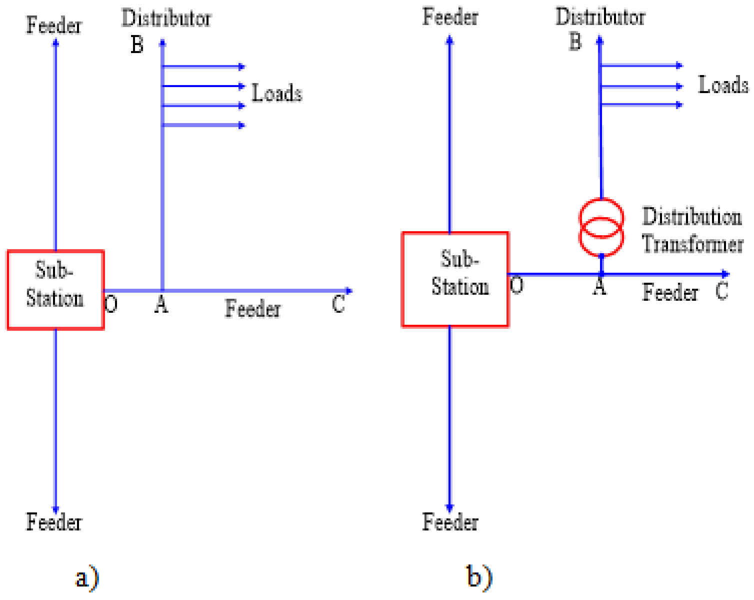


Figure 2:Radial distribution systems

However, it suffers from the following drawbacks:

- ✓ The end of the distributors nearest to the feeder point will be heavily loaded
- ✓ The customers are dependent on a single feeder and single distributor. Therefore, any fault on the feeder distributor cuts off supply to the customers who are on the side of the fault away from the substation
- ✓ The customers at the distant end of the distribution would be subjected to serious voltage fluctuations when the load on the distributor changed.

2.2.2. Ring system

In this system, the primaries of distribution transformers form a loop. The loop circuit starts from the substation bus-bars, makes a loop through the area to be served, and returns to the substation. Figure below shows the single line diagram of ring main system for a.c. distribution where substation supplies to the closed feeder LMNOPQRS. The distributors are tapped from different points M, O, and Q of the feeder through distribution transformers [7].

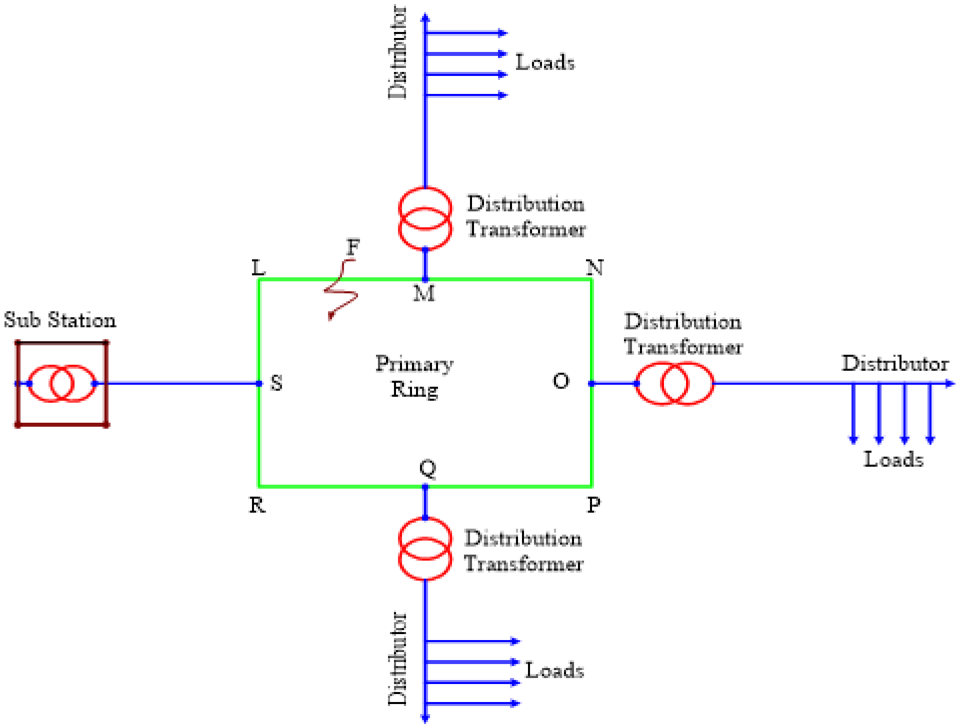


Figure 3:Ring main systems

The ring main system has the following advantages:

- ✓ There are less voltage fluctuations at consumer's terminals
- ✓ The system is very reliable as each distributor is fed via two feeders. In the event of fault on any section of feeder, the continuity of supply is maintained.

2.2.3. Inter Connected System

When the feeder ring is energized by two or more than two generating stations or substations, it is called inter connected system. Figure below, shows a single line diagram of inter connected system where the closed feeder ring ABCD is supplied by two substations $S1$ and $S2$ at point D and C respectively. Distributors are connected to points O, P, Q and R of the feeder ring through distribution transformers [7].

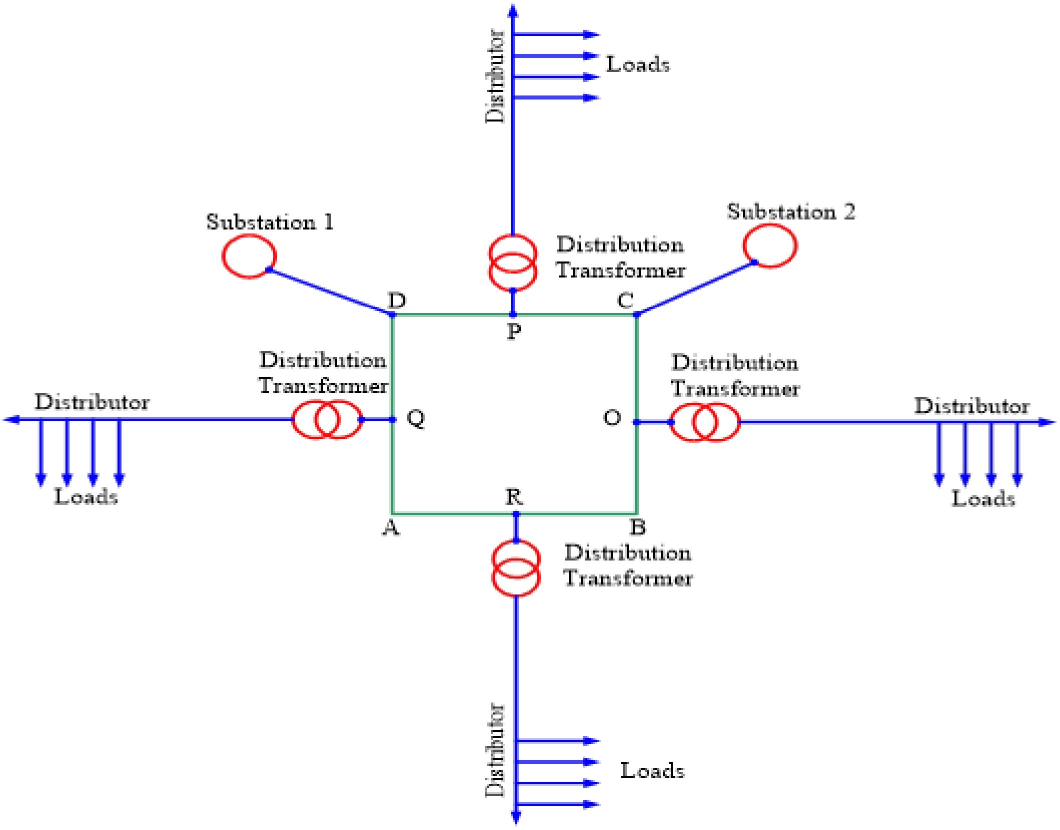


Figure 4: Inter connected system

2.3. Losses of Electrical Power

The losses prevailing in the power distribution system can be classified as:

2.3.1 Technical losses

Technical losses on distribution system are primarily due to heat dissipation resulting from current passing through conductors and magnetic losses in transformers. Technical losses occur during transmission and distribution involves substation, transformer, and line related losses. These include resistive losses of the primary feeders, the distribution transformer losses (resistive loses in windings and the core losses), resistive losses in secondary network, resistive losses in service line and losses in KWh meter. These losses are inherent to the distribution of electricity and cannot be eliminated but can be reduced [8].

2.3.2 Non-Technical losses

Non-Technical losses include tampering with the meter to create false consumption information used in billings, making unauthorized connections to the power grid. Non-payment, as the name implies, refers to cases where customers refuse or are unable to pay for their electricity consumption. Non-Technical losses (NTL) include electricity theft. Electricity theft is defined as a conscience attempt by a person to reduce or eliminate the amount of money he will owe the utility for electric energy. It can be done by tampering with the meter to create false meter reading i.e. create false consumption information used in billings, meters not read, non performing and underperforming meters, making unauthorized connections and direct tapping. [8].

2.4. Voltage Drop in Distribution Systems

There has been a problem of poor voltage stability and power loss on transmission and distribution system due to the increase in load demand. For long time ago, there has been a significant increase in the demand for electrical power energy and as a result electrical power transmission networks are experiencing lack of capacity. This limitation is due to balancing voltage level and maintaining the network stability. This has resulted to lesser practical operation capacity of the power systems compared to the full capacity. The consequence is non-optimal operation of power transmission network, lesser power transfer and voltage instability which can lead to total system collapse, threatening the efficiency and investment on the transmission and distribution system [9].

A basic overview on voltage drop in a distribution system is shown in figure below

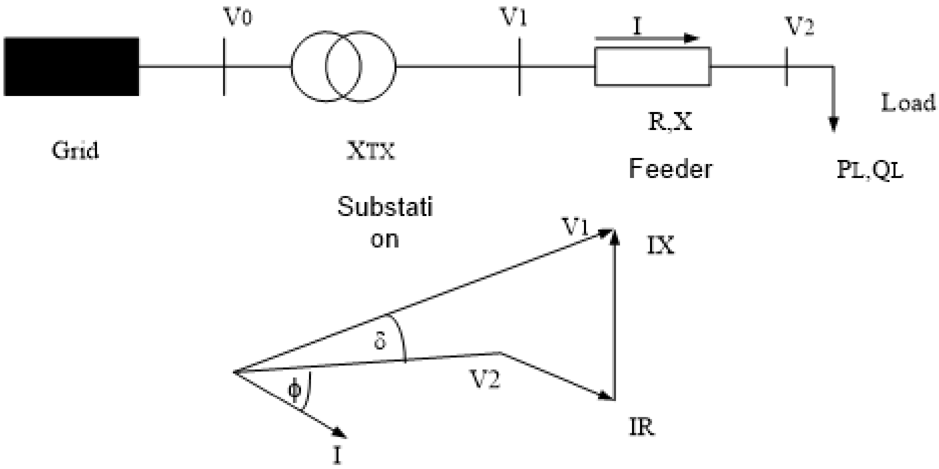


Figure 5:One line diagram and corresponding phasor diagram

The current I as a function of the load complex apparent power $S = P_L - jQ_L$ **(2.1)**

and the load voltage V_2 will be $I = \left[\frac{S}{V_2}\right] = \frac{P_l - Q_l}{V_2}$ **(2.2)**

The voltage drop on the feeder is given by:

$$V_1 - V_2 = I(R + jX)$$

$$= IRCos\theta + IX \operatorname{Sin}\theta$$

$$= \frac{RP_l + XQ_l - j(XP_l - RQ_l)}{V_2} \qquad \textbf{(2.3)}$$

For small power flow, the voltage angle δ between V_2 and V_1 in the above equation is small and the voltage drop $\Delta v = |V_1 - V_2|$ can be approximated by $\Delta v \cong \frac{RP_l + jXQ_l}{V_2}$ **(2.4)**

Where:

I: Current through the feeder

θ: *Power Factor Angle*

R: Resistance of the Feeder

X: *Reactance of the Feeder*

$V1$: *Sending End Voltage*

$V2$: *Receiving End Voltage*

Pl: *Active Load Power*

Ql: *Reactive Power Power*

Δv: *Voltage Drop*

The voltage improvement is a very important aspect for power quality and system stability. Providing adequate reactive power support at the appropriate location solves voltage instability problems. There are many reactive compensation components used by the utilities for this purpose, each of which has its own characteristics and limitations. Flexible AC transmission system components (FACTs) have been designed to stabilize system thereby enhancing controllability and increasing the power transfer capability [9].

The voltage improvement can be done by the following methods:

- ✓ Change the tap setting on the distribution transformer;
- ✓ Investigate ways to reduce voltage drop by possibly reinforcement of lines.;
- ✓ Increase the size of the distribution transformer to remove any overloading condition;
- ✓ Use of flexible AC transmission /distribution devices (FACT devices). In this study the selected method is the use of FACT device called SVC.

2.5 Flexible AC Transmission (FACT) Devices.

In conventional AC transmission, transfer of electrical power capability has been limited by various dynamic and static limits such as voltage stability, thermal limits, Rapid development in the FACTS area has seen the introduction of different types of this component for different purposes. These devices are flexible and help systems to improve power transfer and stability. In terms of the high competition in the power market, using FACTS devices is essential to achieve the maximum transferable power. In this case, the amount and type of FACTS devices should be computed to reach the maximum efficiency with a stable network. There are advantages to using

FACTS devices in power networks, including: controlling power transfer, controlling the stability and certain capabilities of the network and preventing voltage collapse, improving power quality and power factor and voltage profile, improving dynamic stability, enhancing the load-ability of the transmission lines, and decreasing reactive power losses and as a result increasing active power transfer [10].

For maximum power transmission or distribution, there must be a compensation for reactive power. The following are the reasons:

- Improving system voltage profile;
- Better system stability and reliability;
- Power loss minimization;
- Power factor correction;
- Good performance of customers' appliances.

The two following compensation techniques are used:

a) Shunt Compensation

Here, different compensation devices are used and are connected in series or in parallel to the transmission or distribution systems at any particular node. They inject current into transmission or distribution lines in order to control the reactive component of the load current and hence the line losses are minimized.

b) Series Compensation

various compensation devices are mounted in series with lines at a particular node. This compensation gives more control of power flow through the line.

2.5.1. Basic types of FACTS Controllers

- **Series Controllers** The series controller could be a variable impedance or a variable source both are power electronics based. In principle, all series controllers inject voltage in series with the line. Examples for the series controllers are SSSC, TCSR and TSSC.
- **Shunt Controllers** The shunt controllers may be variable impedance connected to the line voltage causes a variable current flow hence represents injection of current into the

line. Examples of the shunt controllers include thyristor controlled Reactor, Static synchronous compensator, thyristor switched reactor and thyristor switched capacitor.

- **Combined Series-series Controllers** The combination could be separate series controllers or unified series-series Controller-Interline Power Flow Controller.
- **Combined Series-shunt Controllers** The combination could be separated series and shunt controllers or a unified power flow controller Examples: TCPST and TCPAR [11].

Table 2:Choice of FACT Controller [12].

Operating Problem	Corrective Action	FACTs Controller
1.Voltage Limit:		
❖ low voltage at heavy load	❖ supply reactive power	❖ STATCOM, SVC
❖ high voltage at low load	❖ absorb reactive power	❖ STATCOM, SVC, TCR
❖ high voltage following an outage	❖ absorb reactive power prevent overload	❖ STATCOM, SVC, TCR
❖ low voltage following an outage	❖ supply reactive power prevent overload	❖ STATCOM,SVC
2.Thermal limits:		
❖ Transmission circuit overload	❖ Reduce overload	❖ TCSC, SSSC, UPFC, IPC, PS
❖ Tripping of parallel circuits	❖ Limit circuit loading	❖ TCSC, SSSC, UPFC, IPC, PS
3.Loop flows:		
❖ Parallel line load sharing	❖ Adjust series resistance	❖ IPC, SSSC, UPFC, TCSC, PS
❖ Post-fault power flow sharing	❖ Rearrange network or use thermal limit action	❖ IPC, SSSC, UPFC, TCSC, PS
❖ Power flow direction reversal	❖ Adjust phase angle	❖ IPC,SSSC,UPFC,PS

2.6 Description of the Static VAR Compensator (SVC)

The Static VAR Compensator (SVC) is a shunt device of the Flexible AC Transmission Systems (FACTS) family using power electronics to control power flow and improve transient stability on power grids.

The SVC regulates voltage at its terminals by controlling the amount of reactive power injected into or absorbed from the power system.
When system voltage is low, the SVC generates reactive power (SVC capacitive).

When system voltage is high, it absorbs reactive power (The variation of reactive power is performed by switching three-phase capacitor banks and inductor banks connected on the secondary side of a coupling transformer. Each capacitor bank is switched on and off by three thyristor switches (Thyristor Switched Capacitor or TSC). Reactors are either switched on-off (Thyristor Switched Reactor or TSR) or phase-controlled (Thyristor Controlled Reactor or TCR) [11].

This is a parallelly connected static type of VAR absorber or generator where the output is modified so as to substitute inductive or capacitive current where this regulates or manages corresponding factors of the current mainly the bus voltage factor. A static VAR compensator is dependent on thyristors having no gate switching off ability. The functionality and features of the thyristors understand the SVC adaptable reactive impedance. The crucial equipment which is included in this device is TCR and TSR which are a thyristor-controlled capacitor and thyristor-controlled reactor [13].

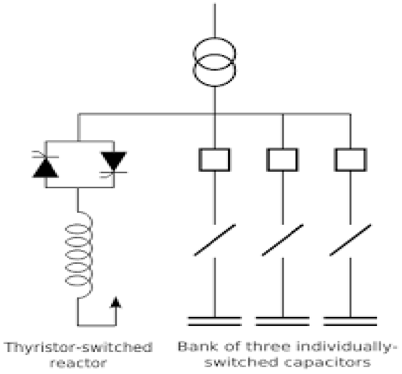


Figure 6:Static VAR Compensator

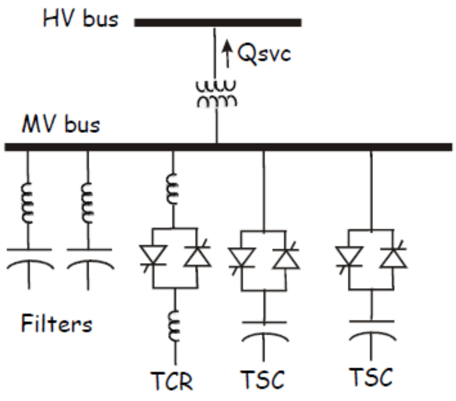


Figure 7:Schematic diagram of an SVC

2.7 REASON FOR THE SELECTION OF STATIC VAR COMPENSATOR

Static var compensator (SVC) is typically a shunt FACTS device which connected on the transmission system's busses. It is a first generation FACTS device that can control voltage at the required bus and hence improving the voltage profile of the system. It behaves like a shunt-connected variable reactance and generates or absorbs reactive power in order to regulate the voltage magnitude at the point of its connection. It also often used to provide fast reactive power and voltage regulation support. SVC is also cheaper and easier to install when compared to some others FACTS devices. This device is static, which means it does not have rotating and mobile components, and this enables SVCs to provide a fast response to the network. In addition, less maintenance of the components is required because there are no rotating parts. There are some advantages to using an SVC in the network, including: rapid response, more flexibility, good certainty, balancing phases, eliminating extra voltage, fast operation, low maintenance cost, simple control, increasing transient stability, prevention of voltage collapse, improving power factor, improving power quality and eliminating harmonics.

The current SVC has been widely used in load compensation and compensation modern power transmission line system to improve the stability of the power system and suppress voltage fluctuations applied to shock loads (such as electric arc furnace) flicker suppression and non-electrified railway balance compensation among power companies around the world and is recognized as a mature industry and effective reactive power management tools and apply it. when SVC supply reactive power that is required at the load, by varying its impedance, to inject reactive current ISV C thereby it indirectly control the line current I. By Ohm's law, the difference between the sending end voltage and the receiving end voltage (i.e. VS −VR) being the voltage drop across the transmission line correlate to the line current I. We can assume the voltage at the se0nding end (VS) to be a constant value, the magnitude of voltage at the receiving end —VR—can be controlled by SVC [12].

$$V_R - IZ = V_S - (I_R - I_{SVC})Z \qquad \textbf{(2.5)}$$

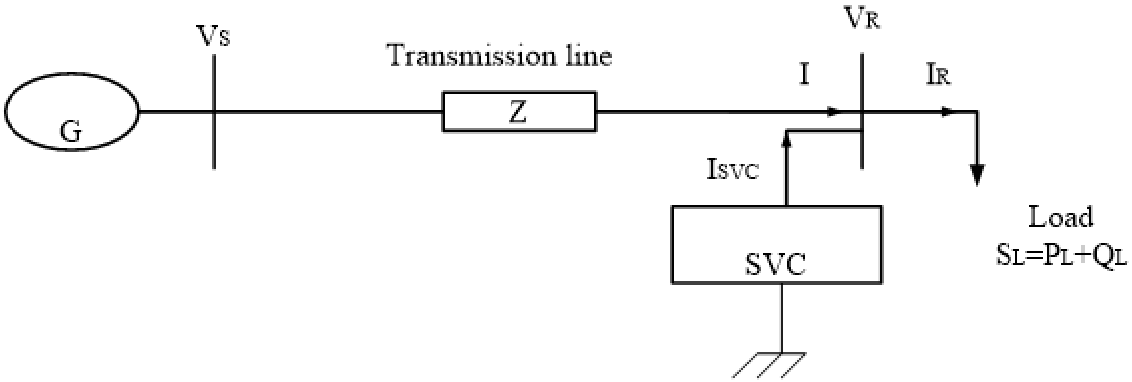


Figure 8:A Simple Two-Bus System with SVC

$$IR = jB_c V_R + \frac{S_L}{V_R} \tag{2.6}$$

Where: $Z = R + jwL$

As seen in equations above the SVC device can control the voltage magnitude by varying it impedance. The line current I in heavy load condition leads to a voltage drop and is reduced by the SVC current I_{SVC}partial compensation for the large load current IR. The receiving end voltage decreases as the load increases and reactive power will be injected by SVC to boost the voltage. Voltage collapse occurs when there is further increase in load after SVC hits its maximum limit. In order to prevent voltage collapse, SVC is considered as fixed susceptance Bc [12].

CHAPTER THREE:

DATA COLLECTION, ANALYSIS AND MODELING OF THE NETWORK

3.1. Kigoma Substation Description

Kigoma substation is located in Ruhango District, Southern Province of Rwanda. It is fed by 110kV Transmission Line from KILINDA Substation. The 110kV is stepped down through one power transformer 110/30kV of 10MVA. There is one outgoing 110kV transmission line to GISAGARA Substation and three 30kV Medium voltage outgoing Feeders namely Butare Feeder, Ntongwe Feeder and Gatumba Feeder.

Figure 9:Photo Image for Kigoma Substation

The feeder under study is Butare distribution feeder which is fed from this substation. It is the feeder which has been experiencing the problems of overload, poor voltage quality and thus experiencing many trips.

3.2. Kigoma Substation Single Line Diagram

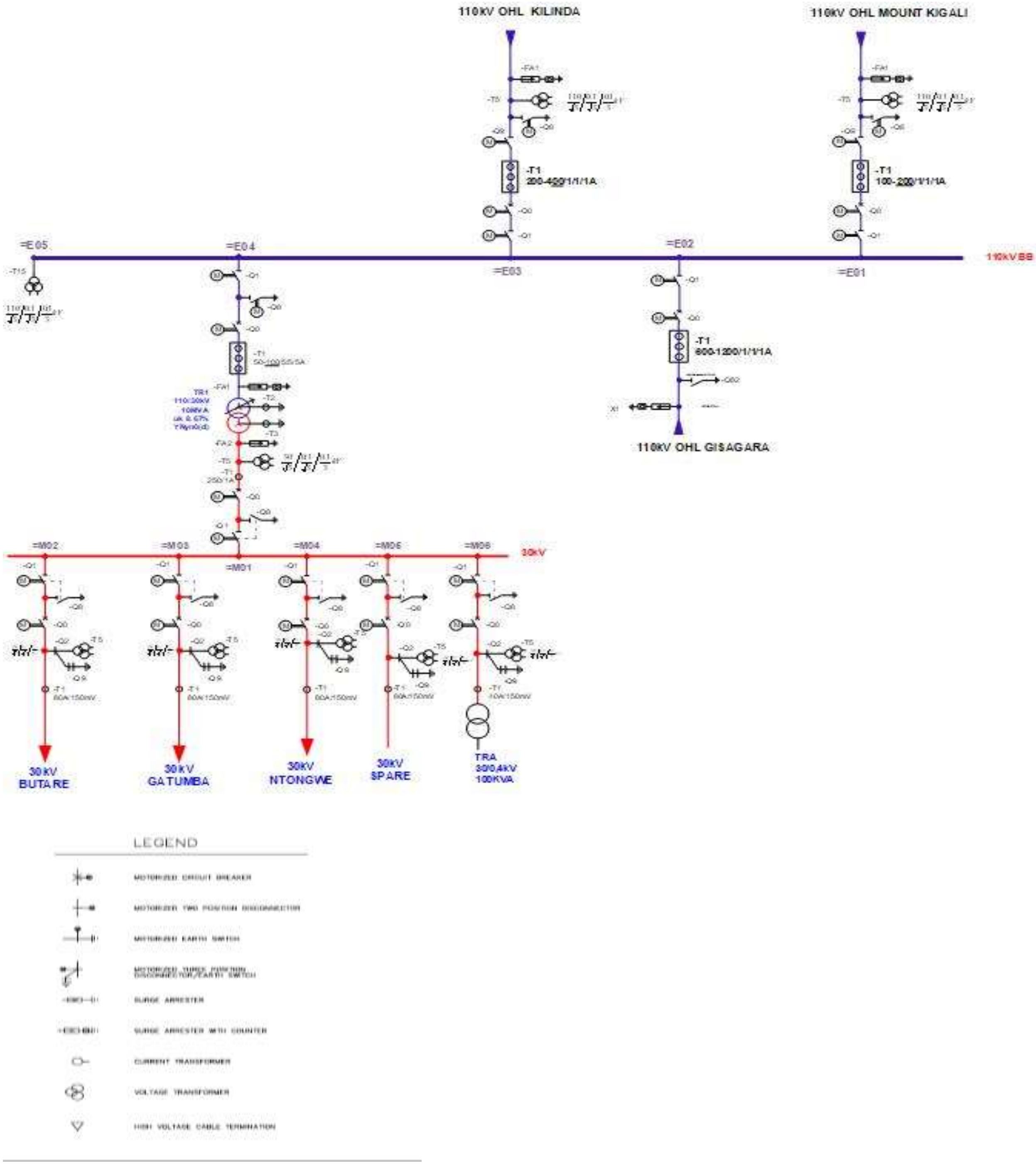


Figure 10:Single Line Diagram of Kigoma Substation

3.3. Data Collection

Data have been collected by direct involvement of the researcher and by previous reports obtained from Rwanda Energy Group (REG). The necessary data collected are the load of Butare feeder (active power, reactive power, power factor, voltage of the feeder). The sampling interval was from January 2022 to June 2022.

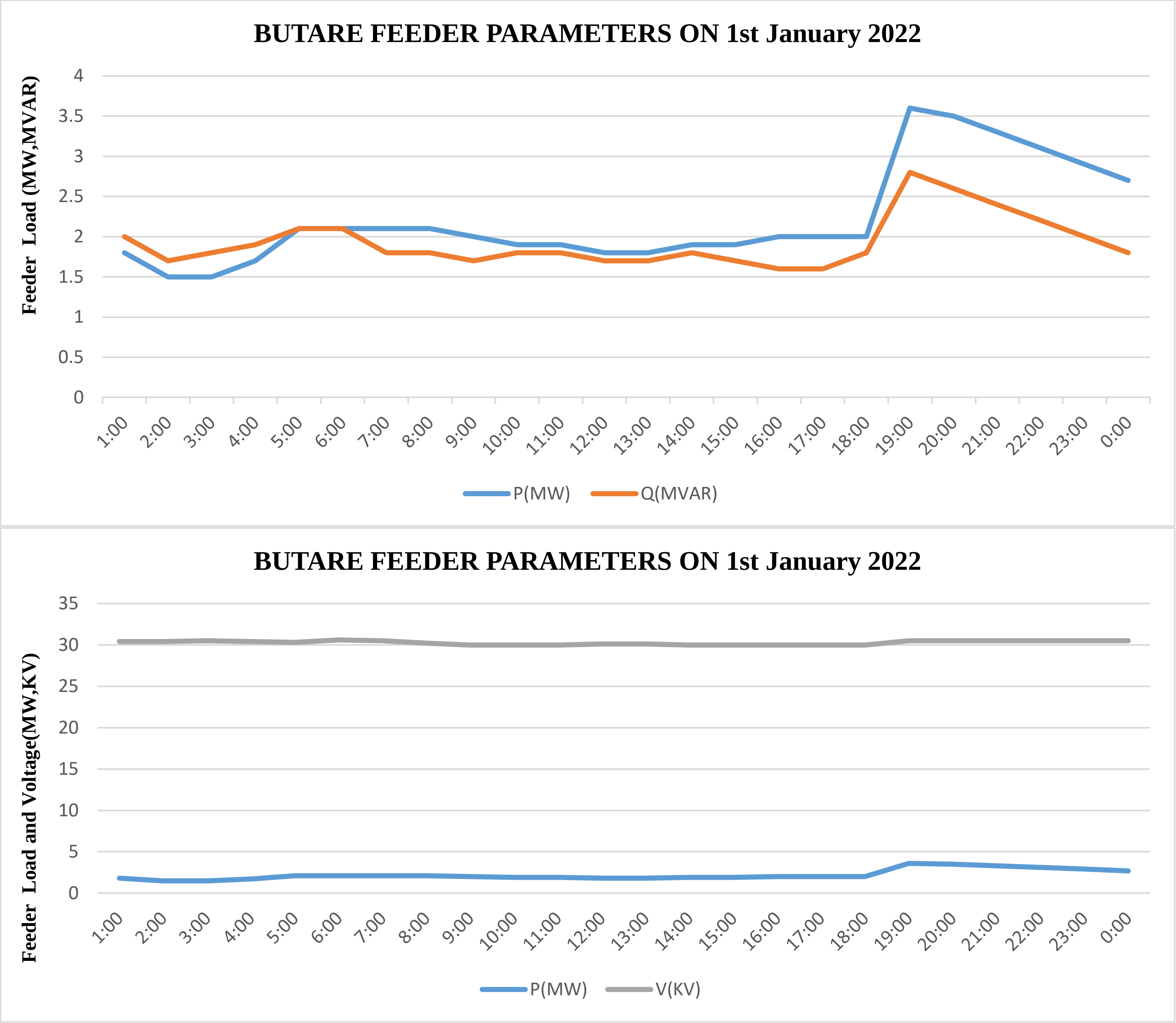


Figure 11: Graphic Illustration of Voltage and Power Data for Butare Feeder (1/1/2022)

The above graph shows the behavior of the feeder from1:00 to 00:00. It shows that when the load increases there was a decrease in the voltage.

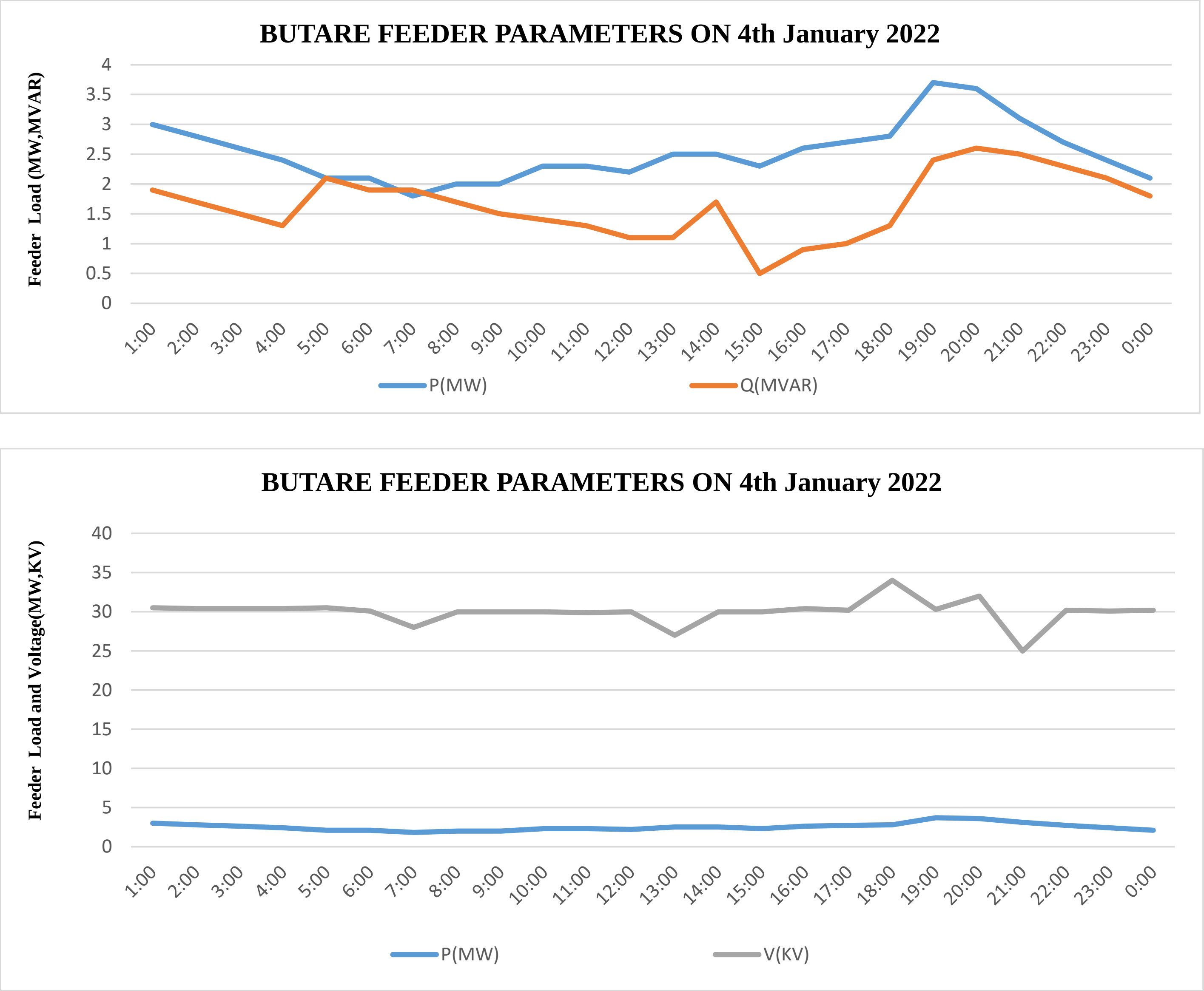


Figure 12: Graphic Illustration of Data for Butare Feeder on 4/1/2022

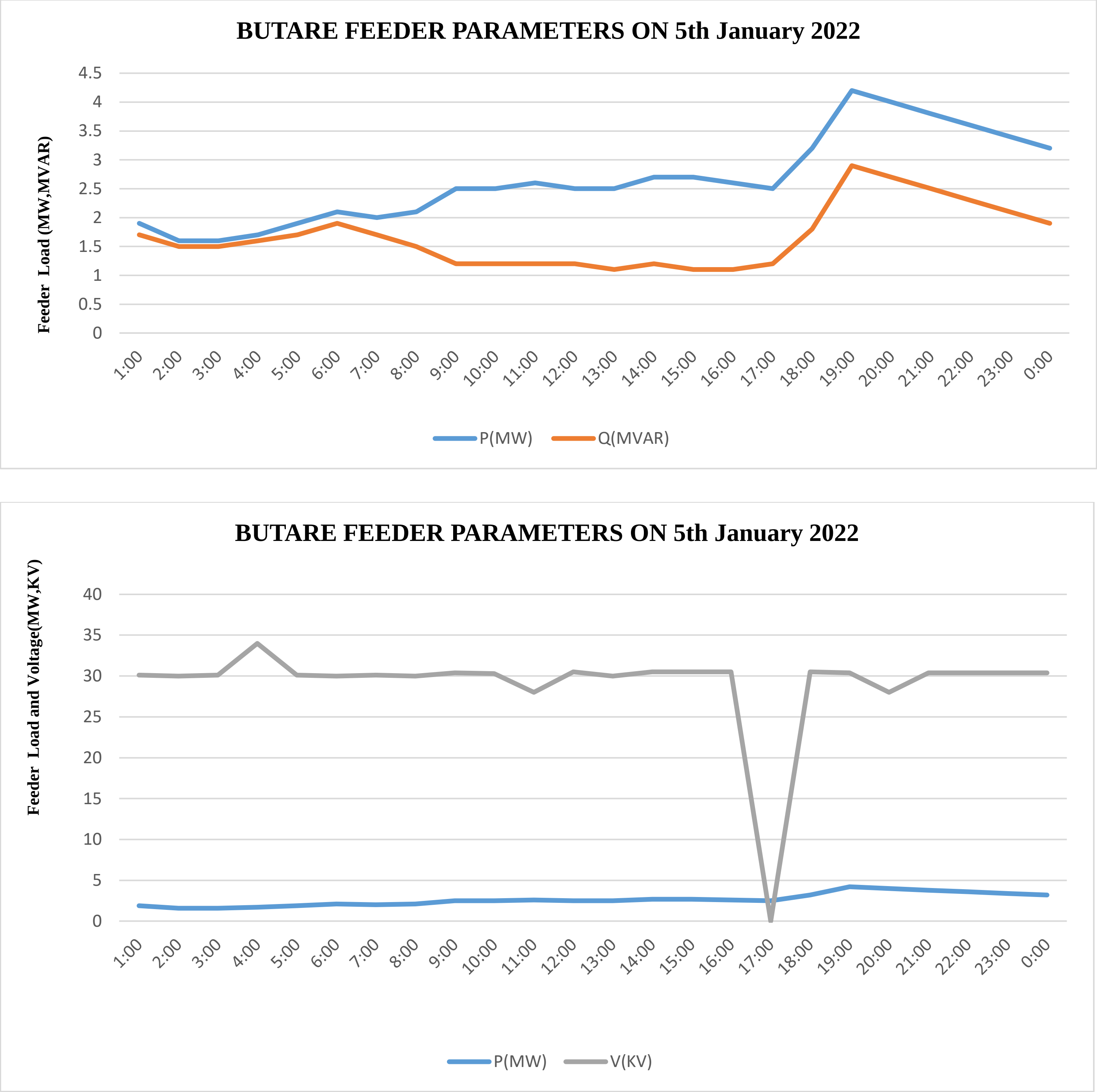
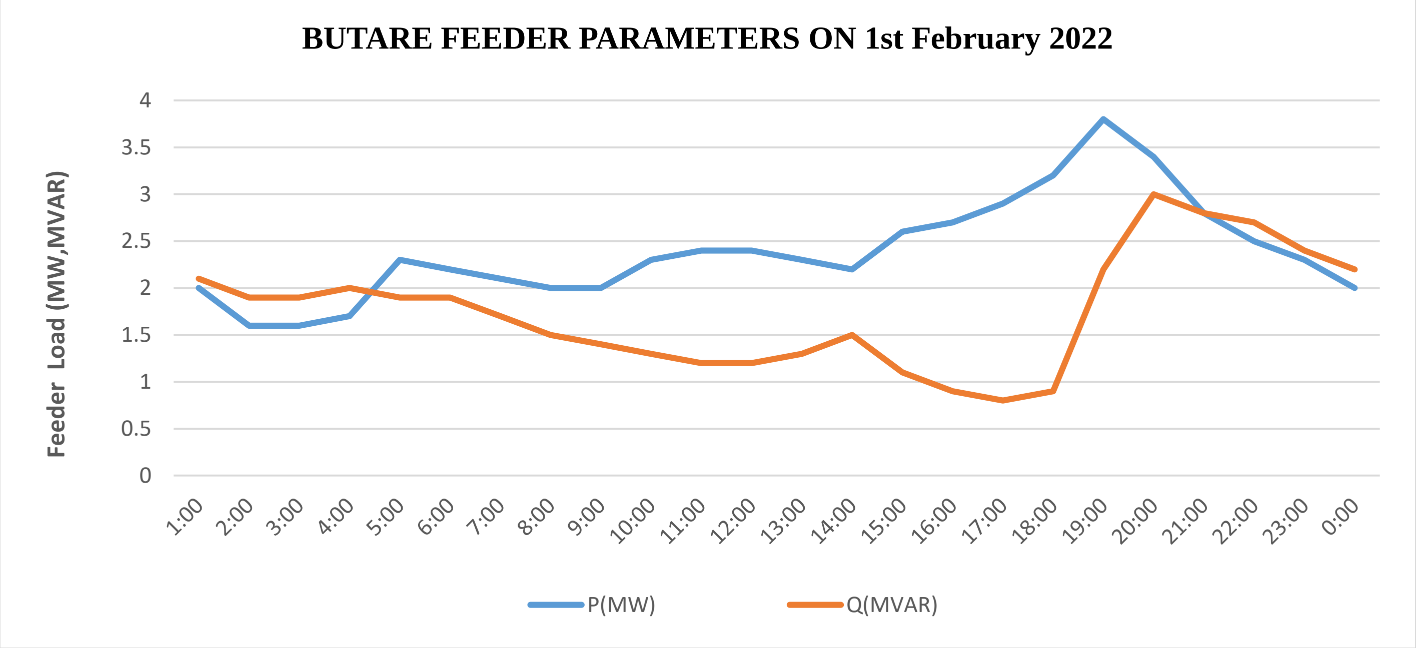


Figure 13:Graphic Illustration of Data for Butare Feeder on 5/1/2022



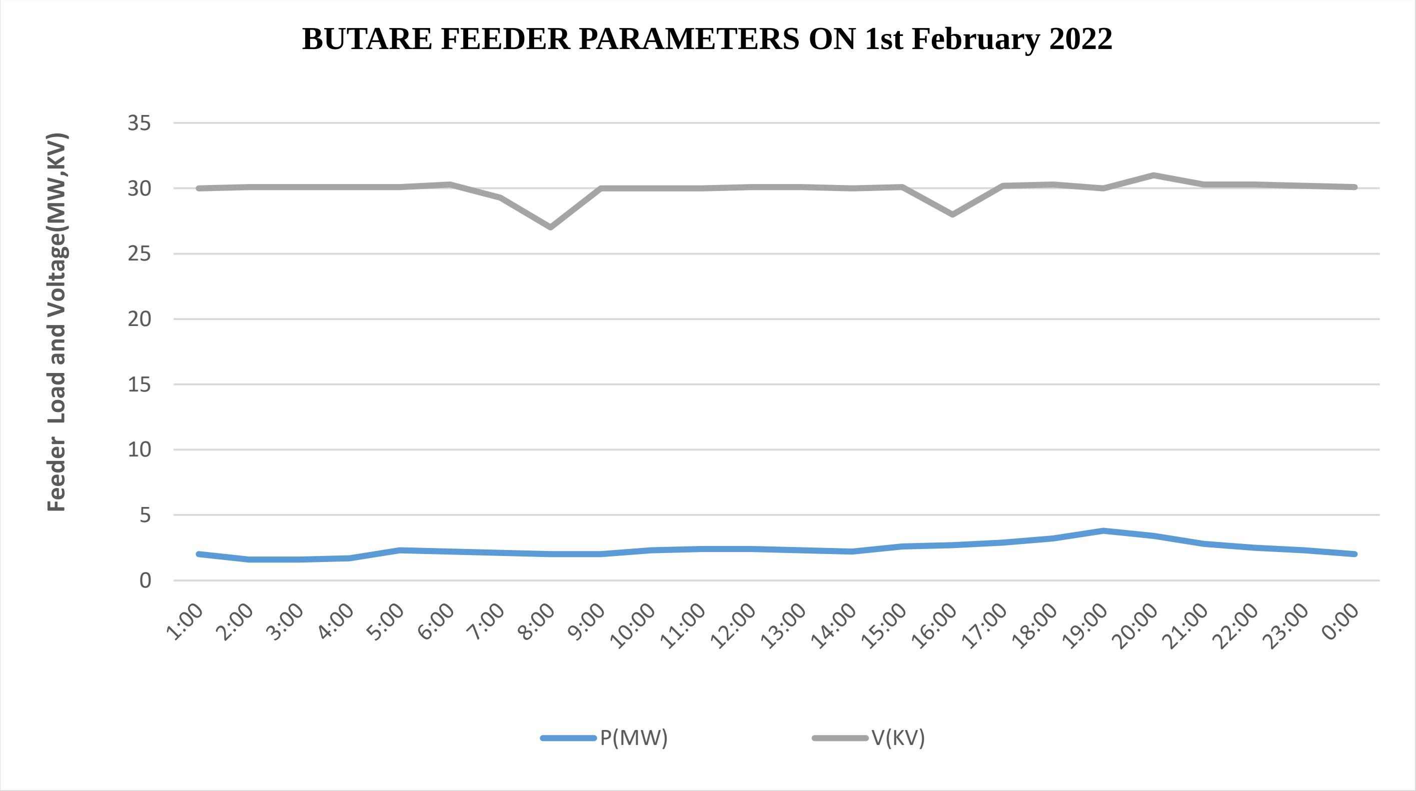


Figure 14: Graphic Illustration of Data for Butare Feeder on 1/2/2022

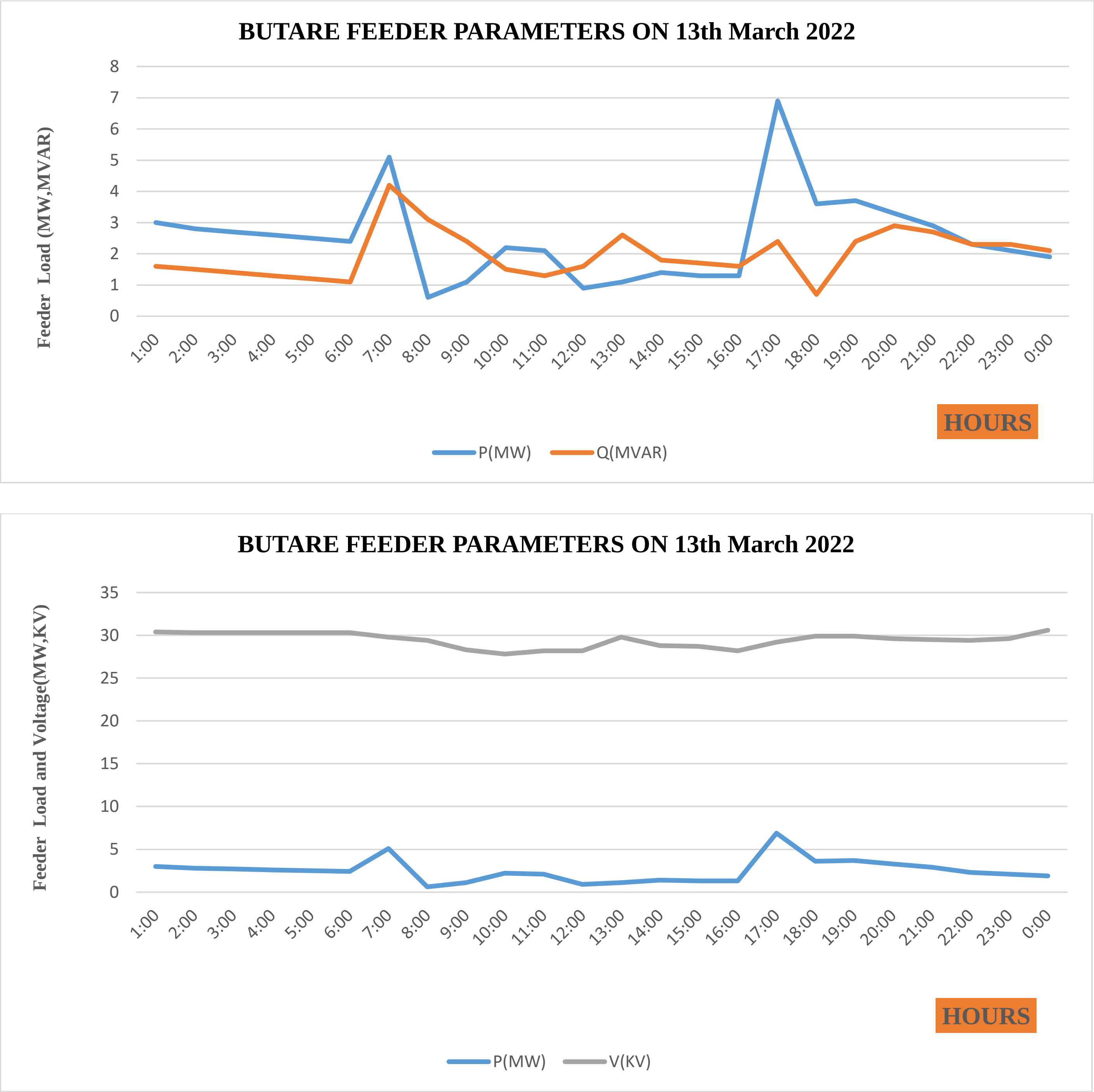
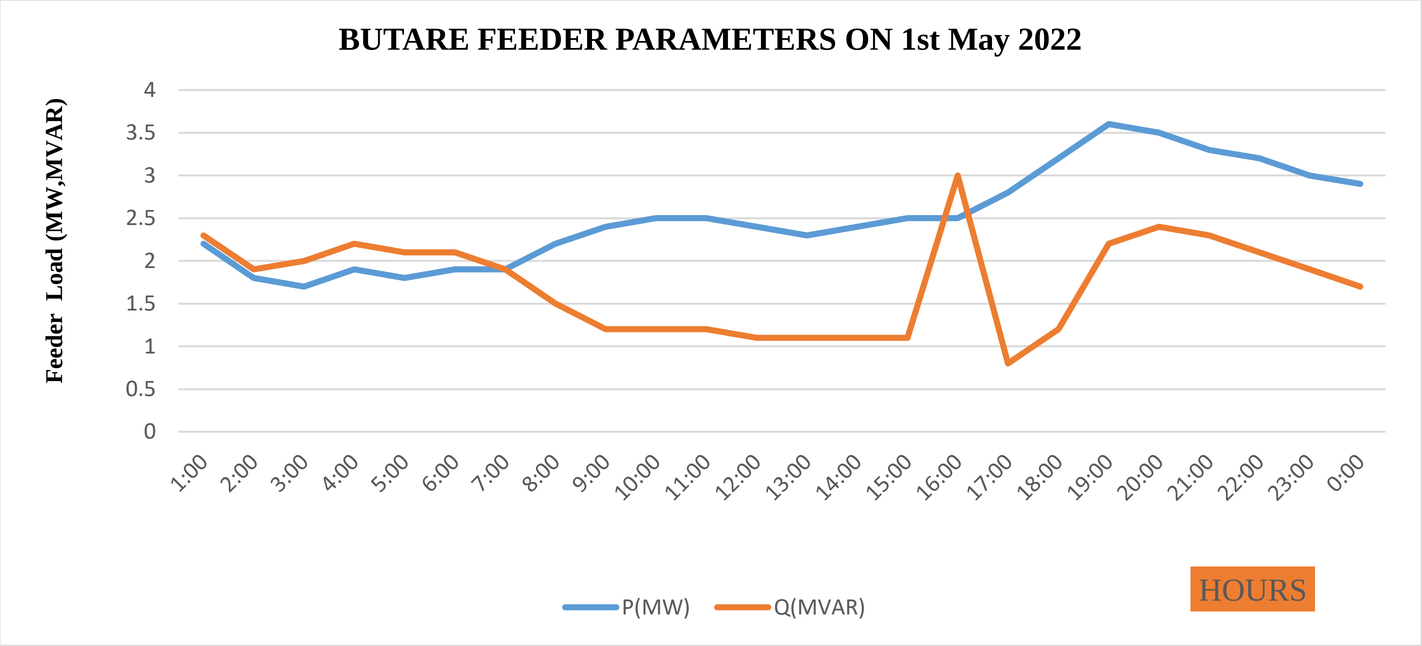


Figure 13: Graphic Illustration of Data for Butare Feeder on 13/3/2022



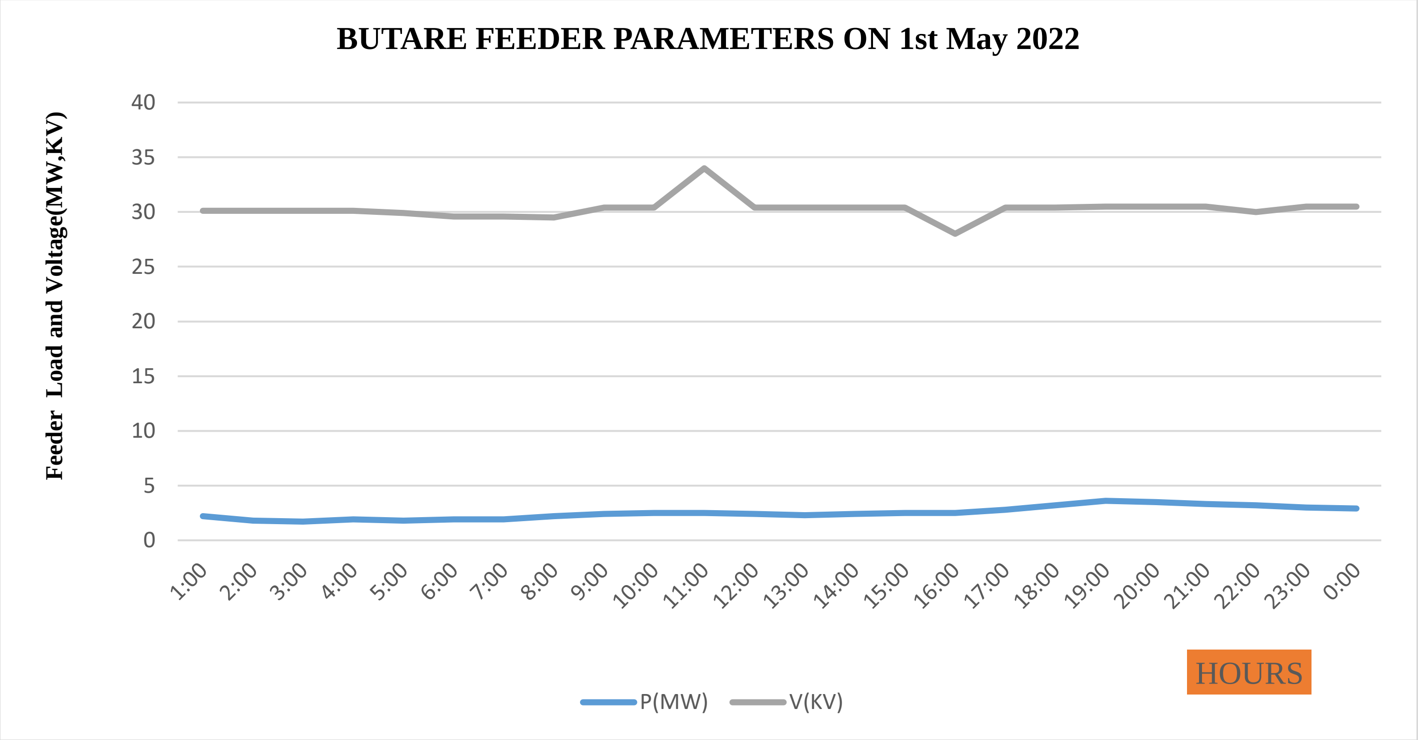
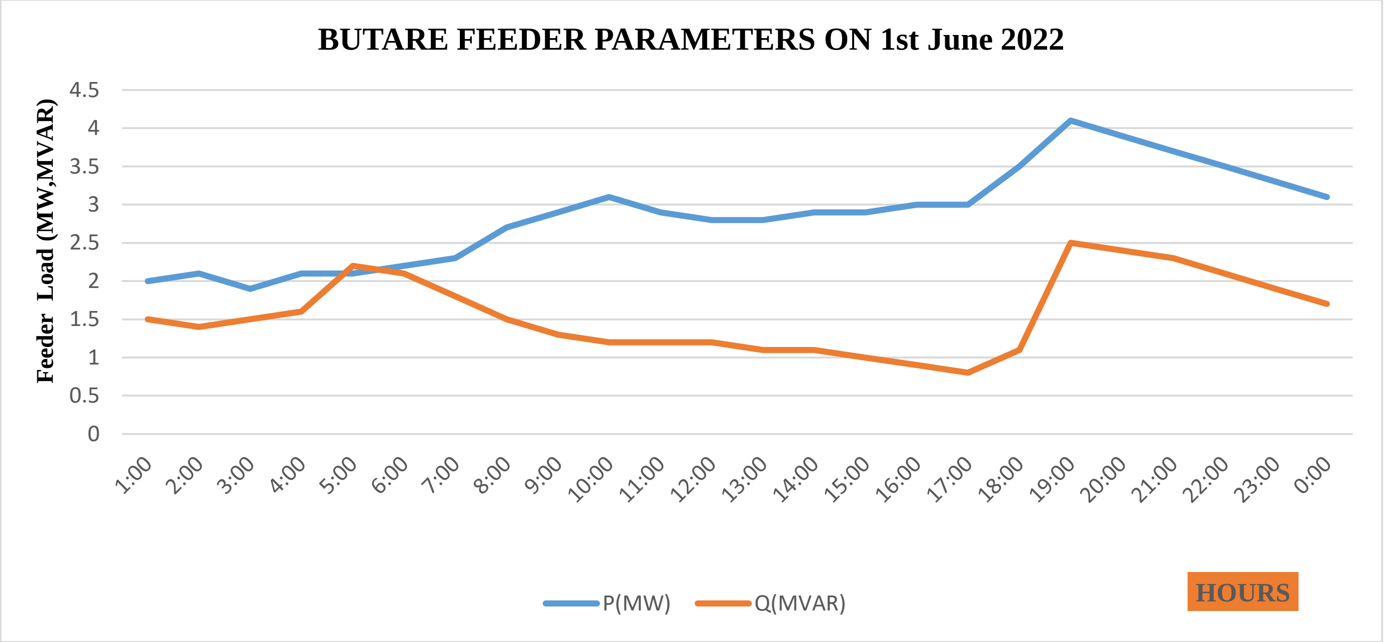


Figure 14: Graphic Illustration of Data for Butare Feeder on 1/5/2022



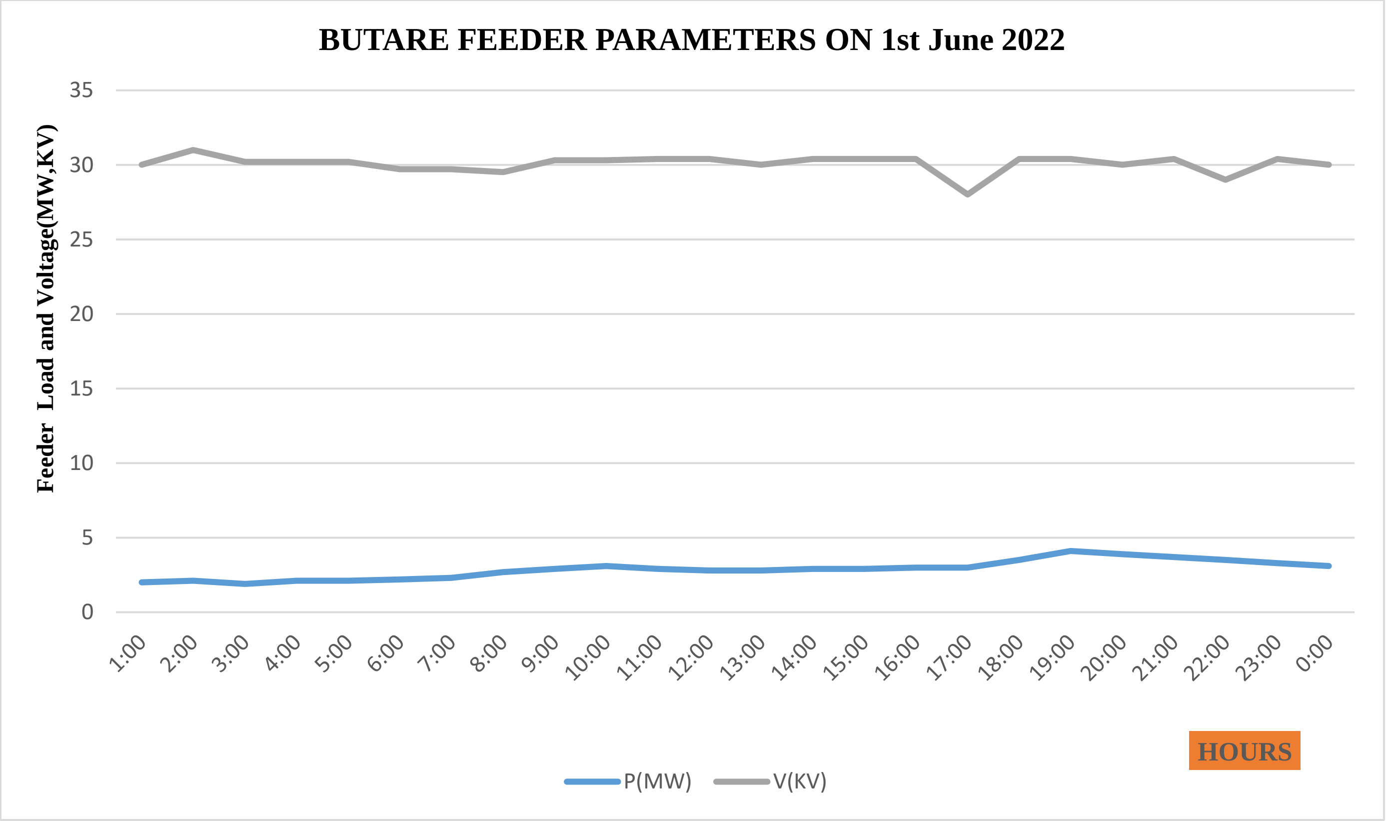


Figure15: Graphic Illustration of Data for Butare Feeder on 1/6/2022

From the above Graphic illustrations shows the variation of power and voltage of Butare feeder from Kigoma substation, it is clearly seen that during Peak hours the load increases and the network voltage decreases.

3.4. DESIGN OF VOLTAGE SOURCE CONVERTER BASED SVC

Depending on feeder data, design of components for reactive power compensating device that is required to improve the voltage profile is done. From power of the SVC, DC link capacitor, etc. are designed.

Table 3: Rating of 30 kV Butare Feeder Distribution Line

No	Type of Data	Amount
1	Feeder name	Butare
2	Feeder Nominal Voltage	30KV
3	Feeder Nominal Current	630A
4	Feeder Maximum Loading	10MW
5	Feeder approximate Length	75km
6	Feeder operational power factor	0.85
7	Resistance per KM	0.065Ω
8	Reactance per KM	0.041Ω

3.4.1. Design of SVC Ratings

From the table 3 above, the apparent power can be determined by $\boldsymbol{S = \frac{P}{\cos \emptyset}}$ **(3.1)**

Where S: Apparent Power

P: Active Power of the feeder

CosØ: Power factor of the feeder

$$\boldsymbol{S = \frac{10MW}{0.85} = 11,765KVA}$$

The feeder reactive power is calculated as:

$$Q_1 = S * \sin\delta = \sqrt{S^2 - P^2} = \sqrt{11765^2 - 10000^2} = 6198Kvar \qquad \textbf{(3.2)}$$

For compensation, the current power factor must be corrected from 0.85 to above 0.95. Here we take the power factor of 0.95 lagging. The designed apparent power of the feeder would be

$$\boldsymbol{S = \frac{10MW}{0.95} = 10526kVA}$$

The feeder reactive power is calculated as:

$$Q_2 = S * \sin\delta = \sqrt{S^2 - P^2} = \sqrt{10526^2 - 10000^2} = 3286Kvar \qquad \textbf{(3.3)}$$

Thus,$Q_{new} = Q_2 - Q_1 = 3286Kvar - 6198Kvar = -2912Kvar$

As the tolerance of 10% must be added;

$$Q3 = Qnew + 10\%Qnew = 2912 + 10\%(2912) = 3203.2\ kVAR \qquad \textbf{(3.4)}$$

The SVC to compensate the reactive power of 2912Kvar has to be rated to 3203kVAR.

The power electronics converters that convert power from 1MVA mostly use high voltage semiconductor devices. The voltage ratings of available semi-conductor devices are 2.5kV, 3.3kV and 4.5kV. The switching frequency of the 3.3kV IGBT should be kept to 1 kHz to limit the active power dissipation in the SVC to 1% [14].

From that, the Power of SVC is: $P = Q * 10\%$

$$P = 3203 * 10\% = 32.03kw$$

The apparent power of the SVC is: $\sqrt{P^2 + Q^2} = \sqrt{3203^2 + 32.03^2} = 3203.16kVA$ **(3.5)**

The SVC of 3203.16kVA should be used to compensate the reactive power and correct the power factor from 0.85 to 0.95

The ratings of the voltage source converter can be calculated as follows:

We can select the IGBT as a semiconductor switch to be used in the witching of the SVC. The IGBT having voltage rating of 3.3kV it means that the coupling transformer is fed from 30kV and its secondary side has an output voltage of 3.3kV to power those high voltage semiconductor switches.

The current through the coupling transformer is: $I = \frac{S}{\sqrt{3} * V} \cong I = \frac{3203Kva}{1.732 * 30Kv} = 61.64A$ **(3.6)**

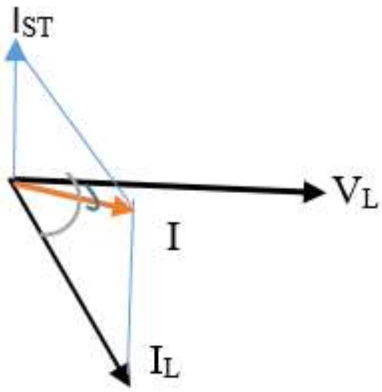


Figure 15: Phasor Diagram of the Resulting Current after Compensation

I_L is the feeder normal operating current at an angle 31.70^0 or 0.85 power factor;

I_{Svc} is the SVC current which is in phase quadrature with the line voltage;

I is the resultant current after insertion of the SVC. This current is calculated as:

$$I = I_L - I_{SVC} = [(630cos31.70 + j630sin31.70) - (61.64cos90 + j61.64sin90)]A \quad \textbf{(3.7)}$$

$$I = (536.01 + j331.04) - (0 + j61.64)A$$

$$I = (536.01 + j269.4)A$$

$$I = \sqrt{536.01^2 + 269.4^2} = 599.9A$$

Angle: $\theta = \tan^{-1}\frac{269.4}{536.01} = 26.68^0$ **(3.8)**

After improving the power factor, the feeder nominal current reduces from 630A to 599.9A. From this reduction of current, we can say that also the losses in the line will be reduced (I^2R losses).

We can also determine the secondary current of the coupling transformer as follows:

$$\frac{V_p}{V_s} = \frac{I_s}{I_p} \cong \frac{30Kv}{3.3Kv} = \frac{I_s}{49.26} \quad \textbf{(3.9)}$$

$$Is = \frac{30 * 61.64}{3.3} = 560.36A$$

3.4.2. Design of DC Capacitor Voltage

The capacitor voltage rating is decided by taking into consideration on DC bus voltage. The DC bus voltage is calculated using the modulation index m and is considered as one. The V_{LL} is the line to line output voltage of the SVC.

By taking the VLL and the modulation index as one, the DC capacitor voltage is calculated as follows:

$$V_{DC} = 2\frac{\sqrt{2}}{\sqrt{3}} * \frac{V_{LL}}{m} \cong 2\frac{\sqrt{2}}{\sqrt{3}} * \frac{3300}{1} = 5388.8V \approx 5400V \quad \textbf{(3.10)}$$

3.4.3 Design of DC Capacitor

There are two main points that must be considered while designing DC Capacitor:

1. The DC capacitor rating should be enough as possible to supply the voltage source converter with enough DC voltage in order to avoid high harmonics in the STATCOM AC output voltage;

2. The capacitor must supply the required reactive power for compensation. When the capacitor is undersized, the result will be high harmonics in the output voltage of the compensator. The oversized DC capacitor will result in slower response time to the controller [15].

The capacitance of the DC capacitor can be calculated using the following formula:

$$C = \frac{0.9I_{rms}}{0.02*4\pi*V_{DC}} \quad \textbf{(3.11)}$$

Where $I_{rms} = \frac{Apparent\ power\ for\ SVC}{\sqrt{3}*V_{LL}} \cong \frac{3203}{1.73*3.3} = 560.39A$ and the Nominal Frequency is 50Hz

Thus,$C = \frac{0.9*560.39}{0.02*4*3.14*50*5400} = 2975\mu F \approx 3000\mu F$

This means that we can need three capacitors of 1000μF of 5400V_{DC} each that will be connected in parallel to be used to generate 3203Kvar.

$$X_L = \frac{V^2}{Q} \cong \frac{30000^2}{3203000} = 280.9\Omega \quad \textbf{(3.12)}$$

$$X_L = 2\pi * f * L, then\ L = \frac{X_L}{2\pi f} = \frac{280.9}{2*3.14*50} = 0.89H = 894.5mH \quad \textbf{(3.13)}$$

3.4.4 Design of the Coupling Reactor

The coupling inductance of the transformer is calculated depending on the voltage source converter switching frequency, the ripple current and the DC voltage of the voltage source converter [16].

$$L = \frac{\sqrt{3}*m*V_{DC}}{12*\propto*fs*Irip} \quad \textbf{(3.14)}$$

L: Inductance

m: Modulation Index=1

V_{DC}: DC Voltage

α: Overloading factor=1.2

fs: Converter switching Frequency

Irip:Ripple Current:$Irip = 0.05\sqrt{2} * I_{rms} \cong I_{rip} = 0.05 * \sqrt{2} * 560.39 = 39.625A$ **(3.15)**

Thus,$L = \frac{1.73*1*5400}{12*1.2*1000*39.625} = 16.4mH$

The reactance of the coupling transformer is determined by:

$$X_L = 2\pi f L = 2 * 3.14 * 50 * 0.01637 = 5.15\Omega \quad \textbf{(3.16)}$$

3.4.5 Design of Input Filter

The input filter is used to filter out the harmonics (unwanted voltages) caused by switching the power electronics components. The input filter may be composed of inductor only or a combination of inductor and capacitor to form an LC circuit. In this thesis, the designed filter uses inductor-capacitor to filter out the harmonics and its design is summarized below: The capacitive Reactance of the LC Filter is calculated as: $X_C = \frac{V^2}{0.15Q}$ **(3.17)**

V: Rated Voltage of Switching Device

Q: Reactive power of the semiconductor Switching device

$$X_C = \frac{3300^2}{3203000 * 0.15} = 22.66\Omega$$

$$C = \frac{1}{2\pi f Xc} = \frac{1}{2*3.14*50*22.66} = 140\mu F$$ **(3.18)**

i.e. that three capacitors of 140μF are required for the designed filter to work on three phase system.

The Reactive power of the filter is

$$Q_{Filter} = \frac{V^2}{X_C} = \frac{30000^2}{22.66} = 39.71Kvar \approx 40Kvar$$ **(3.19)**

CHAPTER FOUR:

SIMULATION AND DISCUSSION OF THE RESULTS

4.1. Simulation of the System without SVC

During this part, system voltage profile with and without Static Var Compensator is simulated using power world simulator Software. The main function of Power World Simulator software is to simulate the operation of connected power system. The simulation is accomplished by selecting Solve Power Flow – Newton from the Power Flow Tools ribbon group on the Tools ribbon tab as it is shown, as long as the load on the system increases the voltage reduces to an extent such that it goes beyond the normal operating limits.

The records were tabulated in table 4 and 5. Fig 16 represents a simple power system in which a generator is supplying power to a load through a 30-kV distribution system feeder. The solid red blocks on the line and load represent circuit breakers.

To open, a circuit breaker simply clicks on it. Since the load is series connected to the generator, clicking on any of the circuit breakers isolates the load from the generator resulting in a blackout. To restore the system, click again on the circuit breaker to close it and then again select the button on.

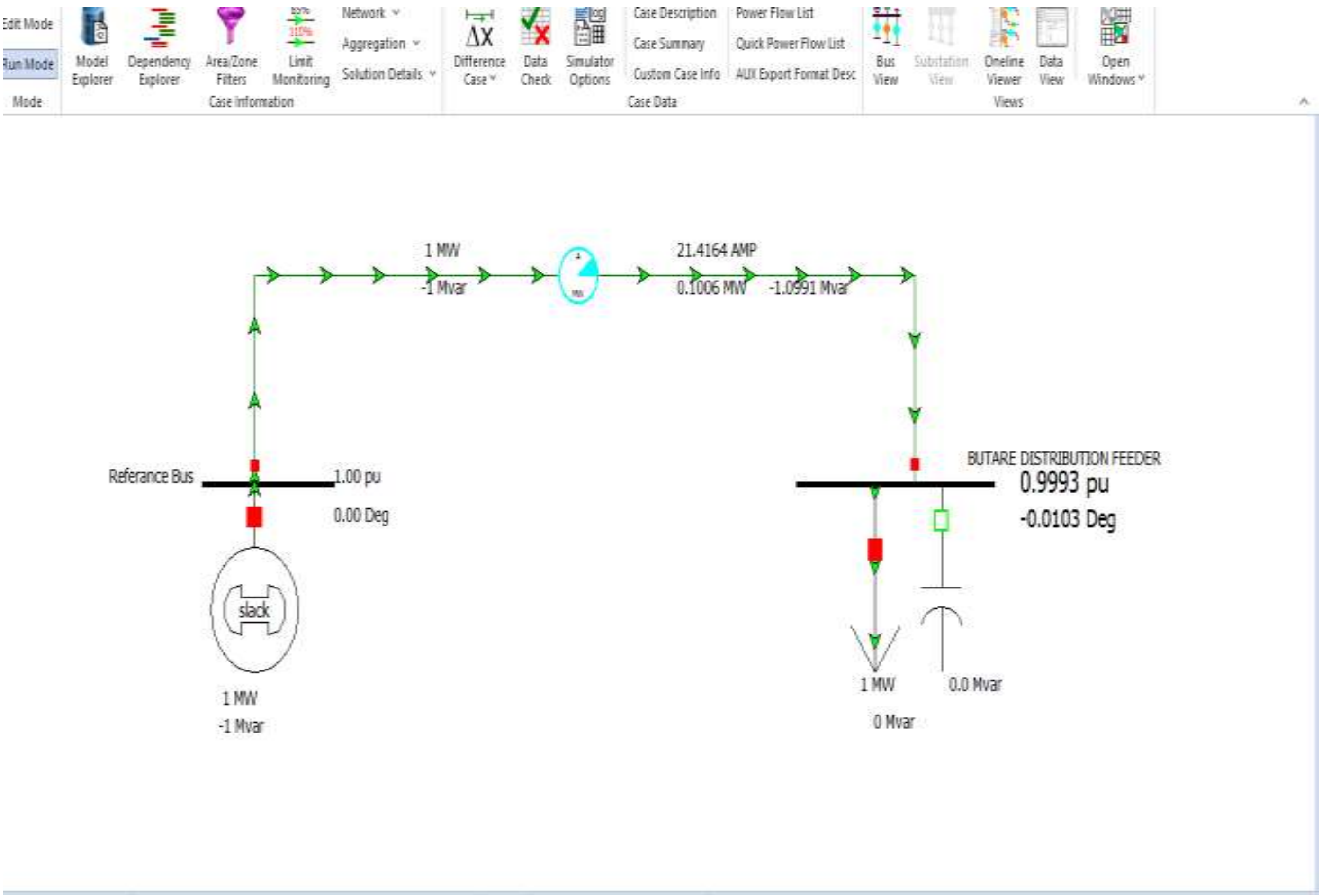
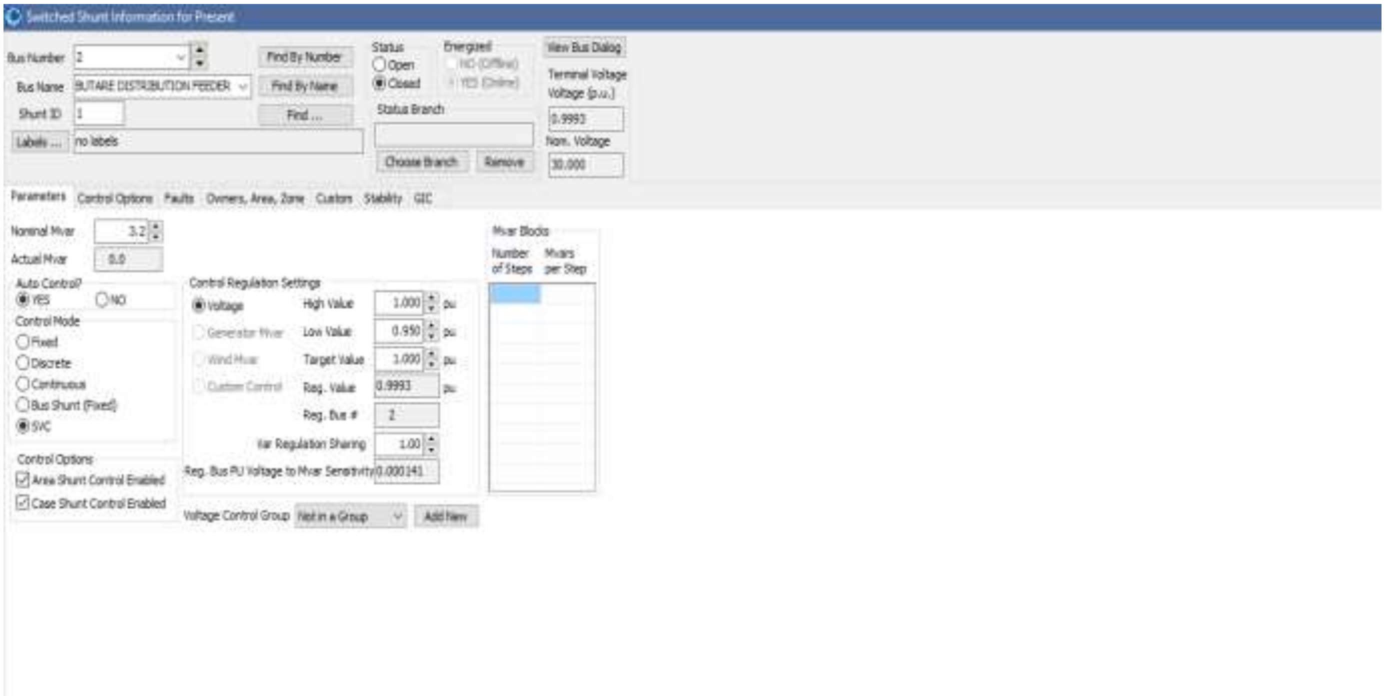


Figure 16:Power flow Simulation Without SVC at 1MW Load

Power flow analysis is a vital component of power systems. Without it, complete description of power systems is not possible. It can be used to monitor voltages, active and reactive power flows at various locations including bus bars in the power system. Moreover, active and reactive losses in distribution lines can be found. For this distribution line the static VAR compensator have been connected in parallel with Load to inject or absorb the reactive power according to the voltage reaching on Butare feeder.



Switched Shunt Information for Present

Bus Number: 2

Bus Name: BUTARE DISTRIBUTION FEEDER

Shunt ID: 1

Labels: no labels

Status: ○ Open ● Closed

Energized: ○ NO (Offline) ○ YES (Online)

Status Branch:

Terminal Voltage Voltage (p.u.): 0.9993

Nom. Voltage: 30.000

Nominal Mvar: 3.2

Actual Mvar: 0.0

Auto Control?: ● YES ○ NO

Control Mode: ○ Fixed ○ Discrete ○ Continuous ○ Bus Shunt (Fixed) ● SVC

Control Options:
☑ Area Shunt Control Enabled
☑ Case Shunt Control Enabled

Control Regulation Settings: ● Voltage ○ Generator Mvar ○ Wind Mvar ○ Custom Control

High Value: 1.000 pu

Low Value: 0.950 pu

Target Value: 1.000 pu

Reg. Value: 0.9993 pu

Reg. Bus #: 2

Var Regulation Sharing: 1.00

Reg. Bus PU Voltage to Mvar Sensitivity: 0.000141

Voltage Control Group: Not in a Group

Mvar Blocks

Number of Steps	Mvars per Step

Figure 17: Designed Static Var compensator

To connect the compensator, only the circuit breaker connected at the load will be closed (Red color) and opened without any compensator. The figure below shows the simulation carried out at various loads like 1MW, 5MW and 10 MW, and the results were tabulated in table 4 and 5.

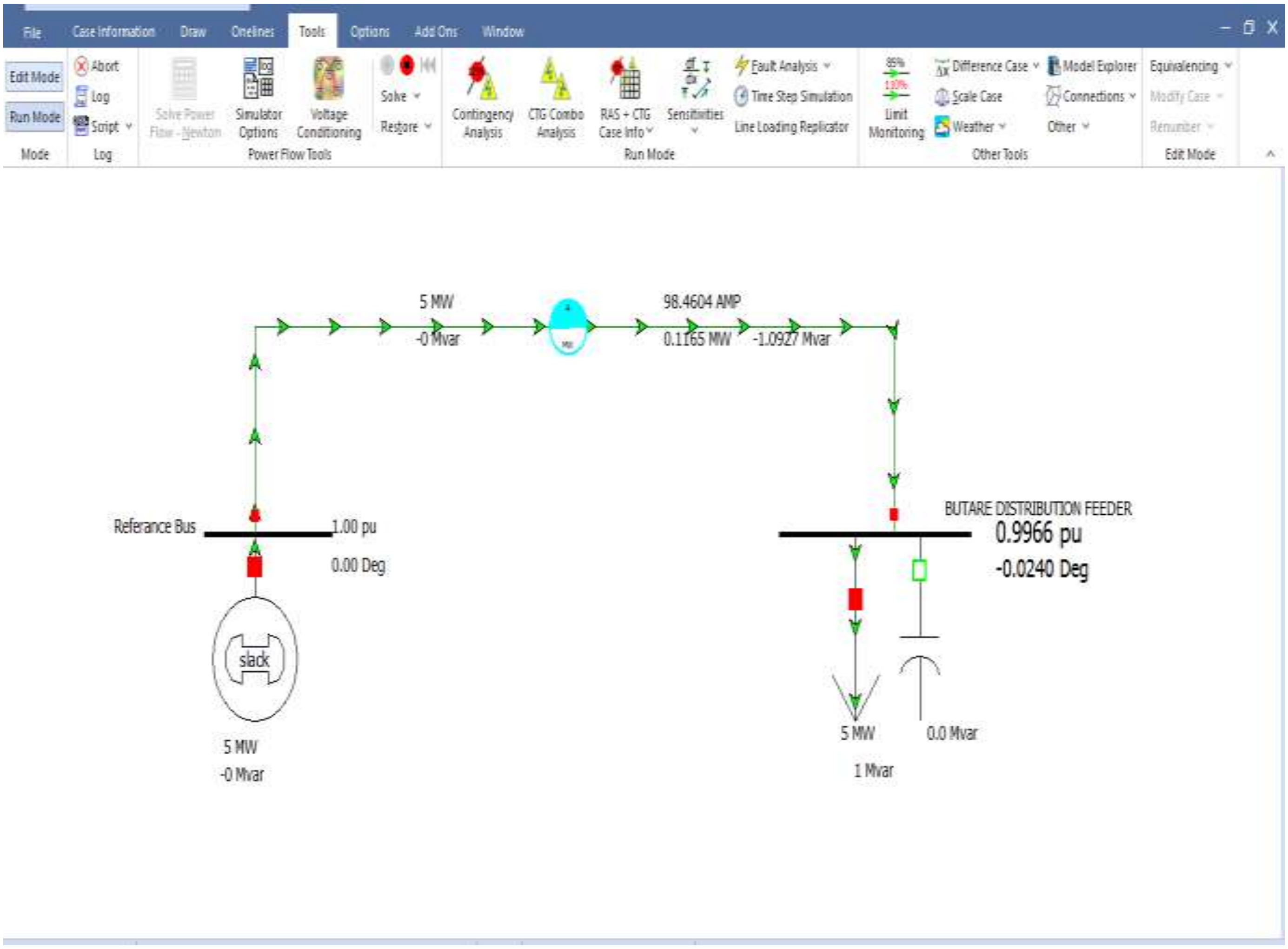


Figure 18:Power flow Simulation Without SVC at 5MW Load

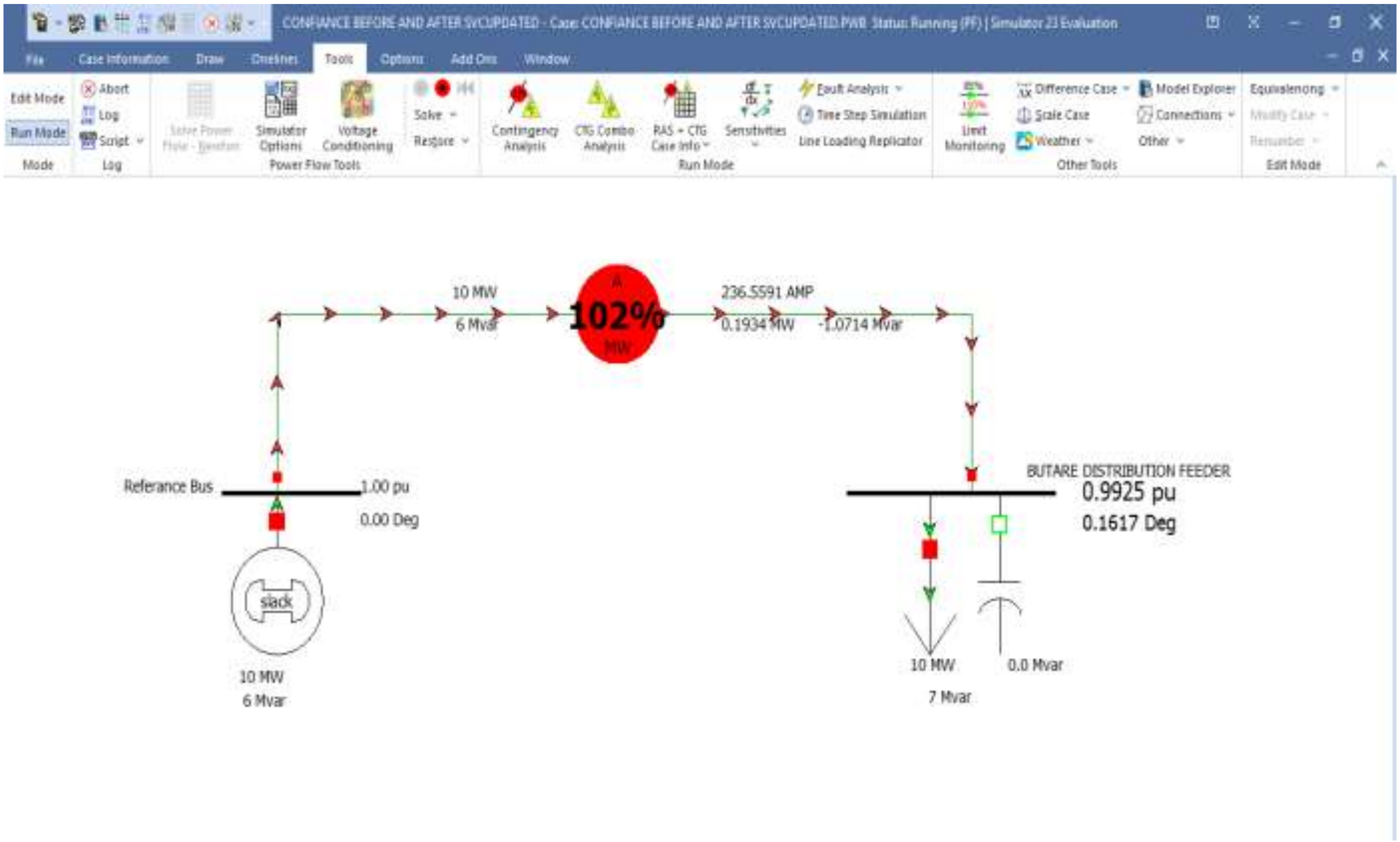


Figure 19:Simulation with SVC at 10MW Load

The line is loaded at 102 percent since the feeder has total of 10MW. The transformer from substation is rated at 10 MVA, it is clear that the system supplies the load under heavy loading conditions. Beyond this limit without any intervention of Compensator and line parameter, the whole system would lead to total blank out.

4.2. Simulation of the System with SVC

For Distribution System The SVC stabilizes the voltage at the receiving end of long distribution lines and reduces the reactive power absorbed from the main grid, which leads to lower losses and improved tariffs as well as voltage at certain acceptable limits, balances the asymmetrical load and of course reduces the voltage fluctuations and light flicker.

The designed SVC is rated on 3.5 Mvar and the compensation depend on system behavior. The figure depicts the load flow in case of the system supply the load of 1MW.

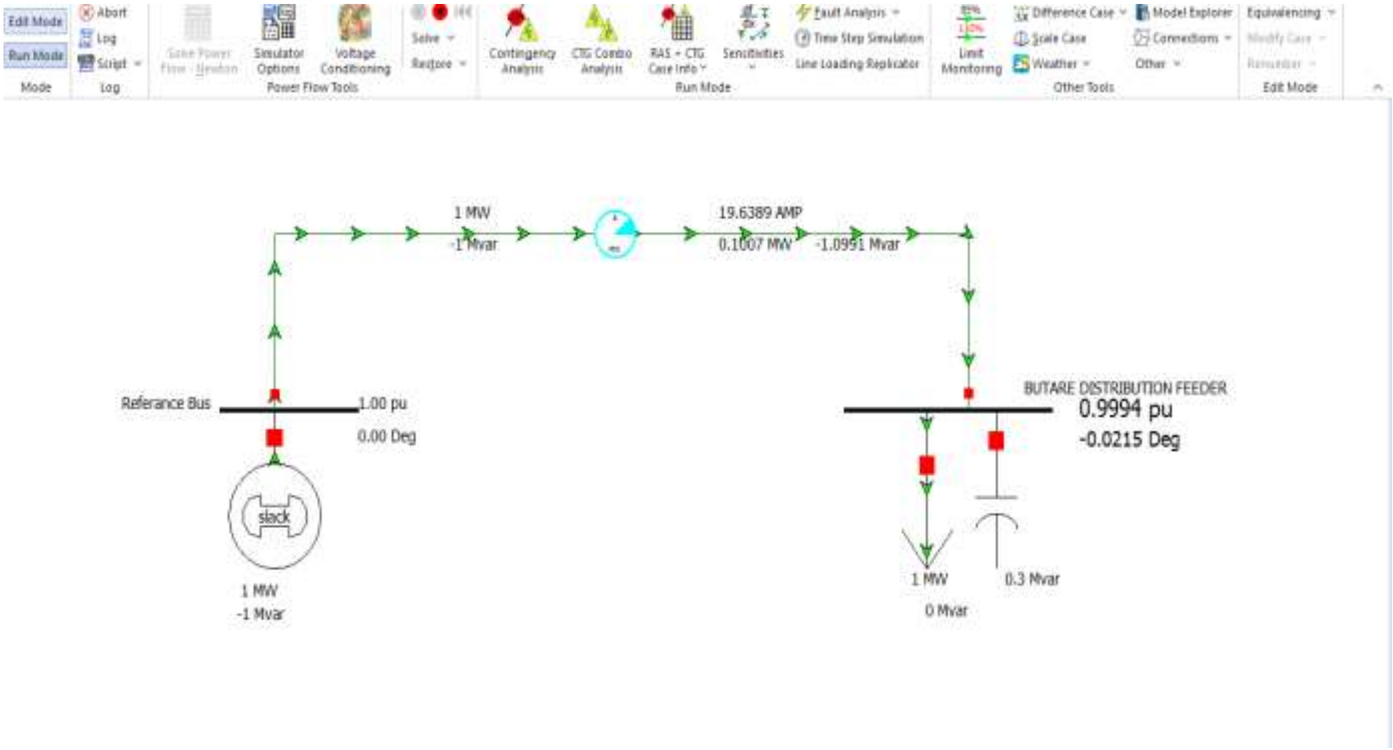


Figure 20:Simulation at 1MW load with compensator

The static Var compensator inject 0.3Mvar as the reactive power into the system via the bus bar connected in parallel to the load. In normal operating conditions, in order to ensure the voltage control at the connection bus, the SVC operates within the linear control domain.

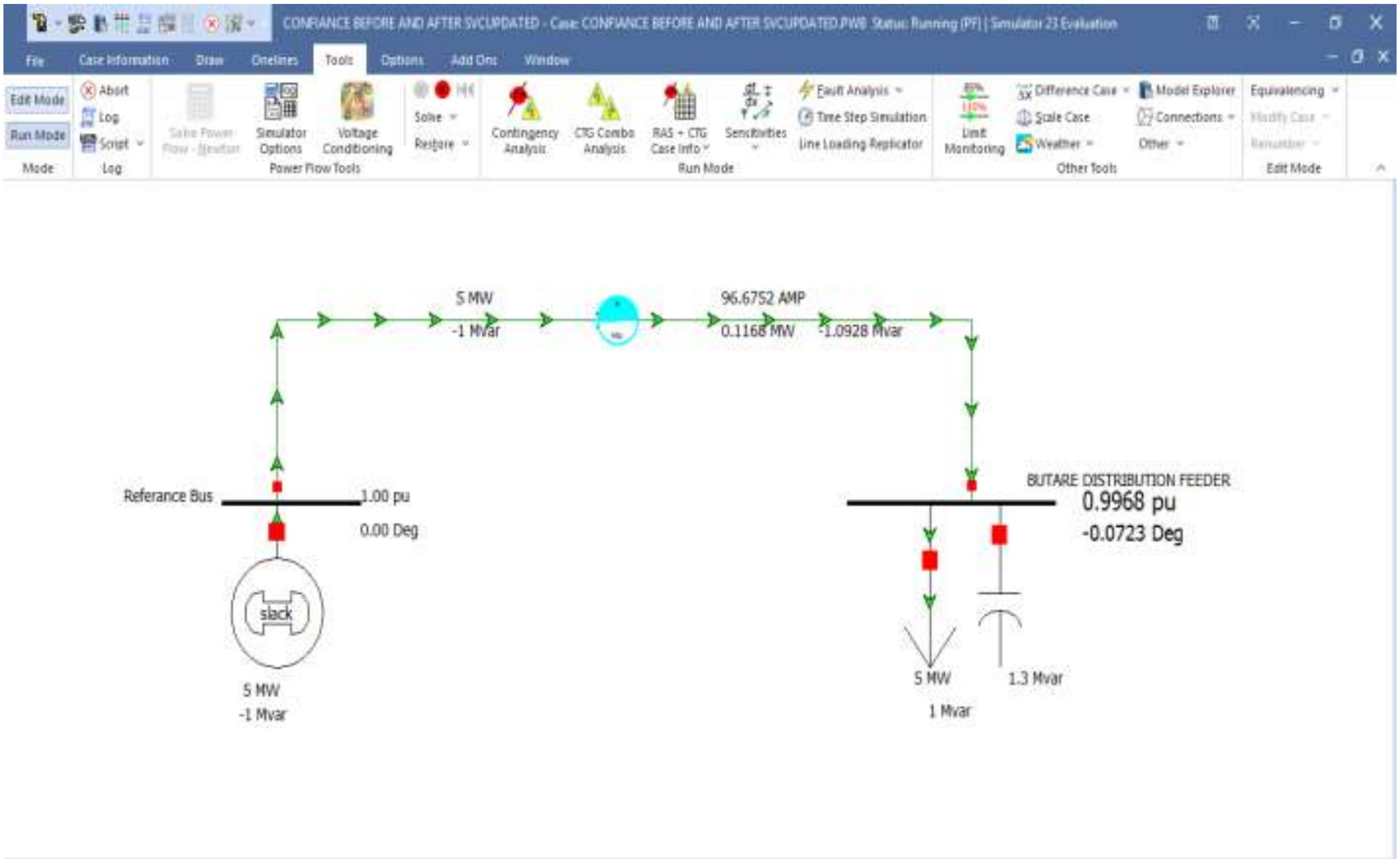


Figure 21:Simulation at 5MW load with compensator

The static Var compensator inject 1.3Mvar as the reactive power into the system via the bus bar connected in parallel to the load. In normal operating conditions, in order to ensure the voltage control at the connection bus, also the SVC operates within the linear control domain. means that SVC are set in auto mode as shown on figure 17.

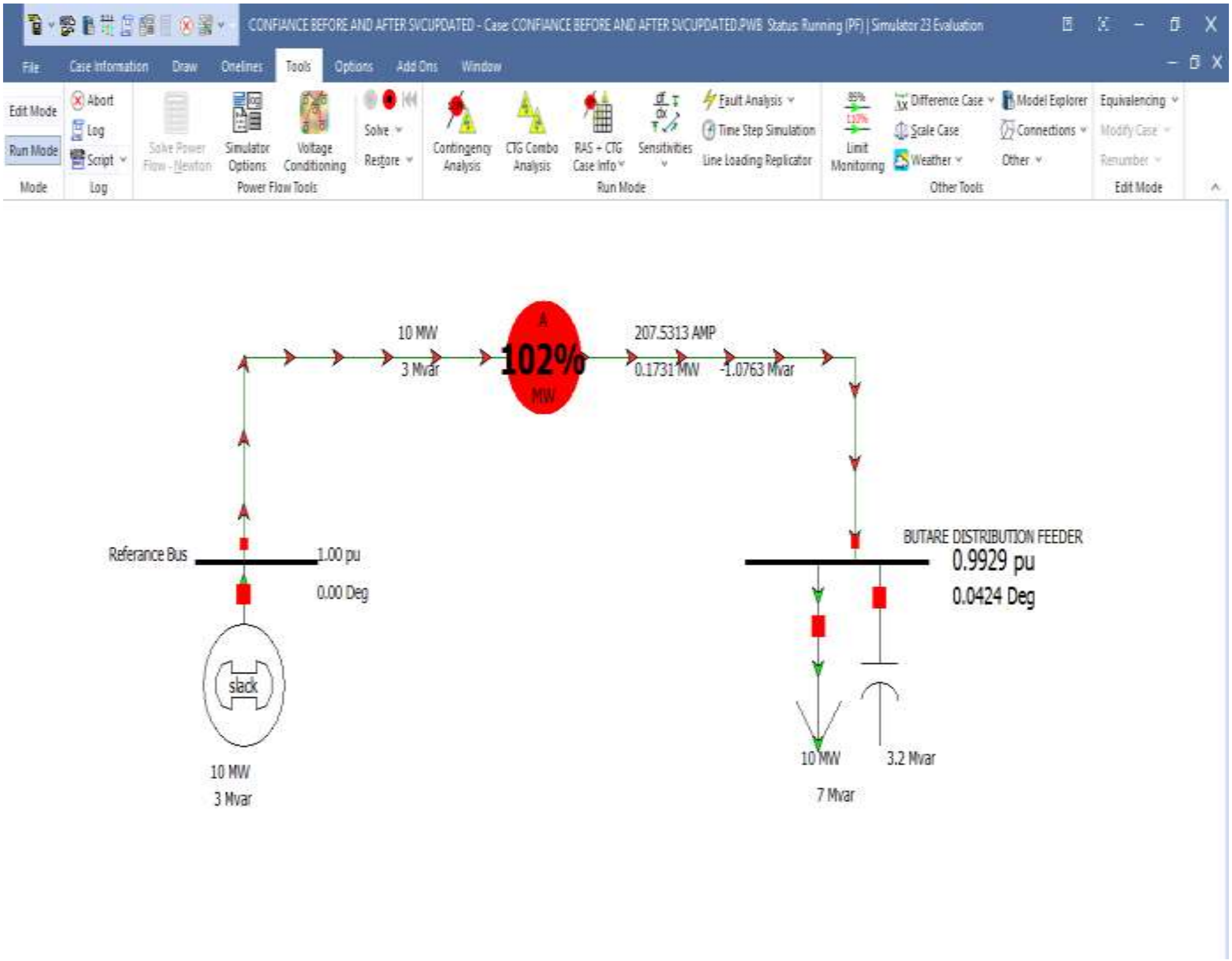


Figure 22:Simulation at 10MW load with compensator

4.2.1. Recorded Results

Table 4:Records before connecting compensation Device

SN	Active Power(MW)	Active Power Loss(MW)	Reactive Power(MVAR)	Reactive Power Loss(MVAR)	Line current(A)	Load Voltage(pu)
1	0	0.1002	0	-1.100	0.004	1
2	1	0.1007	0.5	-1.0991	21.5311	0.9993
3	2	0.1026	0.6	-1.0979	40.2376	0.9987
4	3	0.1059	0.8	-1.0964	59.8689	0.9980
5	4	0.1105	0.8	-1.0947	78.7149	0.9973
6	5	0.1165	1	-1.0927	98.4496	0.9966
7	6	0.125	2	-1.0899	122.2047	0.9958
8	7	0.1400	4	-1.0856	155.92	0.9949
9	8	0.1617	6	-1.0799	193.5891	0.9940
10	9	0.173	6	-1.173	209.5708	0.9933
11	10	0.1935	7	-1.0714	236.6078	0.9925

Table 5:Records After Inserting SVC

SN	Active Power(MW)	Active Power Loss(MW)	Reactive Power(MVAR)	Reactive Power Loss(MVAR)	Line current(A)	Load Voltage(pu)
1	0	0.01002	0	-1.100	0.004	1
2	1	0.01007	0.5	-1.0991	19.5668	0.9994
3	2	0.01029	0.6	-1.098	38.5311	0.9988
4	3	0.01062	0.8	-1.0965	57.9552	0.9981
5	4	0.01108	0.8	-1.0948	77.2551	0.9975
6	5	0.01168	1	-1.0928	96.6752	0.9968
7	6	0.01236	2	-1.0905	116.1682	0.9961
8	7	0.01336	4	-1.0872	141.9626	0.9952
9	8	0.01496	6	-1.0828	172.4267	0.9943
10	9	0.01577	6	-1.0805	184.4708	0.9937
11	10	0.01731	7	-1.0763	207.5329	0.9929

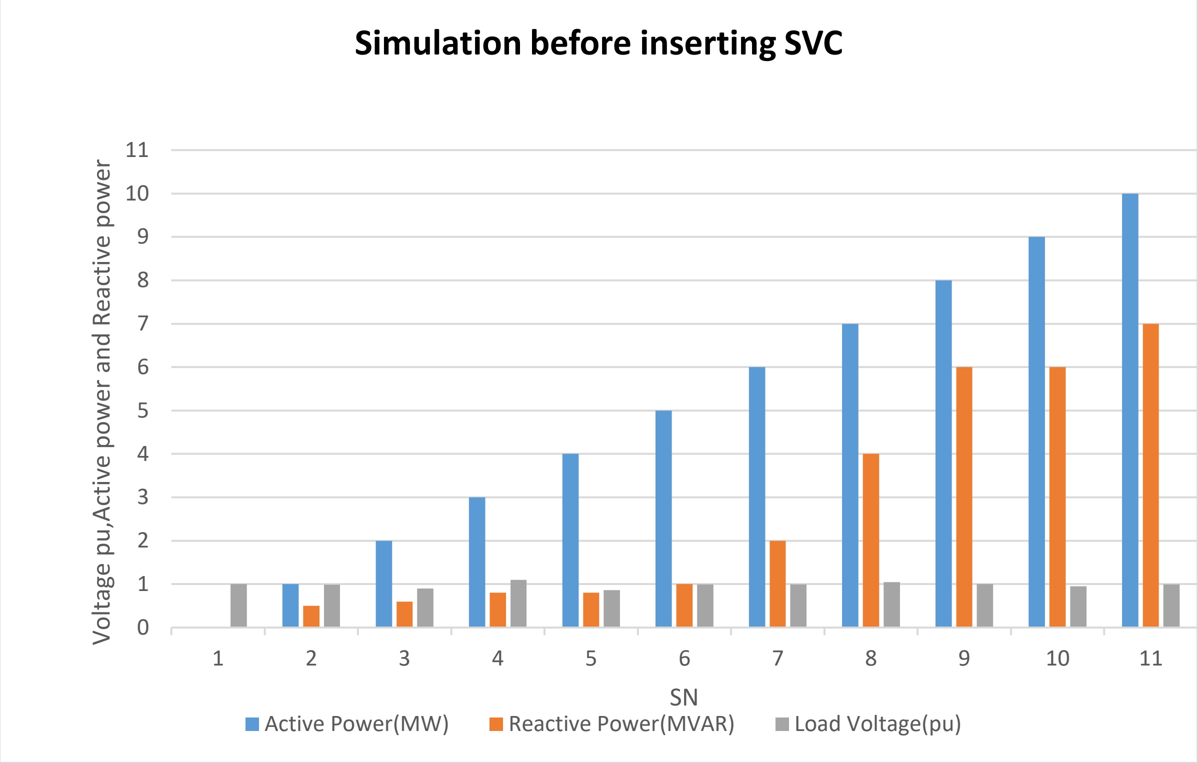


Figure 23:Real power, Reactive power and Load Voltage before Connecting SVC

From the above figure 23 the voltage at the feeder vary from 0.8 pu up to 1. 1 pu. The problem of improving the voltage profile and reducing power losses in electrical Distribution networks is a task that must be solved in an optimal manner, at present time, this optimality can be achieved by efficient usage of existing facilities alongside with installing FACTS devices. The static VAR compensator (SVC) was chosen for study as its maturity and durable solution.

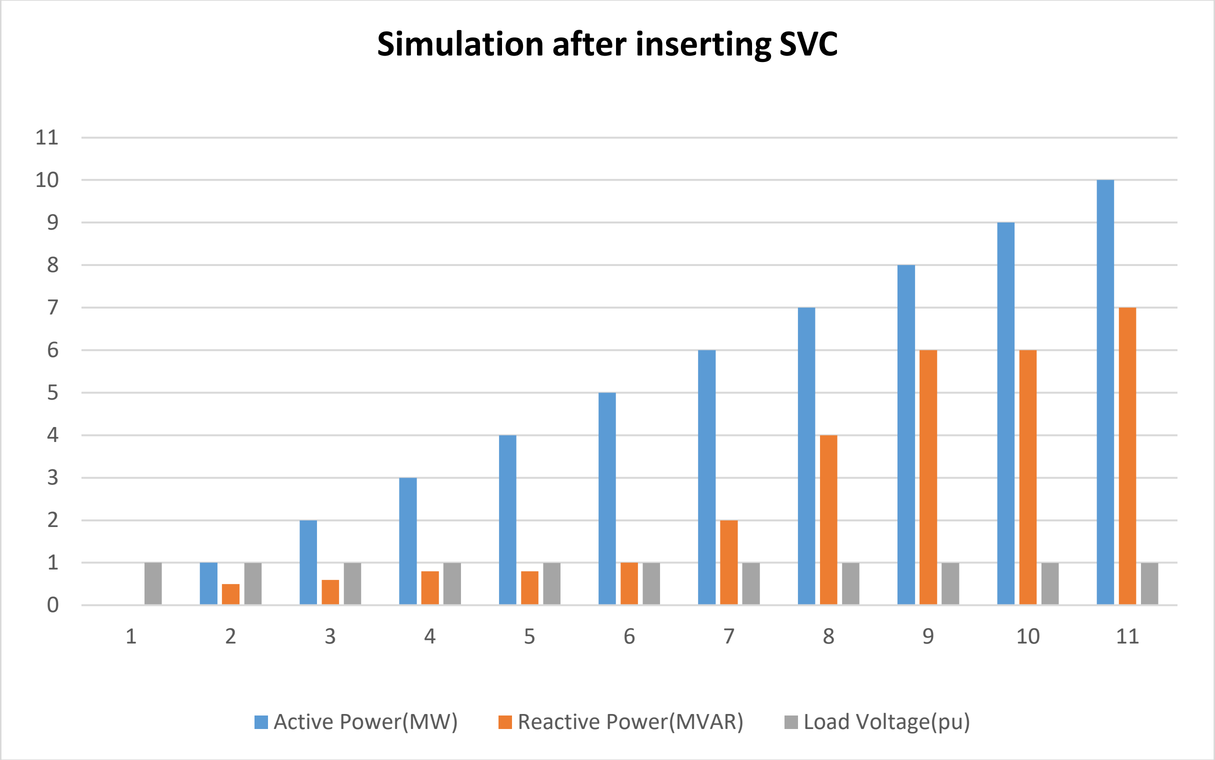


Figure 24:Real power, Reactive power and Load Voltage after Connecting SVC

The two case with SVC and without SVC as well as graphs is plotted for both cases. Graph for losses at respective distribution lines are plotted at figure26 which explains the advantage of SVC for reducing line losses that further increase distribution capacity of the system. After connecting the compensator, the voltage remains in acceptable limits like 0.99pu up to 1 pu. After Connecting the SVC, the line current was reduced from 110.6A up to 101.14 A by average and this reduce real active power losses from 125kw up to 14kw by average. The figure 4.9 and 4.10 represent the line current and active power loss respectively.

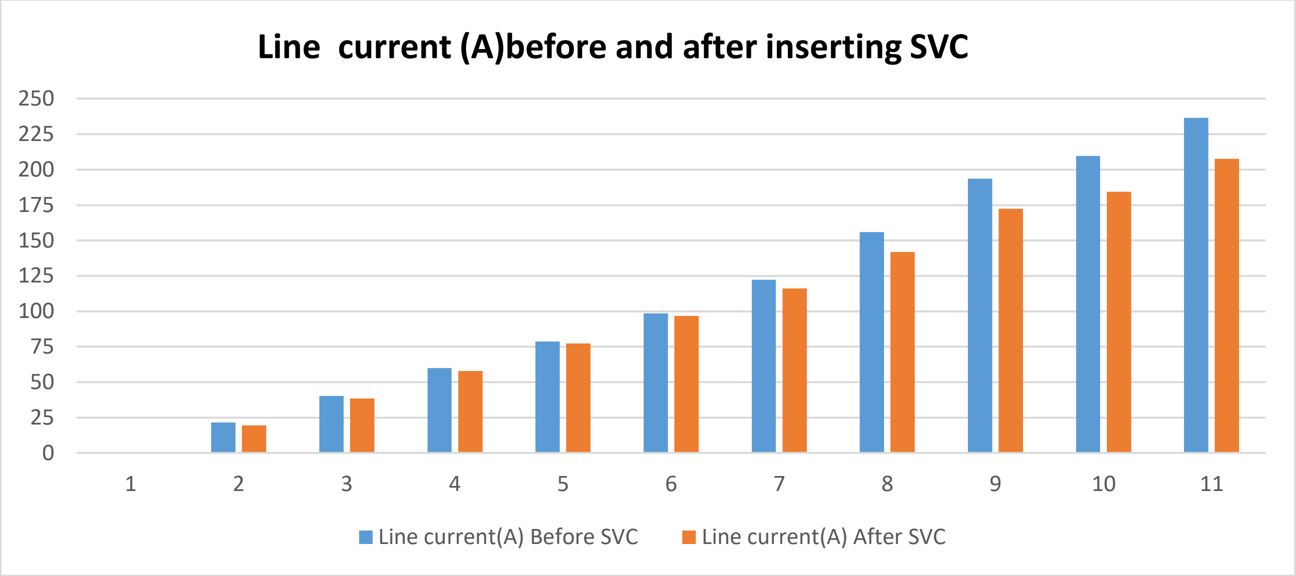


Figure 25:Line Current Before and After inserting SVC

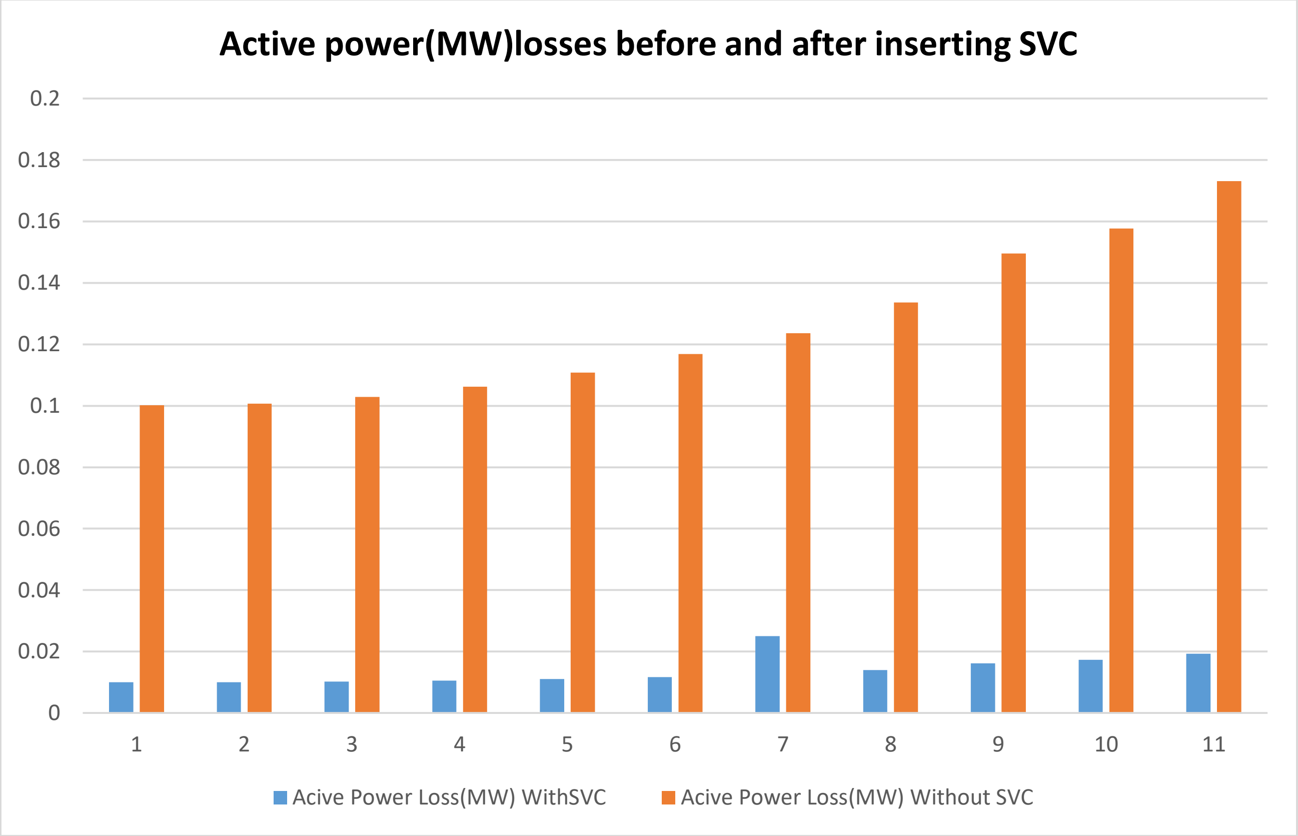


Figure 26:Power losses before and after inserting SVC

4.3 Feeder Power Losses

Due to the feeder's resistance, the power sent from the substation (considered as generation) get wasted along the feeder. It wasted in the form of heat, and this loss can be calculated as follows:

- Before inserting the SVC, the power loss will be calculated as
- $P_{loss} = 3 * R * I^2$ **(4.1)**

Where R is the resistance of the feeder and I is the current of the feeder before inserting SVC, as shown from the table3: the resistance per kilometer is 0.065Ω and the reactance of the feeder per kilometer is 0.413Ω and the feeder current is 630A.

Thus

$$R = \frac{0.065\Omega}{km} * 75km = 4.875\Omega$$

$$P_{loss} = 3 * R * I^2 = 3 * 4.875 * 630^2 = 5{,}804.6kW$$

- After inserting the SVC, the feeder current will reduce from 630A to 599.9A
  Thus $P_{loss} = 3 * R * I^2 = 3 * 4.875 * 599.9^2 = 5{,}263.24kW$

The Total power loss is reduced by $5{,}804.6kW - 5{,}263.24kW = 541.36kW$

The power has been reduced by 541.36kW or $\frac{541.36}{5{,}804.6} * 100 = 9.32\%$

4.3.1 Feeder Power Losses Before inserting SVC

- ✓ When the feeder is loaded by 125% of its nominal current i.e 125% of 630A

Thus,$I_N = 125\% * 630A = 787.5A$

And $P_{loss} = 3 * I^2 * R \cong 3 * 787.5^2 * 4.875 = 9{,}069.7kW$

$$P_N = \sqrt{3} * V_L I_L = \sqrt{3} * 30kV * 787.5A = 40{,}919.70kW \quad \textbf{(4.2)}$$

$$Percentage\ of\ Power\ Loss = \frac{P_L}{P_N} * 100 = \frac{9{,}069.7kW}{10{,}919.70kW} * 100 = 22.16\% \qquad \textbf{(4.3)}$$

- ✓ When the feeder is loaded by 100% of its nominal current i.e 100% of 630A

Thus,$I_N = 100\% * 630A = 630A$

And,$P_{loss} = 3 * I^2 * R \cong 3 * 630^2 * 4.875 = 5{,}804.6kW$

$$P_N = \sqrt{3} * V_L * I_L \cong \sqrt{3} * 30kV * 630 = 32{,}735.7kW$$

$$Percentage\ of\ power\ loss = \frac{P_{Loss}}{P_N} * 100 = \frac{5{,}804.6kW}{32{,}735.7kW} * 100 = 17.7\%$$

- ✓ When the feeder is loaded by 75% of its nominal current i.e 75% of 630A

Thus,$I_N = 75\% * 630A = 472.5A$

And,$P_{loss} = 3 * I^2 * R \cong 3 * 472.5^2 * 4.875 = 3{,}265.12kW$

$$P_N = \sqrt{3} * V_L * I_L \cong \sqrt{3} * 30kV * 472.5 = 24{,}551.8kW$$

$$Percentage\ of\ power\ loss = \frac{P_{Loss}}{P_N} * 100 = \frac{3{,}265.12kW}{24{,}551.8kW} * 100 = 13.2\%$$

- ✓ When the feeder is loaded by 50% of its nominal current i.e 50% of 630A

Thus,$I_N = 50\% * 630A = 315A$

And,$P_{loss} = 3 * I^2 * R \cong 3 * 315^2 * 4.875 = 1{,}451.16kW$

$$P_N = \sqrt{3} * V_L * I_L \cong \sqrt{3} * 30kV * 315 = 16{,}367.8kW$$

$$Percentage\ of\ power\ loss = \frac{P_{Loss}}{P_N} * 100 = \frac{1{,}451.16kW}{16{,}367.8kW} * 100 = 8.8\%$$

4.3.2 Feeder Power Losses After inserting SVC

- ✓ When the feeder is loaded by 125% of its nominal current i.e 125% of 599.9A

Thus,$I_N = 125\% * 599.9A = 749.8A$

And, $P_{loss} = 3 * I^2 * R \cong 3 * 749.8^2 * 4.875 = 8{,}222.17kW$

$P_N = \sqrt{3} * V_L * I_L \cong \sqrt{3} * 30kV * 749.8 = 38{,}960.7kW$

$$Percentage\ power\ loss = \frac{P_{Loss}}{P_N} * 100 = \frac{8{,}222.17kW}{38{,}960.7kW} * 100 = 21.10\%$$

- ✓ When the feeder is loaded by 100% of its nominal current i.e 100% of 599.9A

Thus,$I_N = 100\% * 599.9A = 599.9A$

And, $P_{loss} = 3 * I^2 * R \cong 3 * 599.9^2 * 4.875 = 5{,}263.24kW$

$P_N = \sqrt{3} * V_L * I_L \cong \sqrt{3} * 30kV * 599.9 = 31{,}171.71kW$

$$Percentage\ power\ loss = \frac{P_{Loss}}{P_N} * 100 = \frac{5{,}263.24kW}{31171.71kW} * 100 = 16.8\%$$

- ✓ When the feeder is loaded by 75% of its nominal current i.e 75% of 599.9A

Thus,$I_N = 75\% * 599.9A = 449.9A$

And, $P_{loss} = 3 * I^2 * R \cong 3 * 449.9^2 * 4.875 = 2{,}960.24kW$

$P_N = \sqrt{3} * V_L * I_L \cong \sqrt{3} * 30kV * 449.9 = 23{,}377.48kW$

$$Percentage\ power\ loss = \frac{P_{Loss}}{P_N} * 100 = \frac{2{,}960.24kW}{23{,}377.48kW} * 100 = 12.66\%$$

- ✓ When the feeder is loaded by 50% of its nominal current i.e 50% of 599.9A

Thus,$I_N = 75\% * 599.9A = 299.95A$

And, $P_{loss} = 3 * I^2 * R \cong 3 * 299.95^2 * 4.875 = 1{,}315.8kW$

$$P_N = \sqrt{3} * V_L * I_L \cong \sqrt{3} * 30kV * 299.95 = 15{,}585.8kW$$

$$Percentage\ power\ loss = \frac{P_{Loss}}{P_N} * 100 = \frac{1{,}315.8kW}{15{,}585.8kW} * 100 = 8.4\%$$

Table 6: Comparison of feeder Load losses before and after inserting of SVC

S/N	P_n(Kw)	P_i(Kw)	Loading Percentage (%)	Percentage loss Without SVC	Percentage loss With SVC
1	16,368	1,451	50%	9%	8%
2	24,552	3,266	75%	13%	12%
3	32,736	5,805	100%	18%	17%
4	40,920	9,070	125%	22%	21%

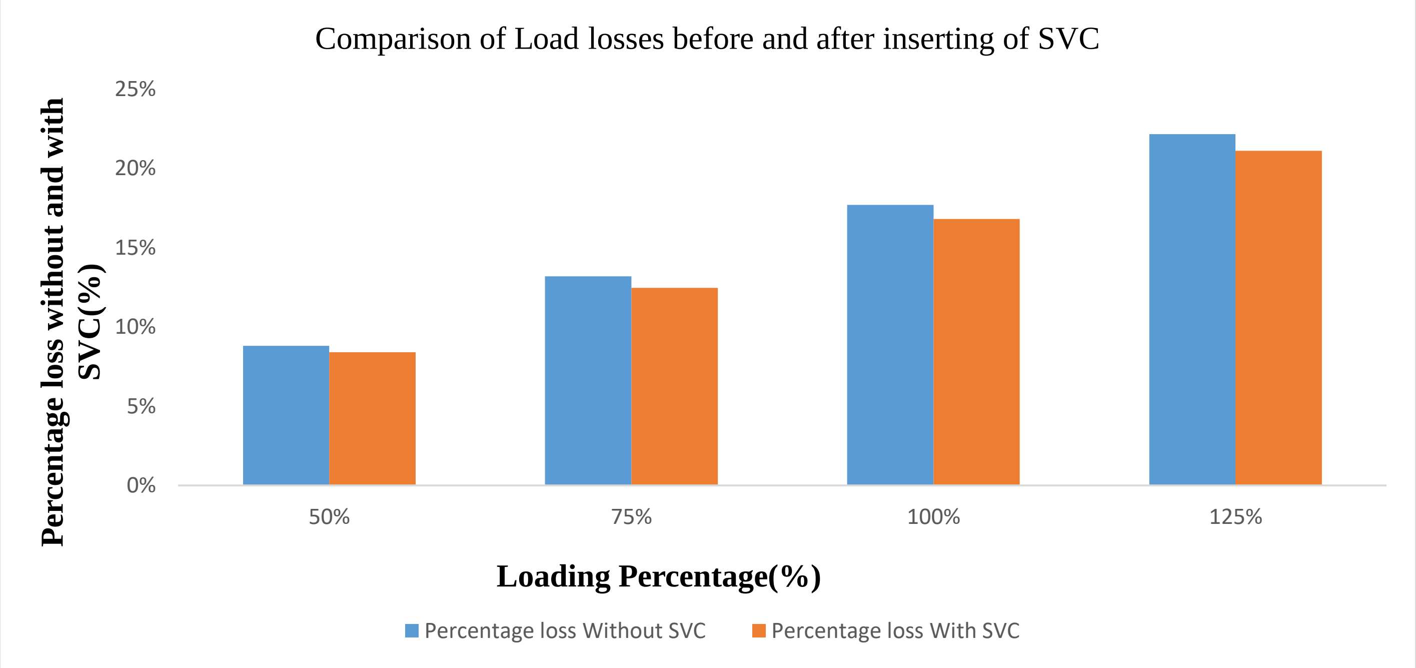


Figure 27:Comparison of feeder Load losses before and after inserting of SVC

4.4 Result and Discussions

From the above table and figure (i.e. Table 5 & Figure 17), it can be seen that when the Static Var Compensator(SVC) is connected to the Butare feeder, the voltage profile will remain in the acceptable range as well as power losses will be reduced. The increase or decrease in the voltage are because of the load demand, impedance and the length of the feeder

CHAPTER FIVE

CONCLUSION AND RECOMMENDATION

5.1. Conclusion

The electrical power flow in the network consists of two types of power namely real measured in watts and reactive power measured in volt-ampere reactive. The real or active power does the useful work such as lightings lamps, heating the furnaces, running the motors, and the reactive power supports the voltage. The source and sinks of reactive power are used to generate or consume reactive power to control the reactive power in the network. These are for example; capacitor, shunt reactors, synchronous condensers, FACT devices, etc. When reactive power is not controlled the losses may increase in the network.

In this study, the various power quality issues are discussed. The voltage profile of Butare feeder from Kigoma substation has been studied and simulated with and without Static Var Compensator using Power world simulator.

It was proved that when the Static Var Compensator (SVC) is placed at the feeder's bus, it improves the voltage profile to 1pu or closer to 1pu and the power losses. Finally, from the result obtained it can be concluded that the use of the Static Var Compensator in the feeder improves the power quality thereby meeting the objective of this study.

5.2. Recommendation

One of the major issues of power quality is voltage fluctuation whenever the reactive power varies from the variation of load. By application of SVC, the voltage profile of Butare Feeder can be improved practically.

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