IMPROVEMENT OF DISTRIBUTION VOLTAGE PROFILE AND SYSTEM EFFICIENCY USING STATIC SYNCHRONOUS COMPENSATOR

A Case Study of Kigali Distribution Feeder

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DECLARATION

I declare that this Dissertation contains my original work except where it has acknowledged, and it was passed through the anti-plagiarism software and found to be in acceptable margin.

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Date: 08.11. 2021

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ABSTRACT

The operation and management of power system has become complex than earlier because the power system is being operated near or closer to its operating limits due to the increasing of electricity demand. This is associated with problem of poor power system stability, reliability and efficiency. This thesis takes into consideration a case study of Kigali distribution feeder from Jabana substation which suffers from poor voltage profile; the problem is that when all major loads are connected, the voltage profile tends to fall below the minimum operating range and when the system is loaded with low load the voltage profile tends to go beyond the maximum allowed operating range. This leads to increased power system losses, poor reliability and poor performance of customers' appliances. To mitigate this issue, this thesis dissertation presents a design of static synchronous compensator of 3.2MVA to improve the operating voltage profile of 0.88-1.11p.u and brings back in normal allowed operating range (0.93pu and 1.08pu) respectively and increase system efficiency by reducing the line losses by 16.7% or 215kW.

Key words: *static synchronous compensator, voltage profile, distribution feeder.*

LIST OF ACRONYMS

MW: Megawatt
REG: Rwanda Energy Group
kV: kilovolt
Km: kilometer
STATCOM: Static Synchronous Compensator
V: Volt
AC: Alternating Current
FACTs: Flexible AC Transmission devices
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
SVC: Static Var Compensator
TCR: Thyristor Controlled Reactor
UPFC: Unified Power Flow Controller
VSI: Voltage Source Inverter
VSC: Voltage Source Converter
DC: Direct Current
MVA: Megavolt Ampere
UTEXRWA: Usine de Textile du Rwanda
TPP: Thermal Power Plant
A: Ampere
kW: kilowatt
kVar: kilovolt ampere reactive
kVA: kilovolt Ampere
Hz: Hertz
µF: microfarad
mH: milliHenry

LIST OF SYMBOLS USED

S: apparent power expressed in VA

Q: reactive power expressed in Var

P: active power expressed in watt

Cosδ: power factor

δ: phase angle

%: percentage

I: current expressed in Ampere

V: voltage expressed in volts or per unit

C: capacitance expressed in Farad

L: inductance expressed in Henrys

Xc: capacitive reactance expressed in ohms

X_L: inductive reactance expressed in ohms

f: frequency expressed in Hertz

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CHAPTER ONE

1. Introduction

This chapter gives a brief background on the energy distribution in Rwanda. It then talks about the problem statement of the research, its objectives, scope of study and the expected outcomes.

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. Rwanda has natural energy resources which include hydropower plants, solar power plants, and methane gas power plants. Currently, the generation capacity in Rwanda is 238.36MW.

According to the Rwanda Energy Group (REG), Rwanda’s national electrification rate as of August 2021 is estimated at 66.8 %(48.4% connected on national grid and 18.4% are connected through off grid). The transmission network is composed of two main voltage levels: 110 and 220kV. Transmission lines are covering 744.7km and many projects are going on. These lines are evacuating power from generation stations as well as facilitating regional interconnections. The total network laid so far 480.4 km (64.5%) are 110 kV and 264.3km (35.5%) are 220kV transmission lines [1].

The distribution network is composed of different 49 sub-stations (high and medium voltage) that include: Ntaruka, Mukungwa, Gifurwe, Rulindo (in Kigali), Musha, Kabarondo, Rwinkwavu (in the East), Kigoma, Kilinda, Karongi, Kibogora, Mururu1, Mururu2 (in the South), Gahanga, Rwabusoro, Nzove, Shango, Ntendezi, Mashyuza, Bugesera, Mont Kigali, etc.

The electricity demand is increasing rapidly due to the electrification of rural and urban areas in Rwanda, industrial zone such as Masoro, free zone, Rwamagana industrial park. A large amount of energy is wasted in the power transmission and distribution process to the end users, about 13% of generated power is wasted during the distribution process only. This power loss is in some cases due to the voltage drop in transmission lines as well as in distribution lines and this reduces the efficiency, reliability of power system. In electric power system, significantly voltage change can be much affected by the load variation and the network topology changes. So it is very necessary to correct the voltage profile of distribution system to prevent power wastage [2].

Modern power systems consist of large, complex interconnected number of buses, generators, transformers, transmission lines and loads. Thus, the current power systems are much more loaded than before. The higher the inductive loads, the more the reactive power or voltage tends to drop and also the losses on the system increases. Any power problem manifested in voltage or current deviations results in failure and malfunction of customer equipment.

1.2 Problem Statement

Electrical power systems play a very important role in the development of industries and social economic development of any country. In Rwanda, load demand has been increasing while expansion of generation and transmission is limited by their high cost and limited resources. This increase in load demand leads to low voltage profile and an increase of power losses. The situation is such that during the times of light load the voltage profile goes beyond the normal range (110% of rated voltage) and during the times of heavy power system loads the voltage profile falls down. In Jabana I substation, voltage is low during the day and becomes high during the night when major loads are off. As a result, the system which operates at voltage that is not in range causes voltage instability and can lead to total system failure of blackout. To improve the voltage profile and minimize power losses a scientific solution is required.

1.3 Objectives

1.3.1 Main Objective

This study aims at improving the voltage profile in Kigali distribution feeder from Jabana I substation by designing a static synchronous compensator (STATCOM) that will be compensating the reactive power to the system when the voltage goes out of normal operating range.

1.3.2 Specific Objectives

The specific objectives to be achieved with the research are as listed below:

- Data collection on the voltage profile of the distribution system in Jabana I distribution feeders in Kigali;
- Data analysis, interpretation and comparison with standards;
- Size the right STATCOM for mitigating the poor voltage profile;
- Modell and simulate the system with and without STATCOM;
- Draw relevant conclusions and recommendation for potential implementation.

1.4 Scope of the Study

In this study, a STATCOM is designed for Jabana I distribution substation in Kigali for improving voltage profile of Kigali feeder. Simulation of the system with and without STATCOM was done using power world simulator tool. Relevant conclusions and recommendations were drawn.

1.5 Expected Outcomes and Significance of the Study

1.5.1 Expected Outcomes Study

The outcome of this research is a report of the study on the improvement voltage profile for Kigali feeder from Jabana I substation in Kigali.

1.5.2 Significance of the Study

This research will help to improve voltage profile and improve system reliability in Kigali distribution feeder from Jabana I substation.

1.6 Organization of the Study

This study is composed of 5 chapters:

1. Chapter one is the introduction which tackles the introduction, the problem statement, research methodology, scope of the study, the objectives of the study;
2. Chapter two is concerned with the literature review of other researchers for similar case; it talks about static synchronous compensator that has been used in this study;
3. Chapter three tackles the feeder's data collected during this research and interprets them;
4. Chapter four talks about simulation of the system without the compensating device and thereafter the simulation of the system after inserting the STATCOM;
5. Chapter five is related with conclusion and possible recommendation for further implementation.

CHAPTER TWO: THEORETICAL BACKGROUND AND LITERATURE REVIEW

2.1 Background of Distribution Systems

Power distribution had become necessary only in 1880s when electricity was being generated at power plants. Before that electricity was usually generated where it was used. Electrical power distribution system is the stage where the electricity is delivered to end users. The distribution substations are connected to the transmission lines and they step down the voltage to medium or low voltage by using step down distribution transformers [3].

2.2 Types of Distribution Systems

The distribution systems are classified into two types: radial and interconnected networks. A radial system starts from the generating station or from the substation and passes through the network area without any connection to any other supply. This is in most cases happening in long distribution lines supplying rural areas. The interconnected system in its behavior, has multiple connections to more than one supply [4]. From this system, configurations are performed by network operators by closing to some supply and opening switches connecting to other supply. Operation of the switching devices may be performed locally or remotely from control center. The benefit of interconnected arrangement is that in case of fault occurrence or in case of required maintenance, a portion of customers may be isolated and the rest remain connected. Distribution systems are also classified based on their operating voltage:

2.2.1 Primary Distribution Systems

They consist of medium voltage (33 and 15kV) network from primary and sub primary substations. These substations are interconnected with high voltage transmission lines. In most cases, large consumers like different factories such as refineries, breweries, flour mills, and steel rolling mills take supply at primary distribution system with associated transformers, switchgears and breakers.

2.2.2 Secondary Distribution Systems

They consist of low voltage (400V) networks from transformer’s secondary. The connections are made to individual consumers by service cables from these network feeder lines. The various system of alternating current distribution for domestic consumers include: Single-phase 2-wire system, Single-phase 3-wiresystem, Three-phase 4-wire system. Of these, the single phase, 2-wires and the three phase 4-wire system are predominant.

2.3 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 [5].

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.

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 STATCOM.

2.4 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 [6]. Traditional methods of solving these problems were using fixed and mechanical switches such as series and shunt capacitors, shunt reactors and synchronous generators. Moreover, the desired response was not effective due to slower response, wear and tear of mechanical devices.

After invention of power electronics devices like thyristor, insulated gate bipolar transistors, the electronic converters were developed and led to the implementation of FACT controllers. These controllers provide smooth, continuous and rapid operations for power system control.

They improve the performance of electrical network by controlling the active and reactive power flow. FACTS devices increase power transfer capability, stability and controllability of the network through series or shunt compensation. These devices are also employed for loss minimization.

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 compensation techniques include generating or absorbing reactive at point it is necessary.

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.

The FACT controllers are classified as:

- ***Shunt connected controllers***: They inject current at node; when this current is in phase quadrature with line voltage, the controller consumes or supplies variable reactive power to the network. Examples of the shunt controllers include thyristor controlled Reactor, Static synchronous compensator, thyristor switched reactor and thyristor switched capacitor.
- ***Series connected controllers***: These controllers inject a voltage in series with the line. If the injected voltage is in phase quadrature with current, the device generates or consumes a variable reactive power to or from the network. These devices can be variable impedance such as a reactor or capacitor or a power electronics based variable source. Examples for the series controllers are SSSC, TCSR and TSSC.
- ***Combines series series controllers***: they are combination of the individual series devices. They can be a unified controller in which separate series devices are used in each line for series reactive power compensation and also to transfer the active power among the lines through a proper link.

- ***Combined shunt-series controllers***: They combine a separate series and a shunt device. They do inject the current into the system with series part of controller and voltage in series with shunt part of the device. Examples: TCPST and TCPAR [7].

2.5 Choice of FACT Devices

The application of FACTs controllers to the solution of steady-state operating problem is outlined in table below:

Table 2. 1: Choice of FACT Controller [8]

Problem	Corrective action	FACT controller to be used
1)Voltage limit:		
• Low voltage profile at heavy system load	• Supply variable reactive power	• SVC, STATCOM
• High voltage profile at load system demand	• Absorb reactive power	• STATCOM, TCR, SVC
• High voltage following an outage	• Absorb reactive power	• STATCOM, SVC, TCR
• Low voltage profile after an outage	• supply reactive power; prevent overload	• STATCOM,SVC
2)Thermal limits:		
• Transmission/distribution circuit overload	• Reduce overload	• TCSC, SSSC, UPFC
• Tripping of parallel circuit	• Limit circuit loading	• TCSC,SSSC,UPFC

2.6 Description of the Static Synchronous Compensator (STATCOM)

The static synchronous compensator is a voltage source inverter that converts a direct current input voltage into alternating current output voltage in order to compensate the needed reactive power. It is a shunt controller used on alternating current transmission and distribution networks. It is able to generate or absorb reactive power to or from the grid and its output can be varied to control some power parameters.

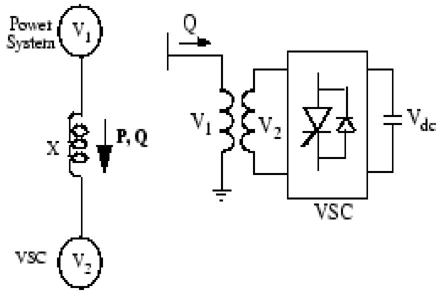

Figure 2. 1: Basic Configuration of STATCOM

Let the voltage at the sending end be V_1,the voltage at the receiving end(node) be V_2. The reactance of the line is X;the angle of V_1 with respect to V_2 is δ. The power that can be transmitted is:

$$P=\frac{VI*V2sin\delta}{X} \tag{1}$$

$$Q=\frac{V1(V1-V2)COS\delta}{X} \tag{2}$$

In steady state operation, the voltage V_2 is in phase with V_1(δ is zero) and the active power is zero.

If V_2 is higher than V_1, Q flows from V_1 to V_2 and in that case the STATCOM is absorbing reactive power.

On the other hand, if V_1 is higher that V_2,Q flows from V_2 to V_1 and the STATCOM is generating reactive power.

The amount of reactive power flow is: $Q=\frac{V1\,(V1-V2)}{X}$ (3).

STATCOM is a member of FACTS devices used for voltage profile improvement. It makes use of VSC to inject a compensation current of variable magnitude and frequency into the system at the bus. It is thus a three phase VSC with capacitance on its DC link. Static synchronous compensator is thus a solid state converter able for generation or absorption of reactive power at its output when it is fed from an energy source.

STATCOM has no moving parts; hence, it generates or absorbs reactive power at a faster rate than other FACTS devices. It is capable of generating as well as absorbing reactive power thereby regulating the voltage profile of the bus to which it is connected.

2.7 Components of STATCOM

The basic configuration of a STATCOM consists of:

- Coupling transformer;
- Harmonic filter;
- Voltage source converter or current source converter;
- DC link capacitor.

The coupling transformer provides inductive reactance and it connects the output of the inverter to the power system. The harmonic filter is used to reduce harmonics. In the inverter high frequency harmonics are generated and they are filtered by this harmonic filter to maintain power quality.

The voltage source converter or current source converter are used to convert DC voltage into AC voltage that is then supplied to the system.

The DC voltage is supplied from a capacitor or capacitor bank and the output is the AC voltage which supplied to the system via a coupling transformer.

The voltage source converter has many advantages like:

- Simple interface with AC system;
- Provides continuous AC voltage regulation;
- No commutation failure;
- Variable frequency;
- Control of active and reactive power;
- Operation in a weak system.

Presently the most used FACT devices are voltage source converted based. The following are the reasons:

- Current source converters require power semiconductors with bi directional voltage blocking capability;
- The current source converter requires capacitor at its AC terminals while the voltage source converter requires the reactors which may be naturally provided by leakage inductance of the coupling transformer;
- The current source converter DC link has more loss compared to voltage source converter DC link

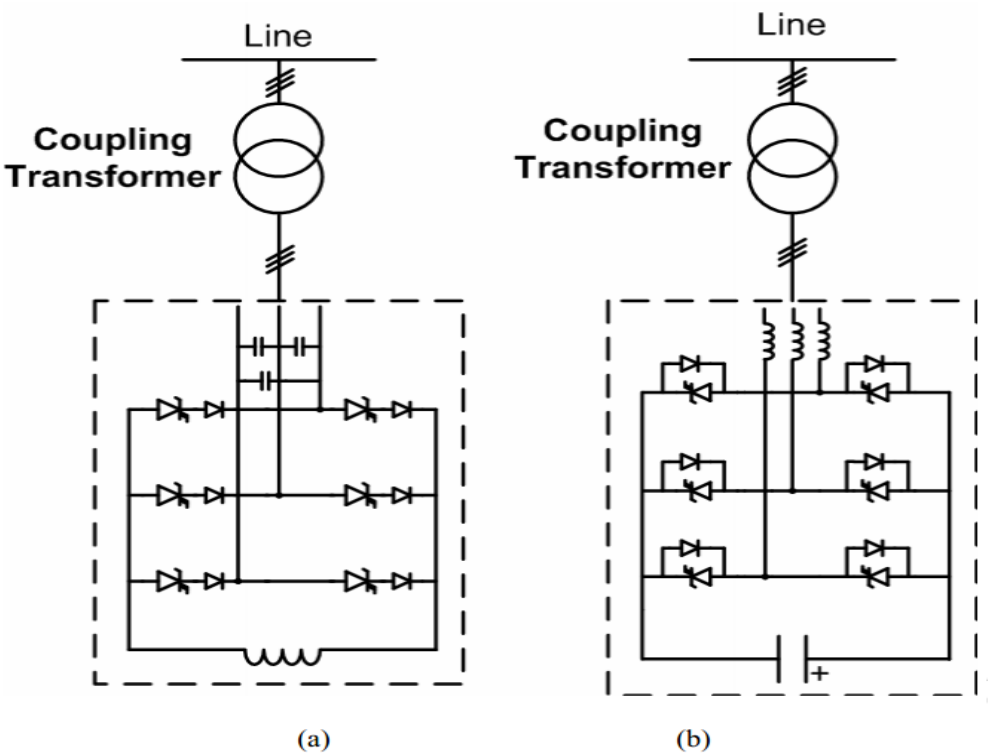

Figure 2. 2: Current Source Converter (a) and Voltage Source Converter (b)

The above figure shows the configuration of a current source converter and voltage source converter. The DC link capacitor of the voltage source converter is a load balancing energy storage device.

2.8 Reason for Selection of STATCOM among Other FACT Devices

Static synchronous compensator (STATCOM) is a shunt FACT device which is connected on the transmission or distribution system's bus. It is a second generation FACT device that can control voltage at the require bus and hence improves 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. Static Synchronous Compensator (STATCOM) has a very promising future application. STATCOM has several advantages:

- It is small/compact and requires less spare;
- Faster response to the network;
- Less harmonic pollution;
- This device is static, which means it does not have rotating and mobile components.

In addition,

- This device is more flexible, balancing phases, eliminating extra voltage, fast operation;
- Low maintenance cost, simple control;
- Prevention of voltage collapse, improving power factor, improving power quality and eliminating harmonics;
- It can be interfaced with active devices such as batteries;
- It has no problem of loss of synchronism under major disturbances/it remains connected with the system.

2.9 Permissible Voltage Drop

Permissible voltage drop necessary to regulate the voltage in order to ensure that these drops stay within a permissible range. High voltage drops below the permissible level, can have many negative consequences. When inductive loads are operated below their rated voltage; they tend to overheat and consume more power. It requires that the voltage available at the consumer's meter terminals should be within range 380/220V±10%. The guidelines for permissible voltage drops under emergency operation conditions as shown in Table below:

Table 2. 2: Permissible Operating Voltage Levels

Nominal Voltage	**Lowest service Voltage**	**Highest Service Voltage**
15kV	13.5kV (-10%)	16.5kV (+10%)
380V	342V (-10%)	418V (+10%)
220V	198V (-10%)	242(+10%)

2.10 Review of Literatures

In literature, a large number of publications have been made on the various aspects of power distribution network system. Quite a number of such publications have been consulted which serve as a guide towards achieving the aim and objectives of the research work. Some of these publications are summarized below:

In 2021 Jaiswal et al [12] presented a paper analyzing the operating Strategies optimization of STATCOM for improvement of voltage profile; the studies showed that during the heavily loaded condition, the voltage stability problem becomes very critical. They proposed that in order to mitigate that issue, an optimal location in the network has to be identified to connect a static synchronous compensator (STATCOM) to achieve a healthy voltage profile resulting in an increase in voltage security.

In 2021, EDEH et al [13] presented a paper analyzing the voltage profile improvement of Nigeria 330kV Power System Using STATCOM device. They showed that due to the population growth, the demand of electricity is increasing continuously. The losses in the system have continued to increase thereby limiting the amount of power that can be delivered to the community. They showed an example of Nigeria where about 40% of power is wasted during transmission. They had also proposed a mitigation method to overcome that issue where after analysis the buses at which the STATCOM were installed experienced an improvement in the voltage profile, ensuring stability, reliability and more controllability of the system.

In 2020, Mezigebu Getinet Yenealem et al [14], did a study that had objective of integrating micro grid system with STATCOM (static synchronous compensator) controller to ensure the higher power flow with enhanced voltage profile and reduced power loss. It was observed that with the STATCOM
Connected to the main distribution system raises the capacity of the distribution line and contributes to voltage profile improvements and power loss reduction.

In 2019, Aadesh Kumar Arya et al [15], presented a paper proposing the accurate placement and size of distribution STATCOM for power loss reduction, voltage profile improvement and annual energy saving. They found that the best performance was achieved with the proposed method.

Moreover, in 2021 Umamaheswararao [16], had conducted a research aiming at improving power quality in a three phase three wire system with a non-linear load using a static synchronous compensator. He concluded that the STATCOM gives better and effective compensation for reactive power variation and hence power quality of distribution system.

CHAPTER THREE: DATA ANALYSIS AND INTERPRETATION

This chapter tackles the site selection for the study. It then talks about the data obtained from Jabana substation and their interpretation.

3.1 Jabana Substation Description

Jabana 1 substation is located at the geographical coordinates of -1.890517, 30.066007. It is fed from Jabana 1 and 2 thermal power stations, Mukungwa, Ntaruka and different micro hydro power plants from the north of the country through 110kV. The 110kV voltage level is stepped down through 2power transformers 110/15kV, 10MVA each. There are different 110kV feeders: Birembo 110kV, Gikondo 110kV going to the national control center, Mount Kigali 110kV. In addition, there are five medium voltage outgoing feeders in total; Kigali feeder, Rutongo feeder, Sucrerie feeder, UTEXRWA feeder and D.W feeder and their nominal voltage is 15 kV.

Figure 3. 1: Google map of JABANA Substation

The feeder under study is Kigali 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.

Figure 3. 2: Photo Image for Jabana Substation

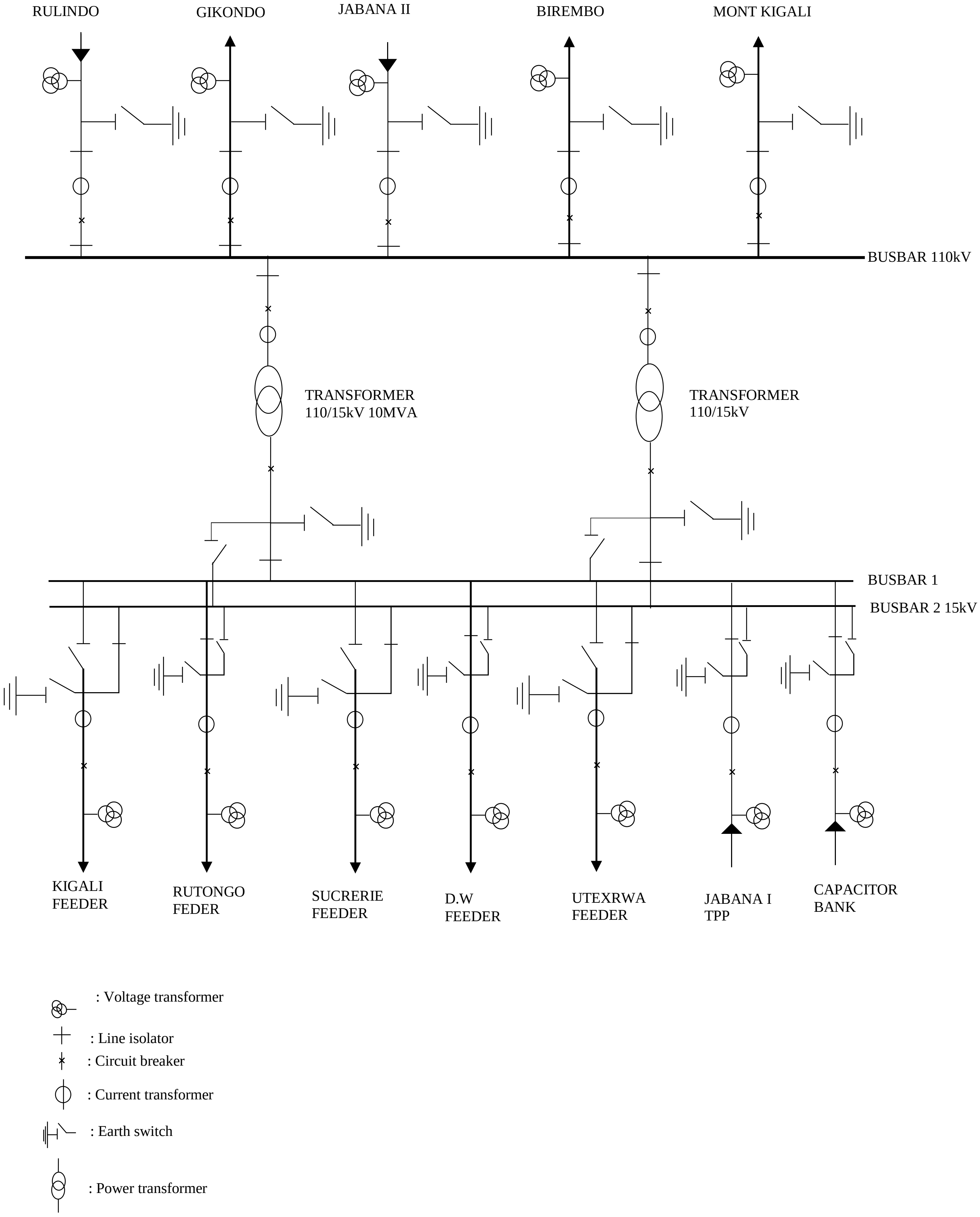

Figure 3. 3: Jabana Substation Single Line Diagram

3.2 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 Kigali feeder (active power), reactive power, power factor, voltage of the feeder. The sampling interval was once a month from August 2020 to July 2021 namely the 1st date of each month.

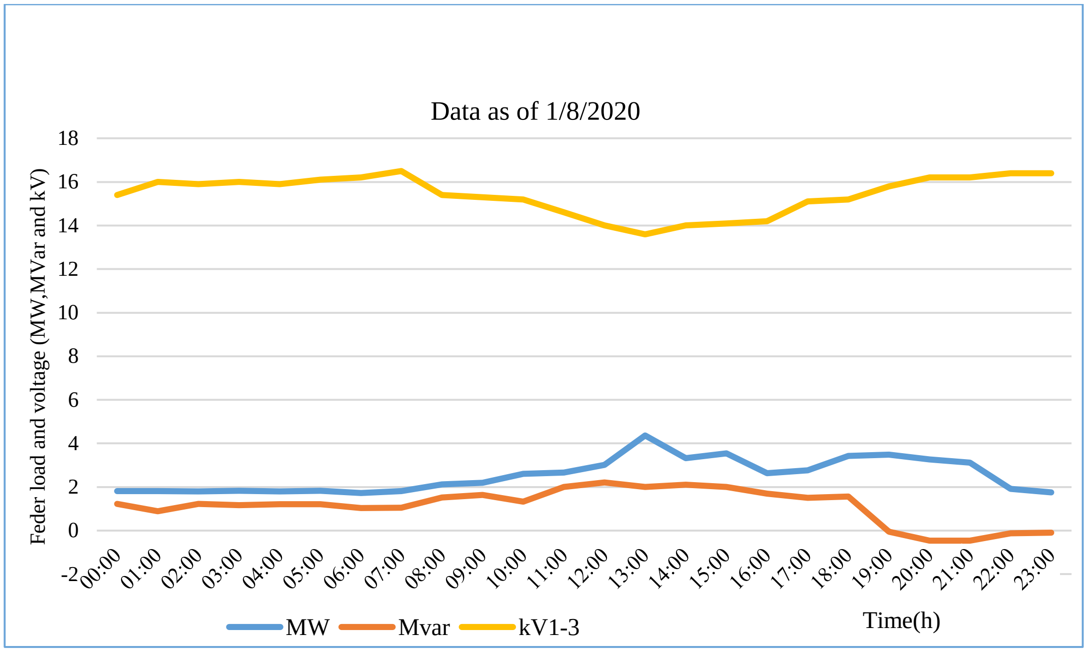

Figure 3. 4: Graphic Representation of Data for Kigali Feeder on 1/8/2020

From the above graph, it is observed that when more load is connected to the system, the system's voltage profile reduces. This occurs during the day when more inductive loads are connected. During peak hours, the inductive loads on the system are reduced and the voltage profile goes high. This is due to the fact that during peak hours, the cost of electricity for industries is higher as compared to the base load hours; the customers (industries) are mostly working in the day and after peak hours.

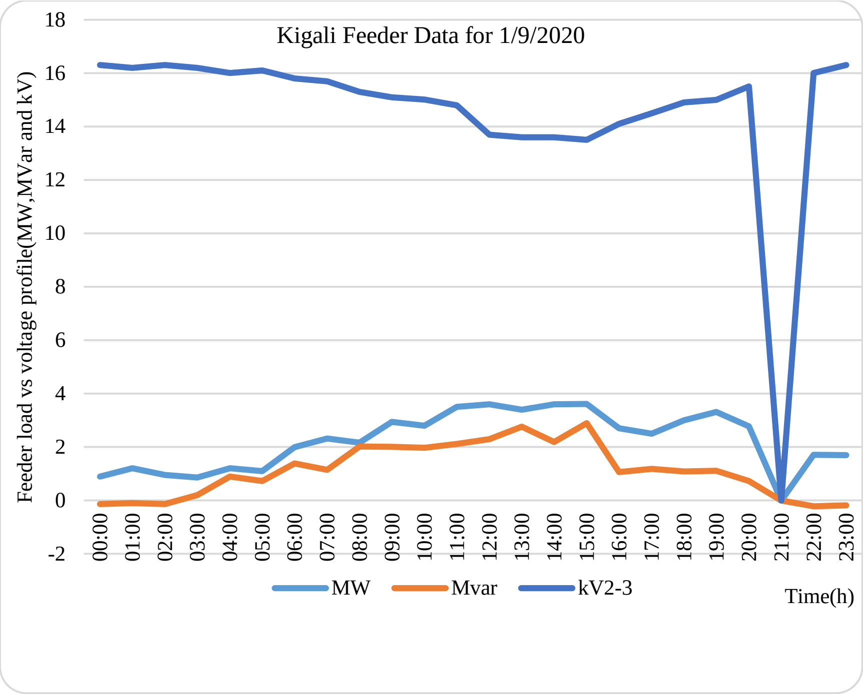

Figure 3. 5: Graphical Representation of Data for 1/9/2020

From the above graph, it is noticed that at 9pm the feeder was off; an outage was requested to fix the fault.

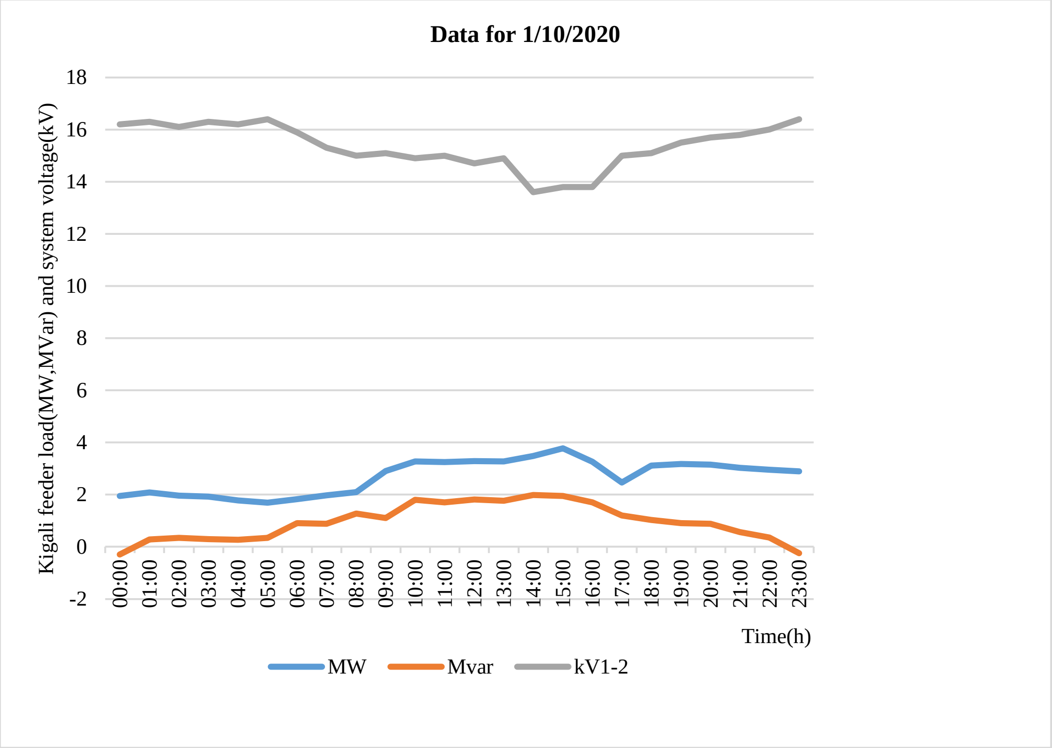

Figure 3. 6: Graphical Representation of Data as of 1/10/2020

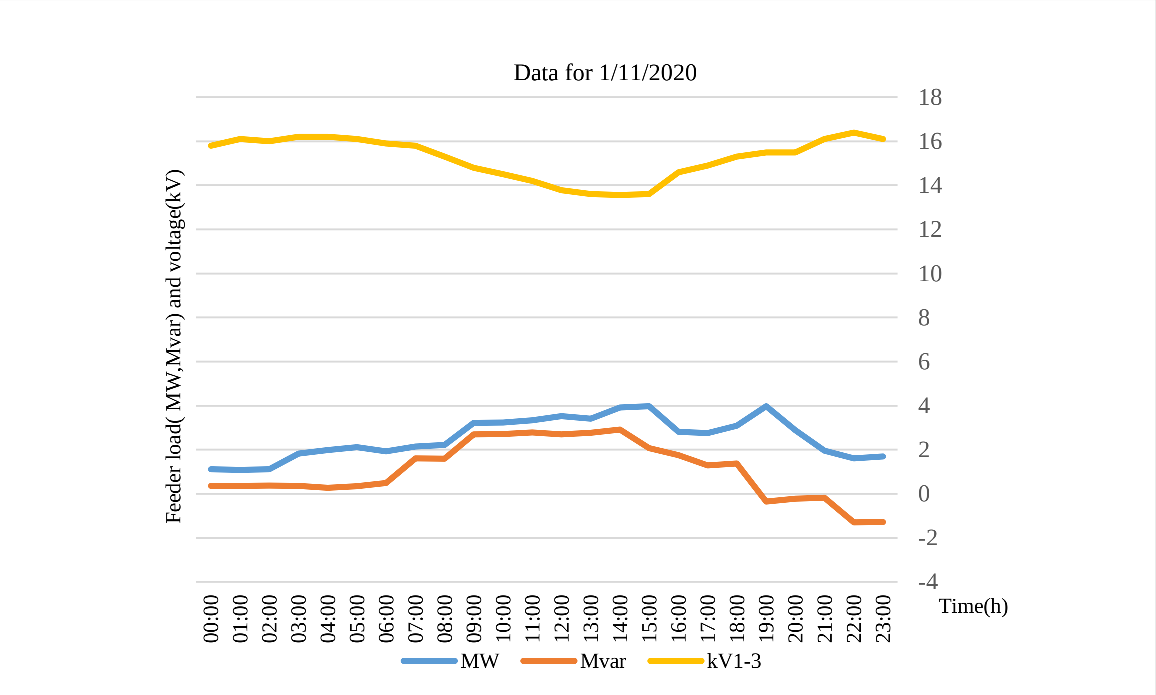

Figure 3. 7: Graphical Representation of Data as of 1/11/2020

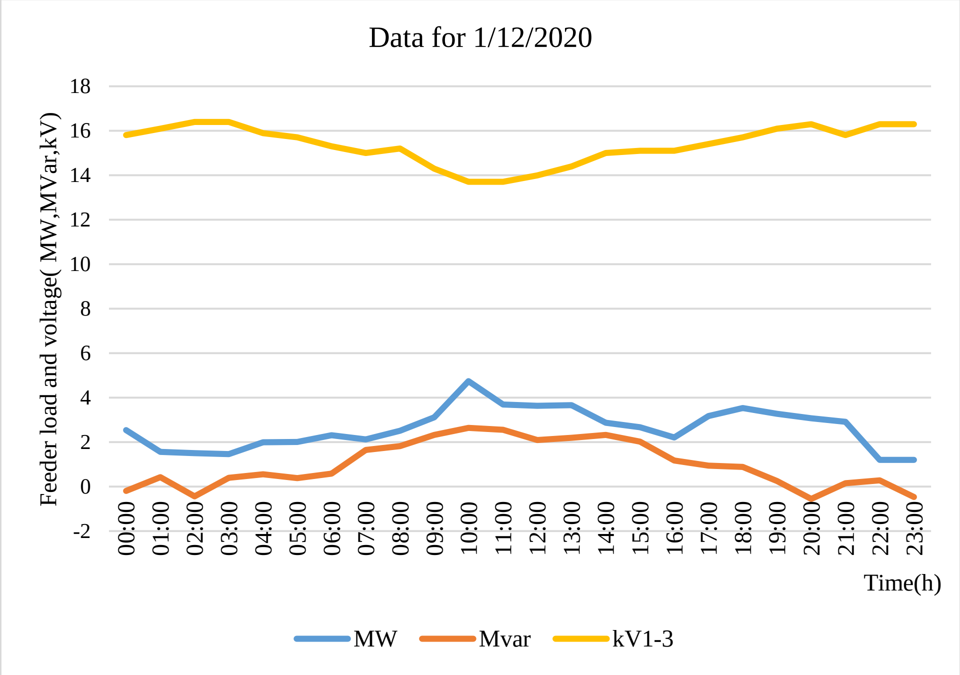

Figure 3. 8: Graphical Representation of Data for 1/12/2020

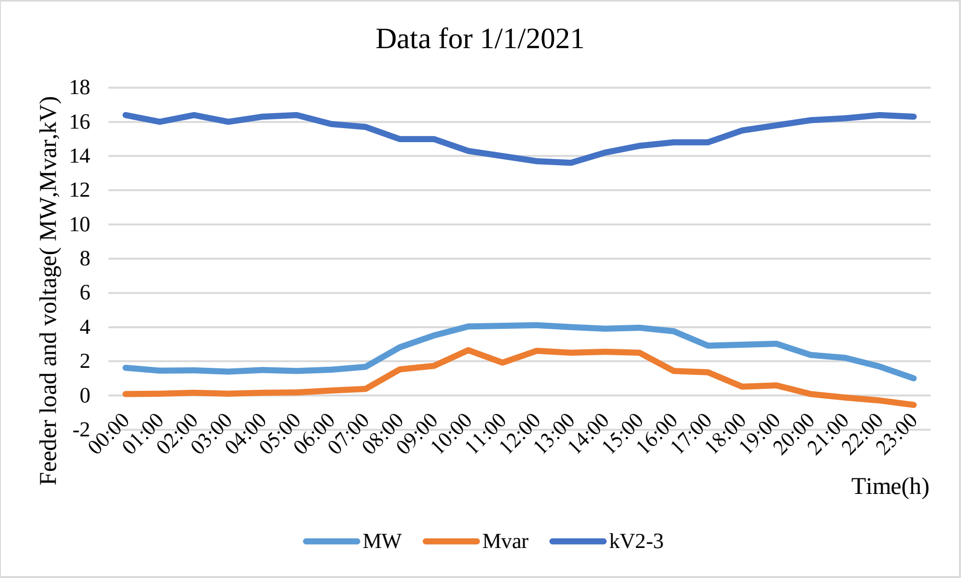

Figure 3. 9: Graphical Representation for Kigali Feeder Data as of 1/1/2021

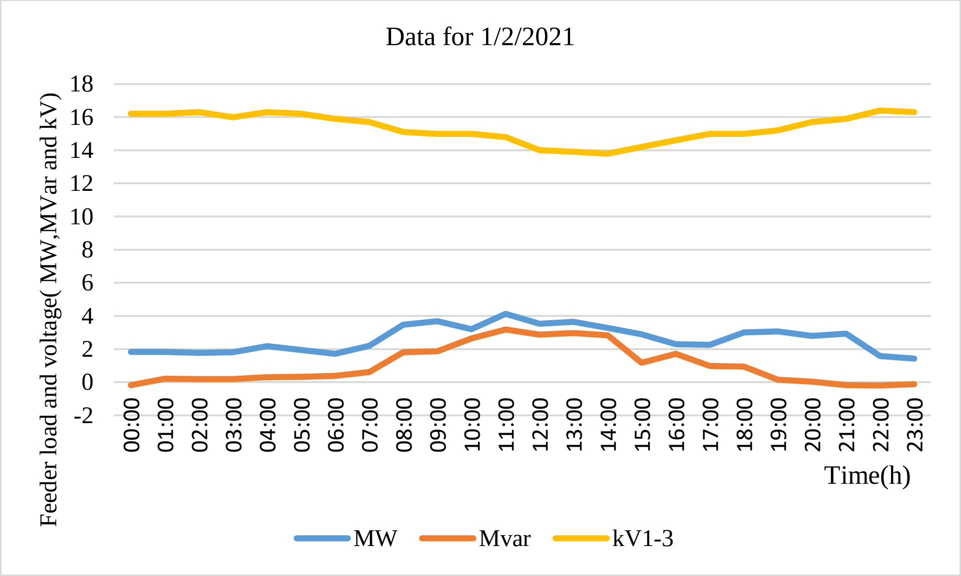

Figure 3. 10: Graphical Representation of the Data as of 1/2/2021

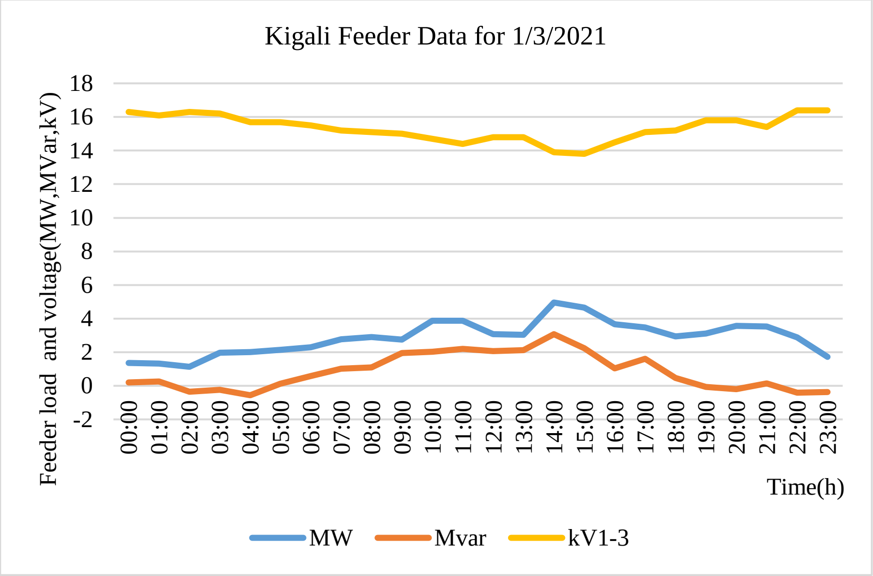

Figure 3. 11: Graphical Representation of Data as of 1-3-2021

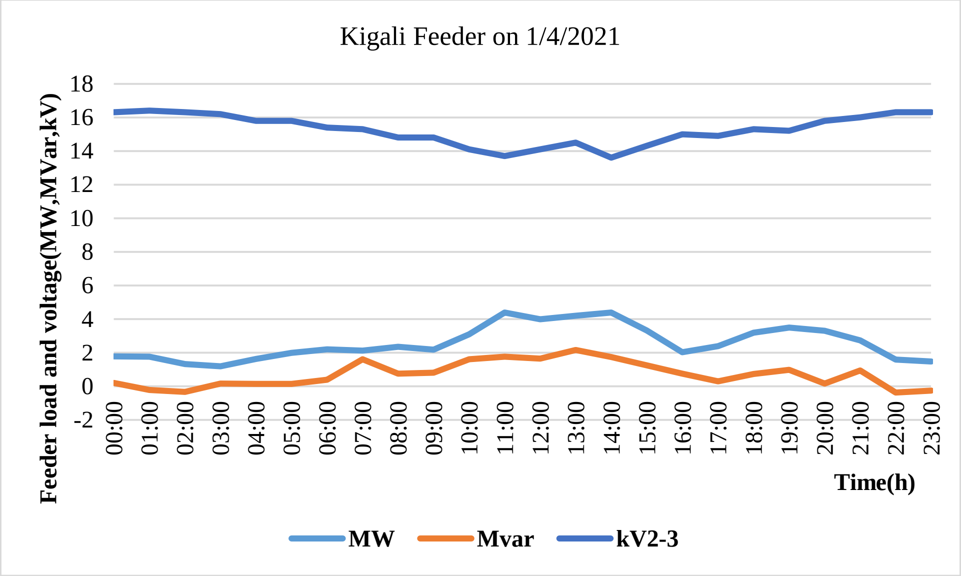

Figure 3. 12: Graphical Representation of Kigali Feeder Data on 1/4/2021

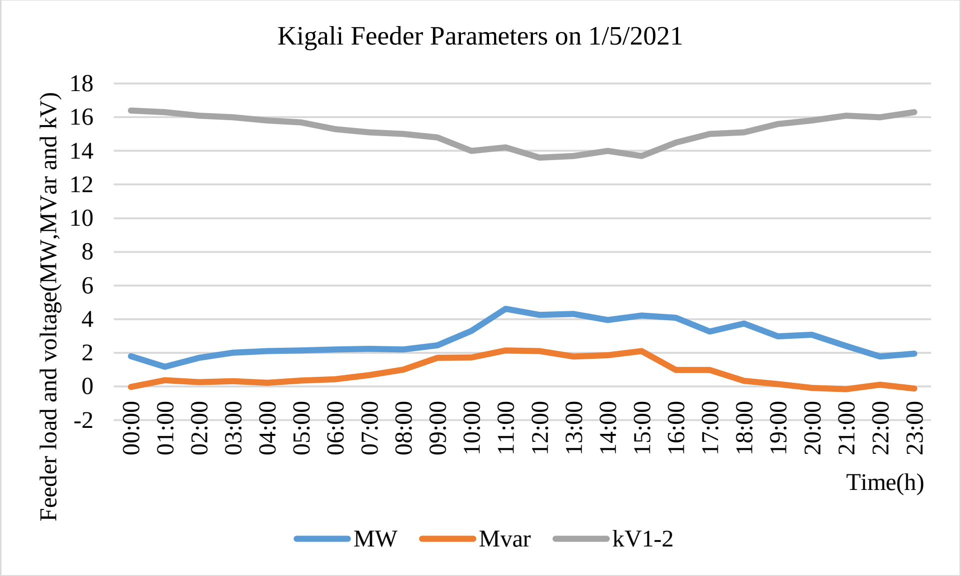

Figure 3. 13: Graphical Representation of Kigali Feeder Data as of 1/5/2021

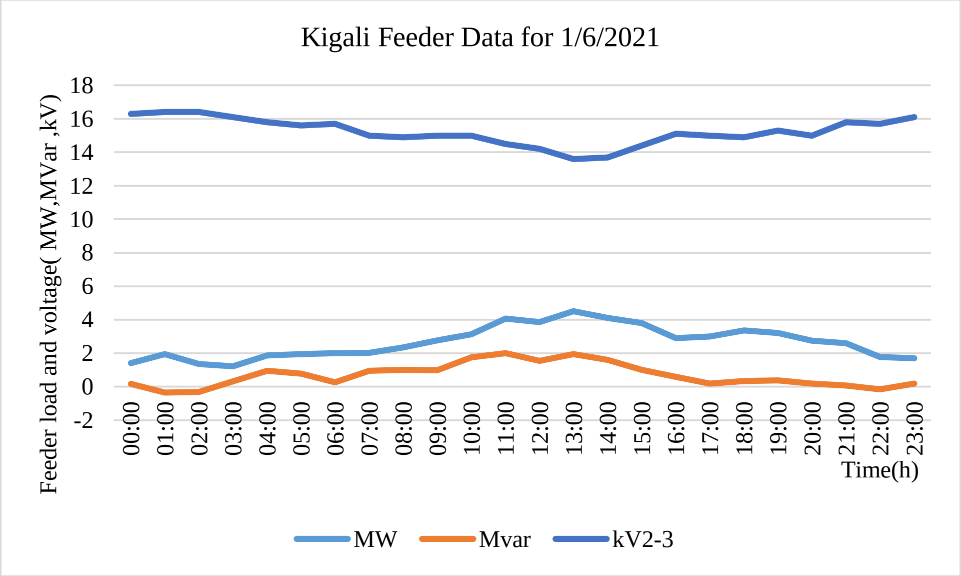

Figure 3. 14: Graphical Representation of Kigali Feeder Data as of 1/6/2021

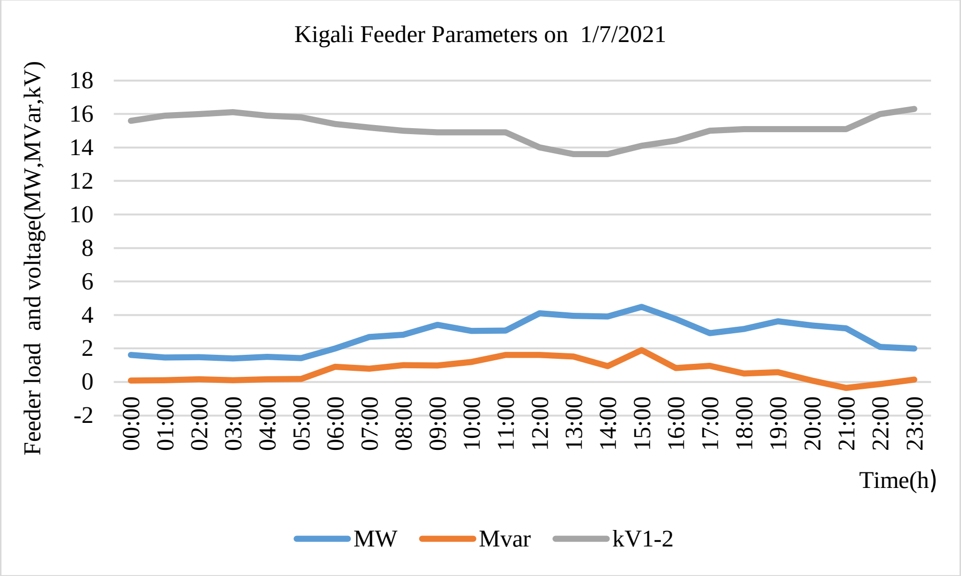

Figure 3. 15: Graphical Representation of Kigali Feeder Data as of 1/7/2021

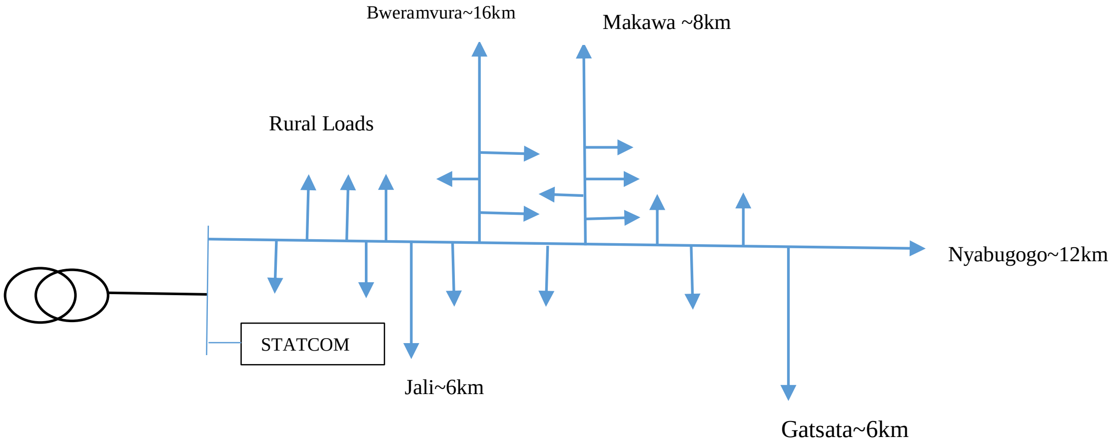

Figure 3. 16: Proposed Single Line Representation of Kigali Feeder with STATCOM

The case study involves a long distribution power line that feeds different loads around 50km away from Jabana substation. The feeder capacity is estimated to be 10MW with the maximum current of 630A.

The minimum voltage of the feeder is 0.9pu and it sometimes gets to 0.88p.u when the feeder is heavily loaded. The maximum voltage reaches 1.10p.u during times of light load and sometimes can get to 1.12 in case of disturbance or when some sub feeder trip and there is a loss of load.

3.3 Design of Voltage Source Converter based STATCOM

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 STATCOM, DC link capacitor, etc. are designed.

Table 3. 1: Existing Data for 15kV Kigali Feeder Distribution Line

No	Type of Data	Amount
1	Feeder nominal voltage	15kV
2	Feeder maximum loading	10MW or 10,000kW
3	Feeder approximate. length	50km
4	Feeder maximum current	630A
5	Feeder operating power factor	0.85lagging or 31.78^0
6	Resistance per kilometer	0.0648 ohms
7	Reactance per kilometer	0.0413ohms

3.3.1: Design of STATCOM Rating

From the above data, the apparent power of the feeder can be determined as:

$$\mathbf{S}= \frac{\mathbf{P}}{\mathbf{cos\delta}} \tag{3.1}$$

Where S: apparent power

P: active power of the feeder and cosδ is the power factor of the feeder.

$$\mathrm{S}= \frac{10{,}000\mathrm{kW}}{0.85} = 11{,}765\mathrm{kVA}$$

The feeder reactive power is calculated as: $\mathbf{Q1}= \mathbf{S} * \mathbf{sin\delta} = \sqrt{\boldsymbol{S}^{2} - \mathbf{P}^{2}}$ (3.2)

$$\mathrm{Q1} = \sqrt{11765^2 - 10000^2} = 6198\mathrm{kVar}$$

For compensation, the current power factor must be corrected from 0.85 to above 0.9. Here we take the power factor of 0.95 lagging. The designed apparent power of the feeder would be:

$$\mathrm{S}= \frac{\mathrm{P}}{\cos\delta} = \frac{4000\mathrm{kW}}{0.95} = 10526.3\mathrm{kVA}$$

The reactive power is Q2= S*sinδ= 10526.3kVA*sin18.19^0 = 3286kVar

From this, the reactive power to be compensated is equal to the reactive power designed Q2 minus the currently operating reactive power Q1.

Q_{new} (compensation) = 3286kVar- 6198kVar= - 2912kVar

From [22], the tolerance of 10% must be added;

Q3= Q $_{new}$+10% Q$_{new}$ =2912kVar+10% (2912) =3203.2kVar.

The STATCOM to compensate the reactive power of 2912kVar is 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 STATCOM to 1% [23].

From that, the active power of the STATCOM is: **P=Q*1%** (3.3)

P=3203*1%=32.03kW

The apparent power of the STATCOM is S = $\sqrt{P^2 + Q^2} = \sqrt{3203^2 + 32.03^2}$ = 3203.16kVA

As it is clear, the STATCOM 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:

Here we select the IGBT as a semiconductor switch to be used in the witching of the STATCOM. The IGBT having voltage rating of 3.3kV it means that the coupling transformer is fed from 15kV 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=**$\frac{\mathbf{S}}{\mathbf{1.732*V}}$ (3.4)

$$I = \frac{3203kVA}{1.732*15kV} = 123.28A$$

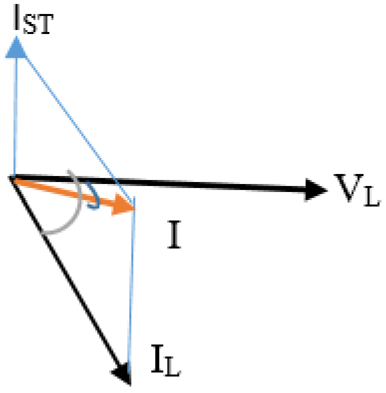

Figure 3. 17: Phasor Diagram of the Resulting Current after Compensation

I_L is the feeder normal operating current at an angle 31.7^0 or 0.85 power factor;

I_{ST} is the STATCOM current which is in phase quadrature with the line voltage;

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

$I=I_L-I_{ST}$ = $[(630\cos31.7^0+j630\sin31.7^0) -(123.28\cos90^0+j123.28\sin90^0)]$ A

= (536.01+j331.04) – (0+j123.28) = 536.01+j207.76

$I = \sqrt{536.01^2 + 207.76^2}$ =575A

Angle is equal to $\tan^{-1}(\frac{207.76}{536.01})= 21.18^0$

After improving the power factor, the feeder nominal current reduces from 630A to 575A. 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:

$\frac{Vp}{Vs} = \frac{Is}{Ip}$; $\frac{15kV}{3.3kV} = \frac{Is}{49.26}$ $I_s= \frac{15*123.28}{3.3}$ = 560.36A

3.3.2 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 STATCOM.

By taking the V_{LL} and the modulation index as one, the DC capacitor voltage is calculated using the following formula:

$$\mathbf{V_{DC} =2\frac{\sqrt{2}}{\sqrt{3}} * \frac{VLL}{m}} \quad (3.5)$$

$V_{DC}= \frac{2\sqrt{2}}{\sqrt{3}}*\frac{3300}{1}$ = 5388.8V approximated to 5400V

3.3.3 Design of DC Capacitor

Hazim Faruk [25] presented his PhD dissertation in 2007 where he showed that during capacitor designing there are two main points that must be considered:

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.

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

$$\mathbf{C=\frac{0.9\,\mathit{I\,rms}}{0.02*4\pi*f*VDC}} \qquad (3.6)$$

$$\text{Where } I_{rms}=\frac{\text{apparent power of STATCOM}}{\sqrt{3}*\text{VLL}} \qquad (3.7)$$

From this, $I_{rms}=\frac{3203}{1.732*3.3}=560.39\text{A}$

f is the nominal supply frequency; in this case f is 50Hz

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

It means 3 capacitors of 1000µF of 5400VDC each which are connected in parallel can be used to generate 3203kVar.

The inductor to be used to absorb such an amount of reactive power when the system's voltage profile goes high can be calculated as follows:

$$\mathbf{X_L=\frac{V^2}{Q}} \qquad (3.8)$$

$$XL=\frac{15000^2}{3203000}=70\ \Omega$$

It is known that $X_L=2\boldsymbol{\pi}f*L$ so the inductance $L=\frac{XL}{2\pi f}=\frac{70}{2*3.14*50}=559.8\text{mH}\approx 223\text{mH}$

3.34 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 [27].

The following formula is used: $\mathbf{L=\frac{\sqrt{3}*}{12*\alpha*fs}\frac{m*VDC}{*I\,rip}}$ (3.9)

Where L is the inductance;

m: is the modulation index;

V_{DC} is the DC voltage;

α is defined as overloading factor =1.2;

fs is the converter switching frequency;

I_{rip} is called ripple current and is calculated using: $\mathbf{I_{rip}=0.05\sqrt{2}*I_{rms}}$ (3.10)

So, $I_{rip}=0.05*\sqrt{2}*560.39=39.62\text{A}$.

The inductance $L=\frac{1.732*1*5400}{12*1.2*1000*39.62}=16.5\text{mH}$

The reactance of the coupling transformer can be determined by $2\pi fL=2*3.14*50*0.0165=5.181\text{ohms}$.

3.3.5 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 XC = $\frac{V^2}{0.15Q}$ (3.11)

Where V is the rated voltage of switching devices and Q is the reactive power of the semiconductor switching devices.

In this case, V=3.3kV and Q=1280kVar; XC= $\frac{3300^2}{3203000*0.15}$ = 23Ω

From this, C= $\frac{1}{2\pi f Xc}$ = $\frac{1}{2*3.14*50*23}$ = 138.5µF≈140µF. It means that 3capacitors of 140µF are required for the designed filter since it works on a three phase system.

The reactive power of the filter is $Q_{\text{filter}} = \frac{V^2}{Xc} = \frac{15000^2}{23}$ = 9.78kVar ≈ 10kVar

CHAPTER4: SIMULATION OF SYSTEM VOLTAGE PROFILE

4.1 Simulation of the System without STATCOM

In this part, system voltage profile before insertion of the static synchronous compensator is simulated using power world software. As it is seen, as long as the load on the system increases the voltage reduces to an extent such that it goes beyond the normal operating limits.

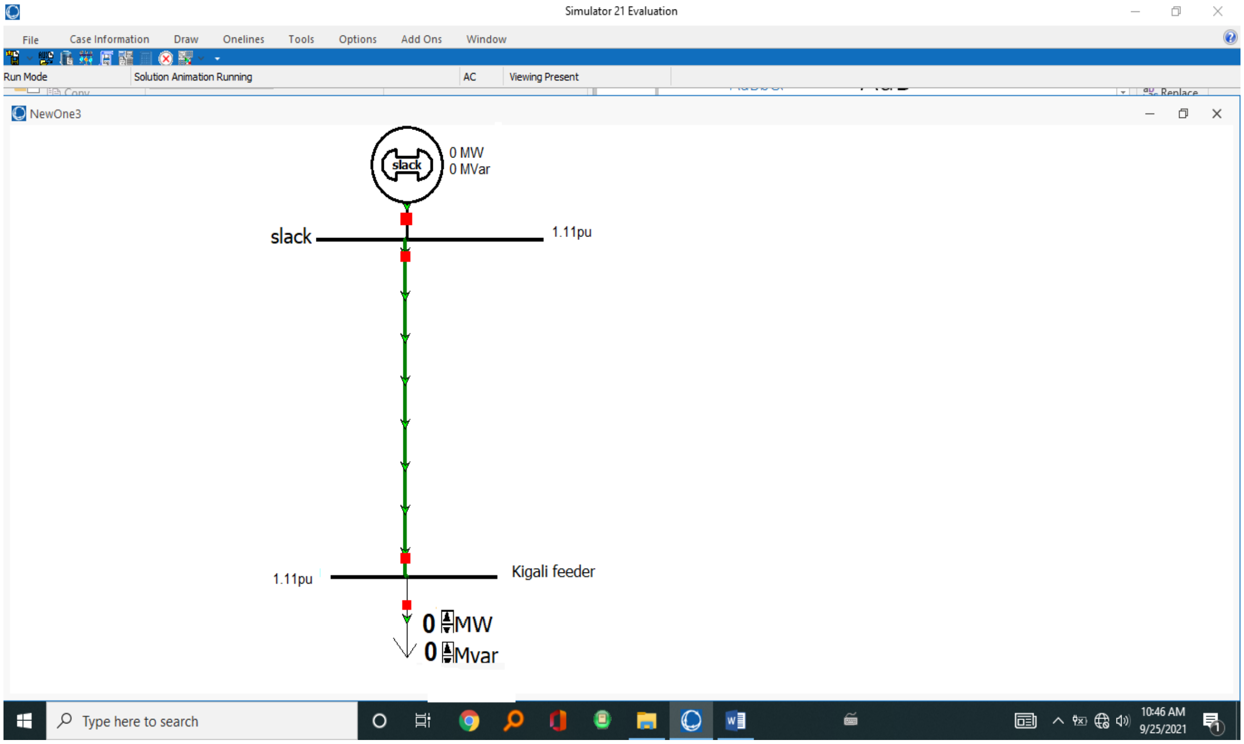

Figure 4. 1: power world simulator Print Screen of the System without STATCOM

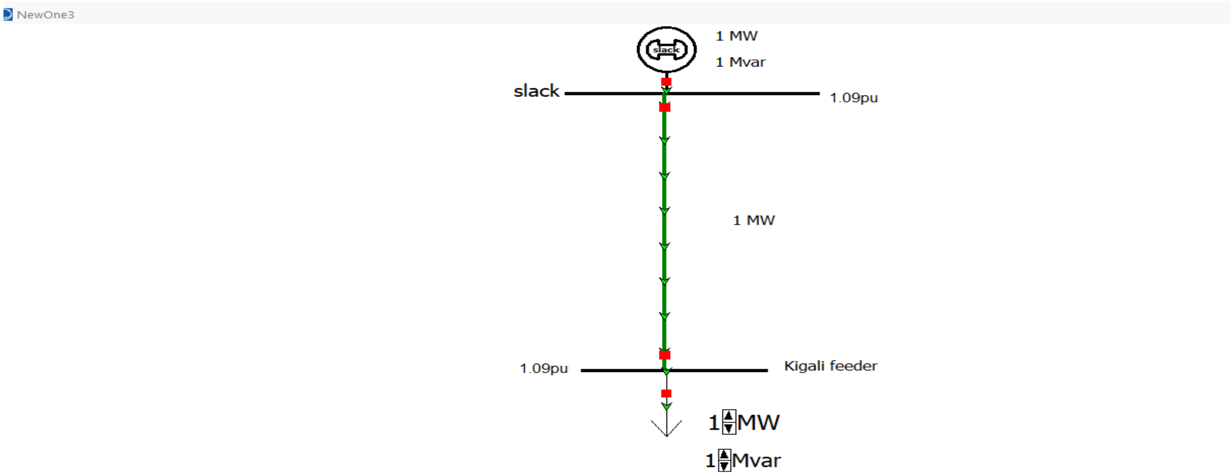

Figure 4. 2: Power System Simulation at 1MW Load

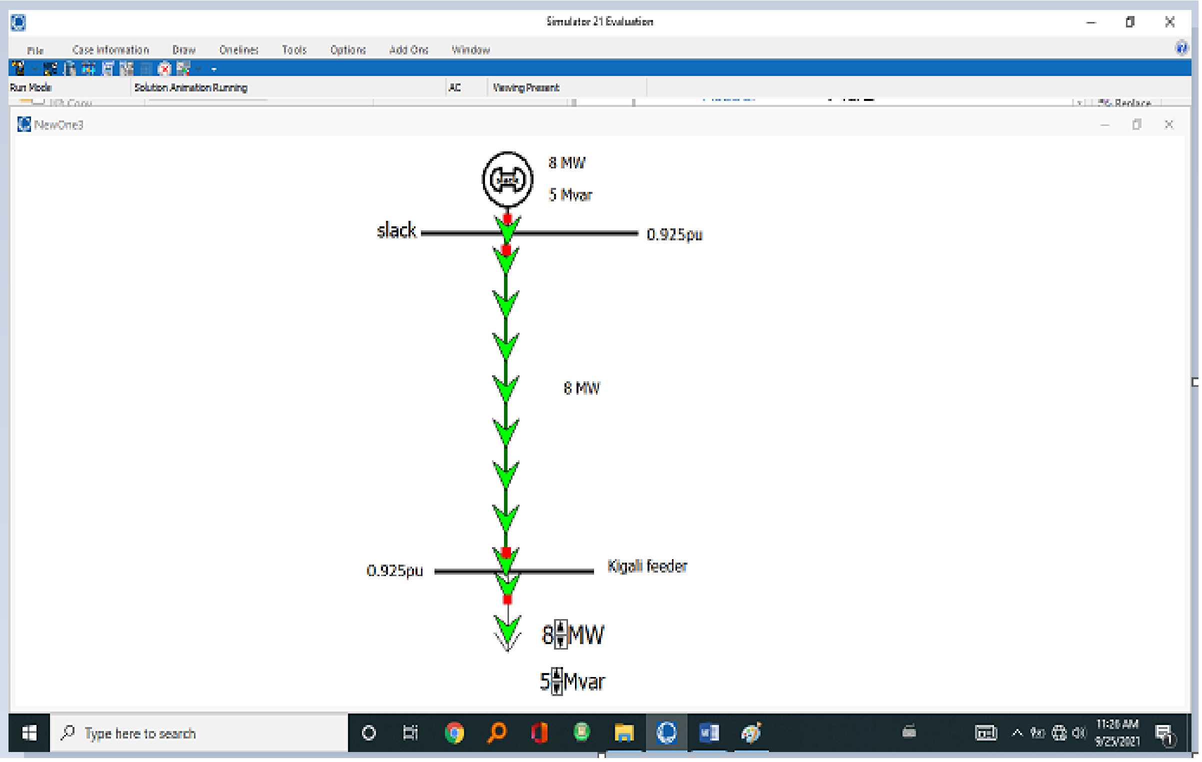

Figure 4. 3: System Simulation at 8MW and 5Mvar Load

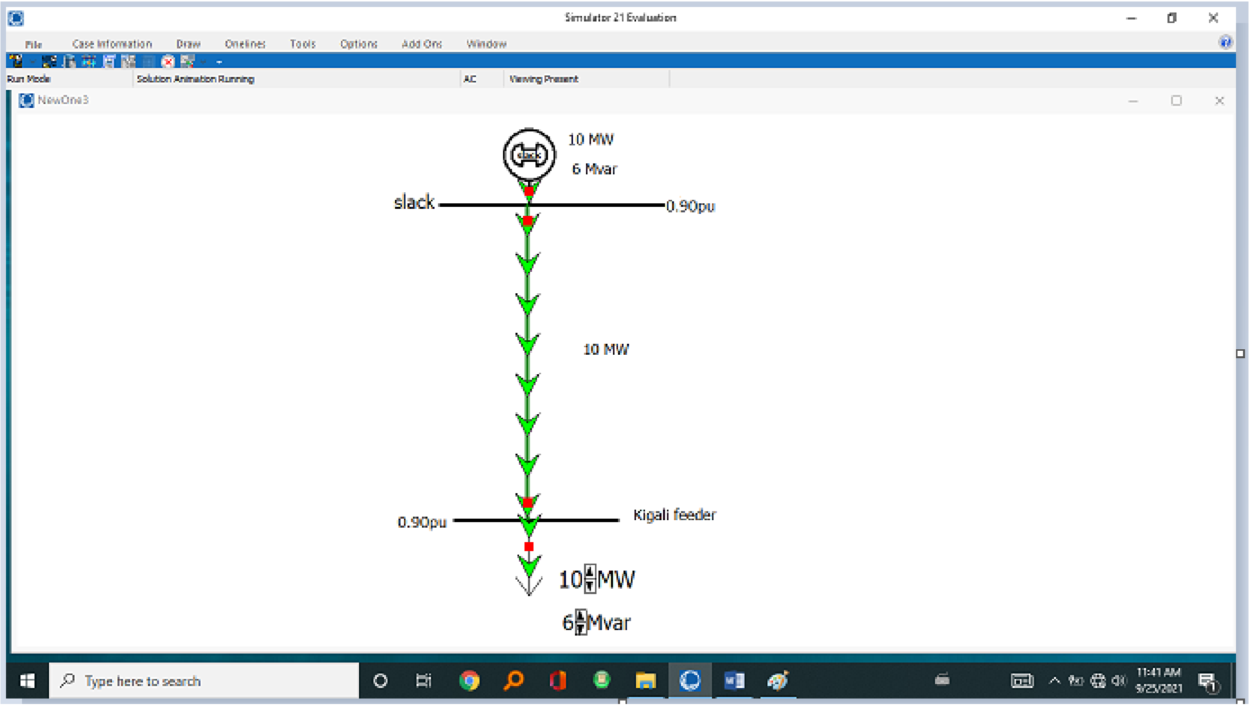

Figure 4. 4: System Simulation at 10MW and 6MVar Load

Table 4. 1: System Load vs. Load Voltage (pu)

No	Active Power(MW)	Reactive Power(MVar)	Load Voltage(pu)
0	0	0	1.11
1	1	1	1.09
2	2	1	1.06
3	3	1	1.02
4	4	2	1
5	5	3	0.99
6	6	4	0.95
7	7	5	0.93
8	8	5	0.925
9	9	6	0.91
10	10	6	0.90
11	10	7	0.88

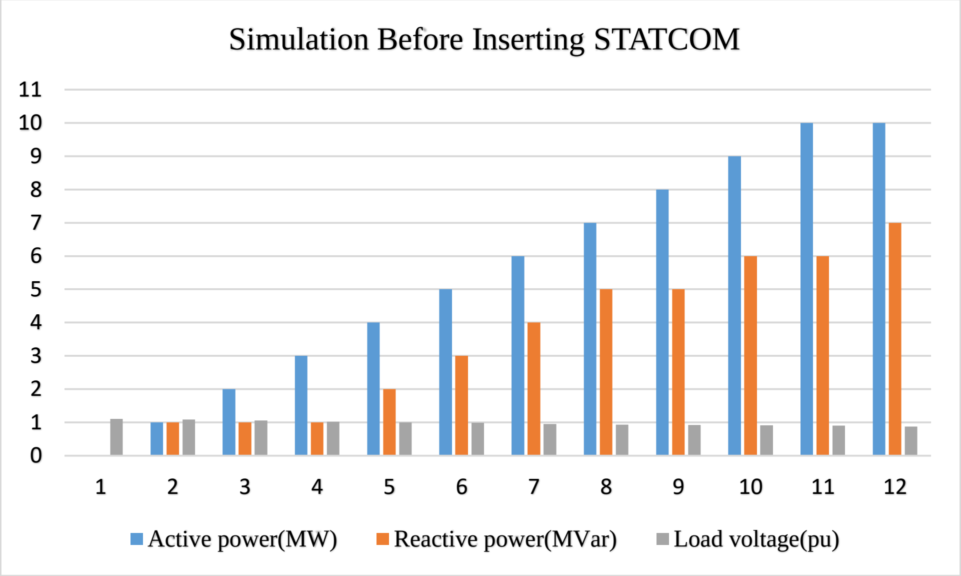

Figure 4. 5: Simulation Results before Inserting STATCOM

4.2 System Simulation with STATCOM

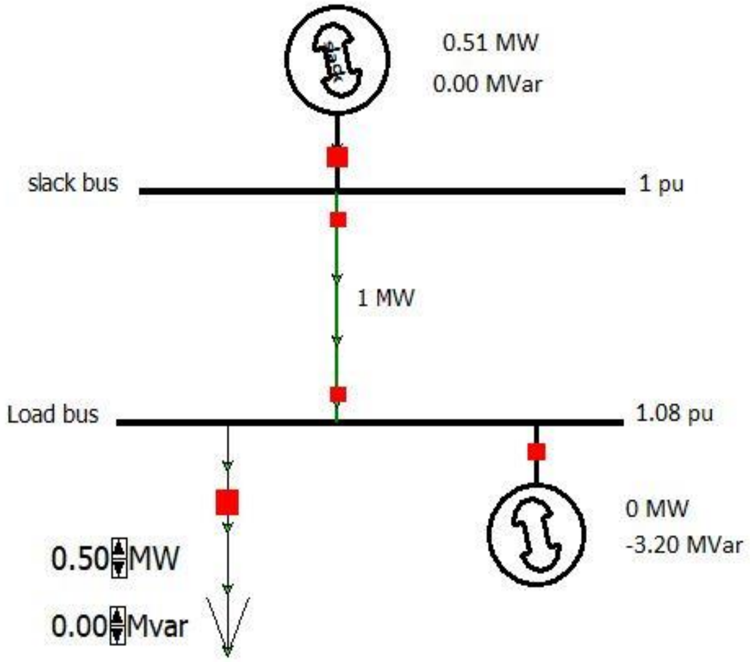

Figure 4. 6: Power World Simulator Print Screen after Insertion of STATCOM at 0.5MW Load

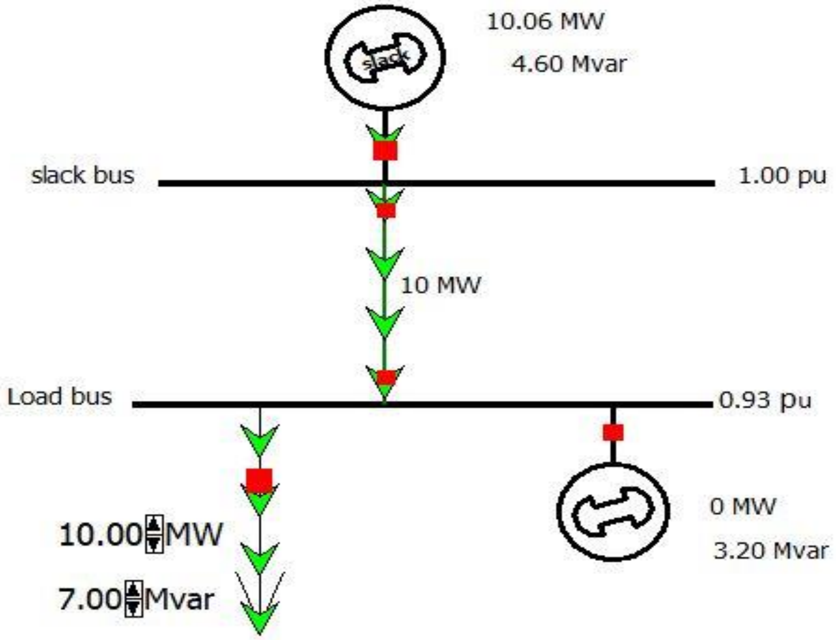

Figure 4. 7: System Simulation for a Load of 10MW and 4.5Mvar

Table 4. 2: System Data Simulation after Inserting the STATCOM

No	Load Active Power(MW)	Load Reactive Power (MVar)	Reactive Power Compensated by STATCOM (MVar)	Load Voltage(pu)
1	0.5	0	-3.2	1.08
2	1	0	-2.8	1.07
3	2	0.5	-2.5	1.03
4	3	1	1.0	1.00
5	4	2	1.72	1.01
6	5	3	2.1	1.01
7	6	4	2.52	1.00
8	7	5	3.20	0.98
9	8	5.5	3.2	0.95
10	9	6	3.2	0.96
11	10	7	3.2	0.93

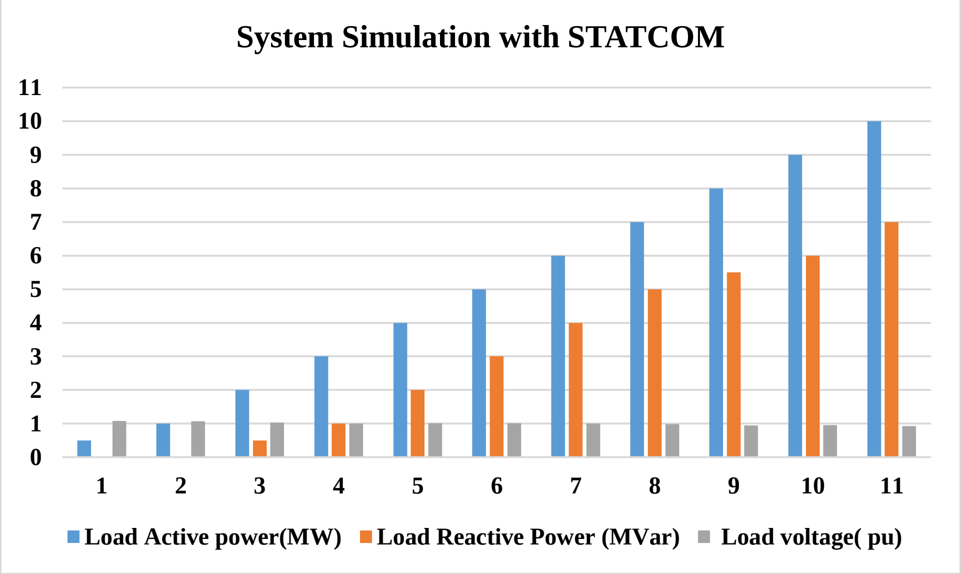

Figure 4. 8: Simulation Results after Inserting STATCOM

From table 4.2, the negative reactive power generated by the STATCOM means that the reactive power flows from the utility to the STATCOM; it means the STATCOM is consuming reactive power.

On the other hand, the positive reactive power generated means that the STATCOM generates the reactive power and flows from the device to the utility.

Table 4. 3: Load Bus Voltage With and Without STATCOM

No	WITHOUT STATCOM	WITH STATCOM
1	1.11	1.08
2	1.09	1.07
3	1.06	1.03
4	1.02	1
5	1	1
6	0.99	1
7	0.95	0.97
8	0.93	0.98
9	0.925	0.95
10	0.91	0.96
11	0.9	0.93
12	0.88	0.91

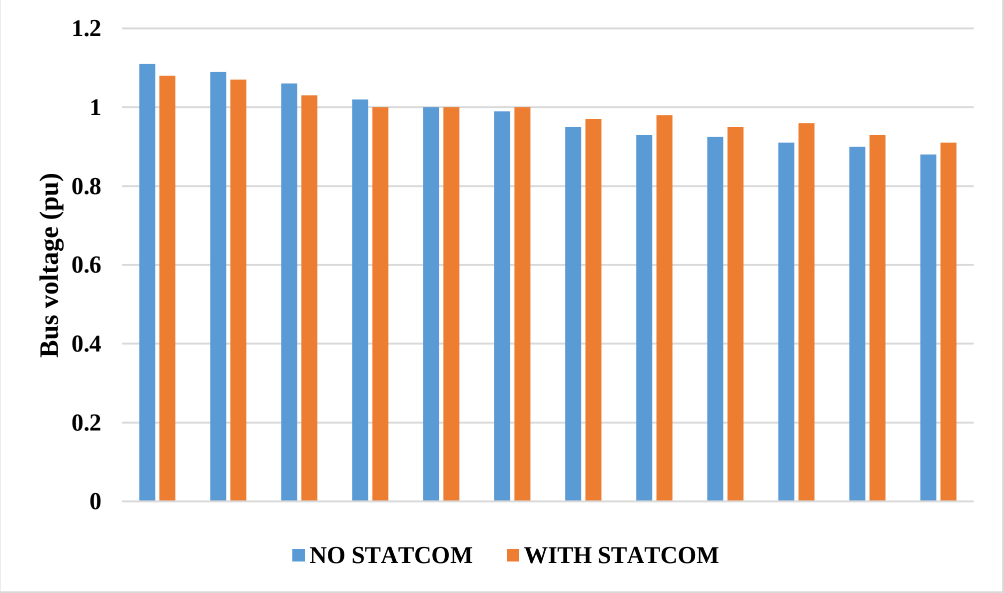

Figure 4. 9: Comparison of Load Voltage Profile with and Without STATCOM

4.4 Feeder Power Losses

Due to the feeder's resistance, the power sent from the substation (here 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 STATCOM, the power loss can be calculated as:

$$\mathrm{Ploss} = \mathrm{R} * \mathrm{I}^2 \tag{4.1}$$

Where R is the feeder resistance and I is the feeder current before inserting STATCOM.

From the table 3.1, the resistance of the feeder per kilometer is 0.0648Ω and the reactance per kilometer is 0.0413Ω. The total resistance is: R=0.0648*50Ω=3.24Ω

From table 3.1, the feeder current is 630A; the Ploss$= R * I^2 = 3.24 * 630^2$ =1286kW

After inserting the STATCOM, line current reduces from 630A to 575A; this reduction will also reduce the line losses as:

Ploss$=R * I^2 = 3.24 * 575^2$= 1071kW

The total power loss is reduced by = 1286kW-1071kW=215kW or 16.7%.

4.5 Results and Discussion

From the figures and tables above, it can be seen that the static synchronous compensator connected to the load bus improved the voltage profile from 0.88pu to 0.91pu and from 1.11pu to 1.08pu which are acceptable operating voltage. The reduction or increase of the voltage profile in Kigali distribution feeder was due to the increase in high or low load demand, the length of the feeder and its impedance. The losses of the feeder are reduced by 16.7% or 215kW.

CHAPTER5: 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 voltage in the network has to be controlled for system reliability and efficiency [28].

The voltage profile can be controlled by controlling the production, consumption and flow of reactive power through the network. 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.

This study focused on the use of static synchronous compensator, a device from FACT devices' family to control the reactive power and thus the voltage profile of Kigali distribution feeder in Kigali, Rwanda.

Its design was done from the currently operating parameters of the feeder and important simulations were been done using power world simulator software tool. It was proved that when the static synchronous is placed at the feeder's bus, it improves the voltage profile to 1pu or closer to 1pu.

From the results obtained, it can be concluded that the STATCOM has an important impact on the stability, reliability of Kigali distribution feeder under study.

5.2 Recommendation and Future Work

The recommendation goes Rwanda Energy Group (REG) to look for a way this study can be implemented.

The future work would consider these:

- The financial analysis of STATCOM against other methods of voltage profile improvement.
- The voltage profile improvement using STATCOM for the whole Rwandan power grid.

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Appendix A: Jabana Substation Incident Report for August 2020

Name of Feeder	Substation	Date	Cause	Start	End	Duration(min)
Rutongo Feeder	Jabana	1 August 2020	Under Frequency	13:48	13:53	0:05
Kigali Feeder	Jabana	1 August 2020	Overcurrent	13:49	13:52	0:03
DW Feeder	Jabana	2 August 2020	Earth Fault	17:04	17:06	0:02
Sucrerie Feeder	Jabana	3 August 2020	Earth Fault	8:40	8:41	0:01
Sucrerie Feeder	Jabana	6 August 2020	Earth Fault	8:59	9:08	0:09
Rutongo Feeder	Jabana	7 August 2020	Under Frequency	10:33	10:37	0:04
Rutongo Feeder	Jabana	7 August 2020	Under Frequency	10:44	10:55	0:11
Kigali Feeder	Jabana	7 August 2020	Overcurrent	21:08	21:09	0:01
DW Feeder	Jabana	8 August 2020	Earth Fault	19:43	19:44	0:01
DW Feeder	Jabana	8 August 2020	Earth Fault	19:55	19:58	0:03
Rutongo Feeder	Jabana	9 August 2020	Under Frequency	1:51	2:01	0:10
Rutongo Feeder	Jabana	9 August 2020	Under Frequency	1:54	2:02	0:08
Sucrerie Feeder	Jabana	9 August 2020	Works	10:00	13:53	3:53
Sucrerie	Jabana	10August 2020	Earth Fault	16:46	16:57	0:11
Kigali Feeder	Jabana	10August2020	Overcurrent	22:18	22:19	0:01
Sucrerie Feeder	Jabana	11 August2020	Earth Fault	13:43	13:44	0:01
UTEXRWA Feeder	Jabana	11 August2020	Earth Fault	17:33	17:34	0:01
Kigali Feeder	Jabana	11 August2020	Overcurrent	23:36	23:44	0:08
DW Feeder	Jabana	12 August2020	Overcurrent	11:18	11:19	0:01
UTEXRWA Feeder	Jabana	12 August 2020	Differential trip	14:52	15:12	0:20
Rutongo Feeder	Jabana	13 August 2020	Under Frequency	17:07	17:17	0:10
Kigali Feeder	Jabana	14 August 2020	Earth Fault	11:18	11:19	0:01
Rutongo Feeder	Jabana	14 August 2020	Under Frequency	21:39	21:44	0:05
DW Feeder	Jabana	14 August 2020	Earth Fault	23:56	23:58	0:02
DW Feeder	Jabana	15 August 2020	Earth Fault	2:53	2:54	0:01
Kigali Feeder	Jabana	15 August 2020	Switching Operation	12:02	13:34	1:32
UTEXRWA Feeder	Jabana	15 August 2020	Switching Operation	12:12	13:27	1:15

Sucrerie Feeder	Jabana	15 August 2020	Earth Fault	12:12	12:13	0:01
Rutongo Feeder	Jabana	15 August 2020	Switching Operation	12:12	13:01	0:49
DW Feeder	Jabana	15 August 2020	Switching Operation	12:12	13:32	1:20
Rutongo Feeder	Jabana	15 August 2020	Under Frequency	13:51	14:05	0:14
UTEXRWA Feeder	Jabana	16 August 2020	Overcurrent	4:51	4:52	0:01
Sucrerie Feeder	Jabana	16 August 2020	Earth Fault	10:40	10:41	0:01
Rutongo Feeder	Jabana	16 August 2020	Overcurrent	10:59	11:00	0:01
Sucrerie Feeder	Jabana	16 August 2020	Earth Fault	11:18	11:35	0:17
Kigali Feeder	Jabana	17 August 2020	Works	12:58	13:27	0:29
Sucrerie Feeder	Jabana	18 August 2020	Earth Fault	9:41	9:44	0:03
UTEXRWA Feeder	Jabana	18 August 2020	Overcurrent	14:45	14:46	0:01
D.W Feeder	Jabana	18 August 2020	Earth Fault	17:41	17:42	0:01
Rutongo Feeder	Jabana	19 August 2020	Under Frequency	9:21	9:24	0:03
Kigali Feeder	Jabana	19 August 2020	Overcurrent	11:01	11:02	0:01
Kigali Feeder	Jabana	20 August 2020	Overcurrent	6:50	6:53	0:03
Kigali Feeder	Jabana	20 August 2020	Overcurrent	10:46	10:47	0:01
Kigali Feeder	Jabana	20 August 2020	Overcurrent	16:10	16:14	0:04
Kigali Feeder	Jabana	23 August 2020	Overcurrent	14:54	14:55	0:01
UTEXRWA Feeder	Jabana	24 August 2020	Earth Fault	9:23	9:24	0:01
UTEXRWA Feeder	Jabana	24 August 2020	Earth Fault	17:34	17:35	0:01
UTEXRWA Feeder	Jabana	26 August 2020	Earth Fault	5:40	5:41	0:01
UTEXRWA Feeder	Jabana	30 August 2020	Overcurrent	16:27	16:29	0:02
DW Feeder	Jabana	31 August 2020	Overcurrent	6:28	6:34	0:06
Rutongo Feeder	Jabana	31 August 2020	Under Frequency	8:46	8:47	0:01
Kigali Feeder	Jabana	31August 2020	Earth Fault	13:32	13:35	0:03

Appendix B: Under frequency Automatic Load Shedding Settings as of June 2021

STAGE	FREQUENCY	FEEDER	SUBSTATION	LOAD
1	48.95Hz	Butare	Kigoma	P 2.36 MW
2	48.90Hz	Rutongo	Jabana1	P 2.13 MW
3	48.875Hz	Zaza	Kabarondo	P 1.99 MW
4	48.85Hz	Kiziguro	Gabiro	P 0.60 MW
5	48. 825Hz	Sucrerie	Jabana1	P 0.09 MW
6	48. 80Hz	Pylone 20	Gahanga	P -0.49 MW
7	48.775HZ	Ngarama	Gabiro	P 0.40 MW
	48.775Hz	Kiyumba	Mont Kgli	P -1.74 MW
8	48.75Hz	Riviera	Kabuga	P 0.10 MW
	48.75HZ	Kabuga2	Kabuga	P 0.59 MW
9	48.725Hz	Gatumba	Kigoma	P 2.72 MW
	48.725Hz	Abattoir	Nzove	P -1.71 MW
10	48.70Hz	Karenge	Musha	P 1.31 MW
11	48.675Hz	Kinyinya	Birembo	P 2.09 MW
12	48.65Hz	Kimiromko	Birembo	P 3.25 MW
13	48.625Hz	Niboyi	Pylone20	0.96 MW
	48.625Hz	Kagarama	Pylone20	0.43 MW
14	48.60Hz	Nyandungu	Rubungo	0.97 MW
	48.60HZ	Kimironko	Rubungo	2.91 MW
15	48.575HZ	Rwamagana	Musha	P 1.87 MW
16	48.55Hz	Kibagabaga-Remera	Birembo	P 4.60 MW
17	48.525Hz	Kibagabaga-Nyaruta	Birembo	P 2.70 MW
18	48.50Hz	Utexrwa	Jabanal	P 3.33 MW
19	48.45Hz	Byumba	Rulindo	P 1.97 MW
20	48.40Hz	Kanazi	Mont Kgli	P -6.32 MW
21	48.35Hz	Gikondo Haut	Gikondo	P 0.64 MW
	48.35 HZ	Master Steel	Gahanga	P -1.07 MW
22	48.30 HZ	Nyamirambo	Mont Kgli	P -1.86 MW
	48.30 HZ	Kigali North	Gikondo	P 2.65 MW

Figure1: Under frequency Automatic Load Shedding Settings as of June 2021

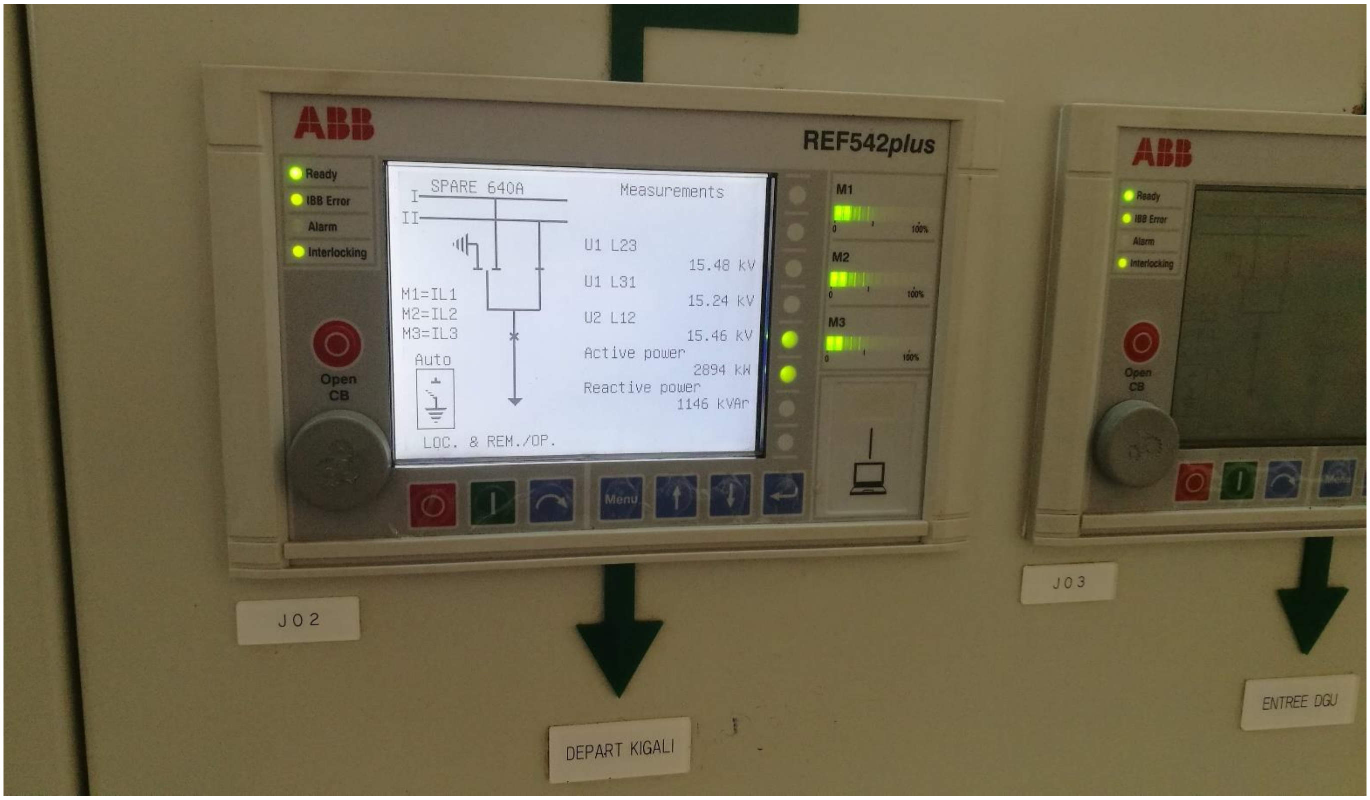

Figure 2: Kigali Feeder Protection Relay REF 542+