University of Rwanda

College of Science and Technology

Title of the thesis: STUDY ON POWER QUALITY IMPROVEMENT USING FACTS DEVICES: Case Study of Kibuye Substation

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

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College of Science and Technology

ACE-ESD AFRICAN CENTER OF EXCELLENCE IN ENERGY FOR SUSTAINABLE DEVELOPMENT

DECLARATION

I, declare that this thesis entitled **STUDY ON POWER QUALITY IMPROVEMENT USING FACTS DEVICES IN DISTRIBUTION NETWORK** is my original work and has not been presented for the award of any degree in any university. All sources of materials that will be used for the thesis work will have been fully acknowledged.

Names	**signature**
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APPROVAL

Date of Submission: October 2022

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

Getachew Biru (Dr. -Eng.)

Getachew

Thesis Advisor

Signature

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ABSTRACT

Due to its dynamic character, the electric power system frequently experiences disruptions. Additionally, high power quality is a significant challenge because there are more nonlinear loads than usual. To enhance its performance, it is therefore necessary to limit these disturbanc esand minimize the problems with the power quality.

FACTS, or Flexible Alternating Current Transmission System, are essential for improving the control and power handling of AC distribution systems. The newest technology, the static synchronous compensator (STATCOM), which is one of the fact family with shunt compensators can maintain voltage during network fault, enhancing short term voltage stability, can provide power factor correction, reactive power control and power quality improvement of distribution lines.

In this study, Flexible AC transmission devices (FACTS) called STATCOM were proposed to improve the power quality issues like poor power factor and current unbalance. Distribution network was used and Matlab/Simulink software was used to model the network. It was seen that the use of STATCOM improves the power factor as main power quality issue to 0.96 and total harmonic distortion is improved by 8.37%. The results of simulation validates the performance of STATCOM in improving the power quality.

Keywords: Power Quality, FACTS, STATCOM, power factor, current unbalance and PQ problem

Table of Contents

List of figures

List of tables

List of abbreviations

FACTS: flexible AC transmission system

TCSC: thyristor controlled series capacitor

SSSC: static synchronous series compensator

STATCOM: static compensator

SVC: static Var compensator

UPFC: unified power flow controller

PQ: power quality

BESS: battery energy storage system

THD: total harmonic distortion

HVDC: high voltage direct current

PI: proportional integral

TTBS: thirty-three bus system

DSSC: distributed static series compensator

V: voltage

P: power

Q: reactive power

DG: distributed generator

CPD: custom power devices

ESS: energy storage system

OLTC: on-load tap changer

Chapter 1. INTRODUCTION

1.1. BACKGROUND

The grid with high efficiency, reliability, and safety are more important than ever before. Due to electricity market activity and rising demand, power system has been severely stressed, and the electricity customers are subjected to power quality disturbances and they could suffer from notable losses due to these power quality problems [1].

The current Rwanda electricity distribution network covers a total of 10,520.1 km of Medium Voltage lines. These include the 30 kV, 15 kV lines, 17.32 kV and 5.5 kV. [2] Due to aging of existing distribution network increase in load demand, nonlinear load, insecurity of power system and power system fault, distribution network is exposed to power quality disturbance. Power quality problem has resulted in lost time, lost production, production of scrap, lost sales, delivery delays, and damaged production equipment, high losses, damage of system equipment and malfunction of equipment [3]. Power disturbances that affect sensitive electronic loads have a variety of sources. Lightning, utility switching, and utility outages are the sources of power disturbances [2], [4]. Power disturbances are often caused by switching of heavy loads, ground faults or normal operation of equipment. The non-linear load can also generate some disturbances themselves [5], [6].

Harmonics, flicker and current unbalance are all examples of power-quality (PQ) issues that have become severe concerns [6], [7], [8]. PQ issues including transients, voltage sag/swell, and interruption can also be caused by lightning strikes on distribution lines, capacitor bank switching, and various network faults [3], [9], [10].

Flexible AC Transmission System (FACTS) devices must be used to address these issues [11]. FACT devices, when compared to traditional devices such as shunt and series capacitors, are high power electronic devices with the ability to switch at a very fast rate. [12], [13] FACTS devices can increase power transfer capability, stability and controllability of the network, they also increase load ability by controlling the power flow in the network through series and/or shunt compensation [14]. FACTS devices control the power flow and affect numerous system parameters.The FACTS devices can be particularly useful in controlling the active and reactive power flow of the system in all operating conditions, and they offer several benefits to the system owners [15], [16]. This research studies the power quality problem in distribution network and assesses potential PQ improvement methods.

1.2 PROBLEM STATEMENT

Electrical power networks are getting more complicated around the world due to the following factors:

i) Increasing in loads demand (inductive loads)
ii) Renewable energy integration
iii) Power system fault
iv) Ageing of the existing distribution line
v) Insecurity of power system
vi) Integration of electric vehicles

The mentioned obstacles, all of which can have an impact on power transfer capabilities and power quality, cause all grid voltage variations, unbalance, harmonics, transient, flicker, interruption, low power factor and reactive power compensation problem. As a result, utilizing FACTS devices is a viable solution to the problems. This thesis proposes to identify and analyze power quality problem such as low power factor and reactive power compensation problem, unbalances. The research study also presented feasible device(s) that can potentially improve the power quality.

1.3 OBJECTIVES

1.3.1 MAIN OBJECTIVES

The main objective of this study is to analyze power quality problems, identify particular FACTS device/s, and assess potential PQ improvements of a distribution network through modeling and simulation.

1.3.2 SPECIFIC OBJECTIVES

i) Collect relevant data of the distribution system to evaluate the existing PQ problems.
ii) Select effective FACT device to mitigate the PQ problem.
iii) Model the FACT devices within the distribution network
iv) Simulate and evaluate the result of the improvements using MATLAB/Simulink Software
v) Draw conclusions and recommendations for further implementation.

1.4 SCOPE OF THE STUDY

The scope of thesis is limited to study the power quality problem of the distribution substation, identify the feasible fact device for PQ improvement and modeling and simulation of the system with and without FACT device(s) by using MATLAB /Simulink.

1.5 SIGNIFICANCE OF THE STUDY

Nowadays power network is facing the power quality issues that affect the stability and power quality of power network. This research collects and analyzes power quality data and model and simulates FACT devices to validate the improvement of power quality problem in the distribution system.

Chapter 2. THEORETICAL BACKGROUNG AND LITERATURE REVIEW

2.1. THEORETICAL BACKGROUND

2.1.1. POWER QUALITY

The demand for power from industries increased as well as domestic electricity use increased, pushing the capacity of electricity generation and maintaining the quality of power to its limit is the key for satisfying the client needs with enough energy. However, one of the key public worries is whether the nation's power utility can handle the consumers' increased demand for high-quality power. [6] Voltage collapses and voltage instabilities typically happen when there are power system problems. This issue of power system problem will contribute to electrical system poor power quality.

Due to fault incidence, rising electricity consumption, increased use of non-linear loads, and network complexity, the grid confronts difficulties in providing consumers with high-quality power [2]. Numerous factors in the distribution network that affect the delivery of electric power must be accounted for so as to increase the quality of that power.

Power Quality

The term "power quality" has varied connotations to different individuals. "The notion of powering and grounding sensitive electronic equipment in a manner suited for the equipment," is how IEEE defines power quality [17], [18]. The restriction of power quality to "sensitive electronic equipment" may not be as universally agreed upon as this term might suggest. An apparently infinite domain would include electrical equipment that is subject to power quality, or more accurately lack of power quality. Electrical equipment(s) are susceptible to malfunction or failure when subjected to one or more power quality issues [3]. Electrical appliances and equipment like home appliance, computer, transformer, motor or generator that runs on electricity, depending on the degree of the difficulties respond negatively to poor power quality.

"Power quality is a set of electrical boundaries that permits a piece of equipment to function in its intended manner without significantly reducing performance or life expectancy," Power quality problem are any issues with power that jeopardize either quality, Involving the interaction between the system and the load.

The variables that make up power quality include transient voltages and currents, harmonic content in the waveform of the system, variation in voltage magnitude [3], [10] and service continuity lead to equipment failure or malfunction. In addition, when the low poor quality occurred in the system, the system will experience more repercussions of the harm.

Power Quality Problems

Any voltage or current issue that causes frequency variations and equipment failure or improper operation is referred to as a power quality issue [6]. Power quality has significant effects on consumers. Non-linear loads exist in power grid, particularly in distribution system; they have an important impact on the quality of the power supply and may distort the supply waveform [2].

Power quality issues are also caused by certain system events, such as capacitor switching, motor starting and malfunctions. The power quality affects the efficiency and life span of generating equipment, transmission line and electrical equipment due to additional loss of power system device. noise can be produced due to any disturbance, overheating, ageing of insulation, life-span shortening and even damages in capacitor and transmission line due to harmonic [3].

Power quality problem classification [2]

1. Short duration voltage variations
    - Interruption
    - Sag
    - swell
2. Long duration voltage variations
    - Under voltage
    - Overvoltage
    - Sustained interruption

3. Transients
    - Impulsive transient
    - Oscillatory transient
4. voltage fluctuations,
5. voltage unbalance,
6. frequency changes,
7. waveform distortions
    - harmonics
    - Dc offset
    - Inter harmonics
    - Notching
    - Noise

i) Short Duration Voltage Variation

Short-term voltage fluctuations are mostly brought on by heavy loads that need high starting currents to be energized or by fault conditions and the related fault currents. [2] The disturbance may result in a brief voltage loss, a brief voltage increase, or any combination of these voltage changes and happens for time less than a minute at various nodes of the system. Voltage sage, voltage swell, and short interruption are examples of the short duration voltage change.

Voltage sag

Voltage sag also called voltage dip is the greatest typical power quality issue. It is described as a drop in rms voltage that occurs over a timeframe of 0.5 cycles to 1 minute, with a value between 0.1 and 0.9 p. u [19].

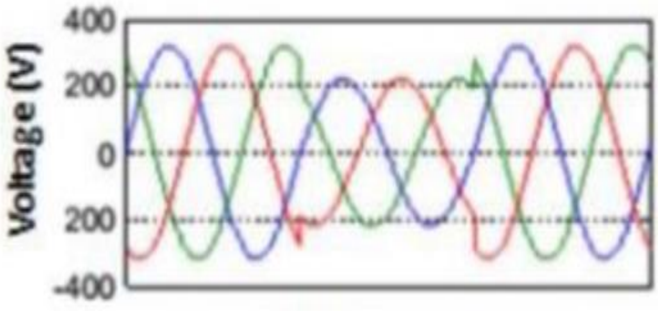


Figure 1: Voltage sags

A voltage spike may be brought on by switching processes related to temporary cut off power, the heavy current flow during the start of large electric motor, the flow of fault currents, or the movement of load from one power source to another [2]. A number of variables, including the fault type, fault location, and fault impedance, affect the size of the voltage sag. The length of the voltage sag essentially depends on how quickly the protective mechanism clears the fault. Discharge lamp extinction, electrical low-voltage device malfunction, computer system crash, and contactor trip are all potential effects of voltage sags.

Voltage Swell:

When voltage increase in rms voltage above the nominal voltage, between 1.1p.u and 1.8p.u at frequency lasting 0.5 Cycles to 1 minute is referred to as voltage swell [19]. The switching of big capacitors or the starting and stopping of heavy loads are the primary sources of voltage swell. Distribution systems are less likely to experience voltage swell. Swells may be brought on by the sudden stoppage of current, the de-energization of a heavy load, or both. The effects of voltage swell include equipment and Insulation failure, overheating, and overvoltage [9]. They also cause damage to the power factor correction capacitor and contactor, light flickering, and variable speed drive trip.

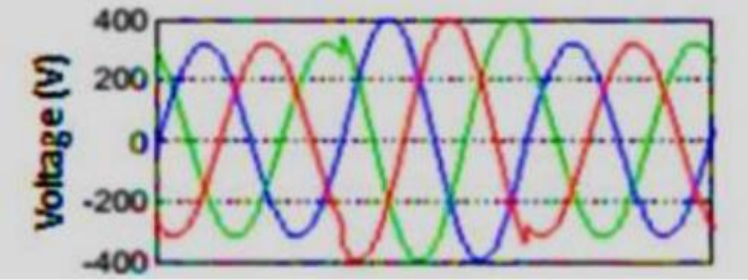


Figure 2: Voltage Swells

Short Interruption:

A short interruption is referred to as a drop in line voltage or current that lasts no longer than one minute and is less than 0.1pu of the nominal value [19]. Lightning, insulator flashover, and insulation failure are the main causes of faults [3]. Short interruptions can cause sensitive equipment to stop working, information to be lost, data processing equipment to malfunction, and protection mechanisms to trip.

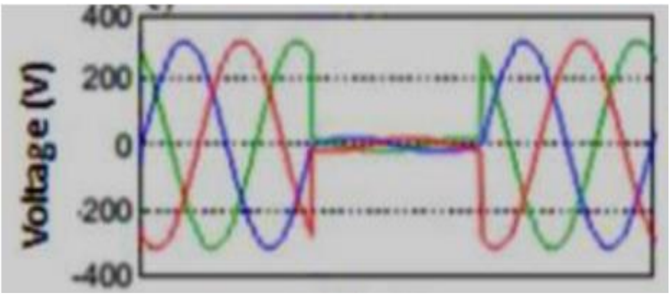


Figure 3: Short voltage interruption.

ii) Long-Duration Voltage Variation

Long-duration variations are deviations in the operational rms values that happen for more than a minute. They may be connected to system switching procedures, load changes, or permanent problems depending on the amplitude variation [10], [8]. Overvoltage, under voltage, and continuous interruption are three types of long-duration fluctuations.

Overvoltage:

A rise in the rms ac voltage of more than 110 percent in a period longer than one minute is referred to as an overvoltage. Load changes or improper tap settings on transformers cause overvoltage.

Under Voltage:

When the applied voltage drops to 90% of rated voltage, or less, for at least 1 minute is referred to as an under voltage. A load switching on or capacitor bank switching off can produce an under voltage. Additionally, under voltage can be caused by overloaded circuits.

Sustained Interruptions:

The long-duration voltage variation is regarded as a continuous interruption when the supply voltage has been zero for longer than one minute. It is caused by the fail of equipment in the power system or by fail of protection devices.

iii) Transients

Another name for transients is surge. Power quality disruptions known as transients include destructively high current and voltage magnitudes, or even both. Even in low voltage systems, it can reach tens of thousands of volts and amperes [2]. However, such events only occur over very brief periods ranging from 50 nanoseconds to 50 milliseconds. Lightning strikes, switching activities, opening and closing of disconnects on energized lines, switching capacitor banks, reclosing procedures, tap changing on transformers, loose of connections in the distribution system and other factors are the sources of transients. The effects of voltage transients are insulation failure, data loss, damage of equipment, overheating, and shortened transformer and motor lifetimes. Other impacts are malfunctioning fuses, computer system data changes, and faults on equipment, tripping of variable speed drives, and damage to other electronic devices. Impulse and oscillatory transient are categories of transient.

Impulsive Transient:

A brief, unidirectional fluctuation in voltage, current, or both on a power line is known as an impulsive transient. It can enter the power system and is a sort of transient disruption.
it is a quick, non-power frequency change that is primarily either positive or negative.

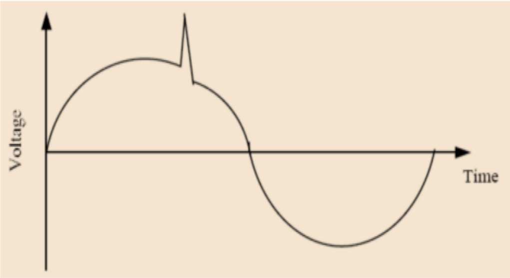


Figure 4 : Impulsive Transient

Lightning strikes, switching of inductive loads, and switching in the power distribution system are the main causes of impulsive transients. Lightning strikes can create currents that reach up to several thousand amps in just 2-3 seconds.

Oscillatory Transient:

Abrupt non-power frequency changes in a steady state condition of voltage, current, or both that has both positive and negative polarity values is referred to as an oscillatory transient.

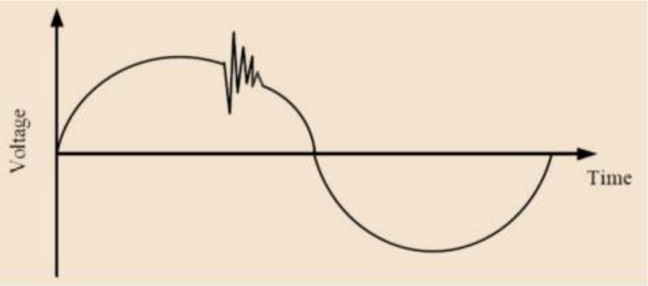


Figure 5 : Oscillatory transient

iv) Voltage Fluctuations

Voltage fluctuations are a sequence of sporadic changes in the voltage magnitude or systematic variations of the voltage envelope which lies in the range of 0.9 - 1.1 p. u[2][20].

Voltage flicker typically has a frequency spectrum that ranges from 0 Hz to 30 Hz.

Lighting and screens flicker as a result of voltage fluctuations, creating the appearance, that visual perception is unstable. These effects are essentially the same as those in the under voltage situation.

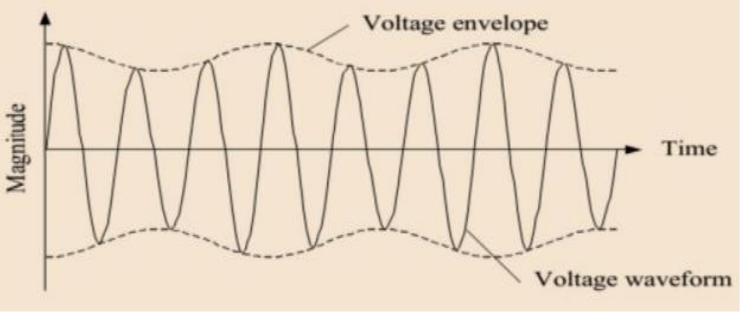


Figure 6 : Voltage Fluctuation

v) Voltage imbalance

There is a voltage imbalance in a three-phase system, when there is phase angle variances or three phase voltage magnitudes are not equal [7], [20]. Large single-phase loads and improper distribution of all single-phase loads among the three phases system are the main sources of voltage imbalance.

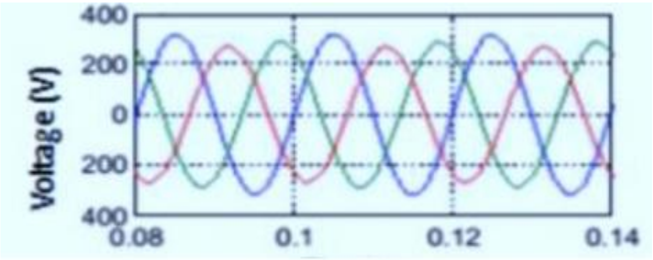


Figure 7 : Voltage Imbalance

vi) Frequency Variations

The divergence of the system frequency from its specific value of 50Hz or 60Hz is referred to as a frequency variation. Any demand imbalance result in frequency changes. Large variations in frequency are brought on by rapid load changes or generator failure [8], [3].

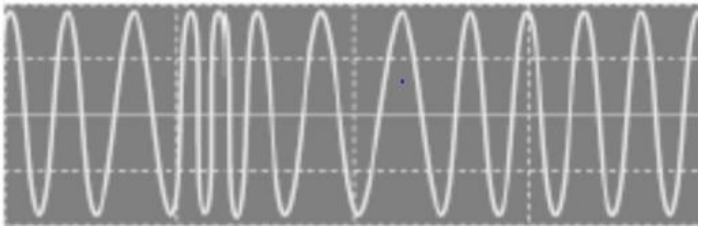


Figure 8 : Frequency variation

vii) Waveform Distortion

The term "waveform distortion" refers to a steady-state divergence from a power frequency sine wave that is primarily identified by its spectral content. Waveform distortion comes in five main categories:

DC offset:

The availability of direct current or direct voltage in an ac system may be referred to as DC offset. It happens as a result of an electrical power converter's asymmetry or a geomagnetic disturbance [20].

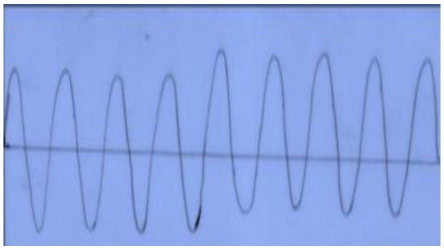


Figure 9: DC offset

Harmonics:

When a voltage or current sine wave deviates periodically from a smooth sinusoidal shape, it is said to exhibit harmonic distortion. A measurement of distortion of the complete waveform is called total harmonic distortion (THD). The principal harmonics sources at the receiving end are non-linear loads, or equipment that do not consume voltage or current in a normal sinusoidal shape, such as computer, television, arc furnaces, mercury lamps, battery chargers, medical diagnostic devices, and fluorescent lights [19], [2]. Consumer gadgets, as well as distribution and transmission networks, are susceptible to harmonic damage. Harmonics primary affects electrical equipment through overloading of electric motors, fuse misbehavior, overheating of electric motors and transformers, and failure or damage to electrical equipment.

Percentage of voltage THD is, $V_{THD=}\sqrt{\frac{\sum_{n=2}^{\infty} v^2}{v_1}} * 100$ (Eq.1)

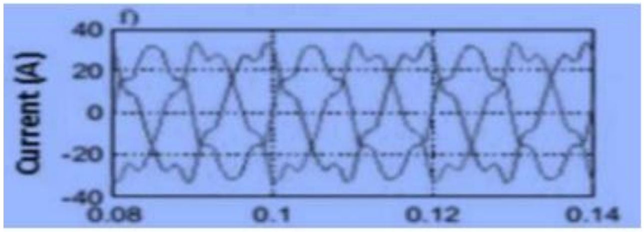


Figure 10: Current harmonics

Inter-harmonics:

Inter-harmonics are voltages or currents with frequency components that are not integer multiples of specified operating frequency (50 or 60 Hz) of the supply system. The main contributors to inter-harmonic waveform distortion are arcing devices, cyclo-converters, static frequency converters, and induction furnace.

Notching:

When current is exchanged from one phase to another during the regular functioning of power electronic devices, a periodic voltage disturbance known as notching results.

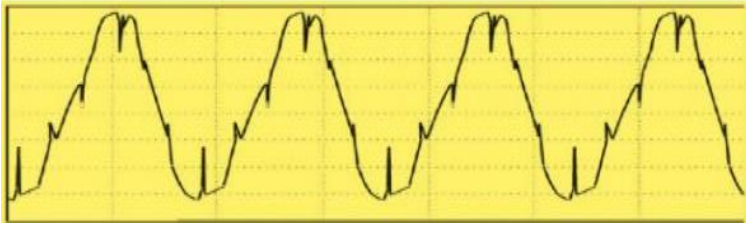


Figure 11: Notching

Noise:

Noise is the term for unwanted electrical signals that are superimposed on the voltage or current of the power system and have a wideband spectral content lower than 200 kHz. The problem could perhaps be incorrect grounding. Interference with fragile electrical components, data loss, and improper data processing are the some of the impacts [9].

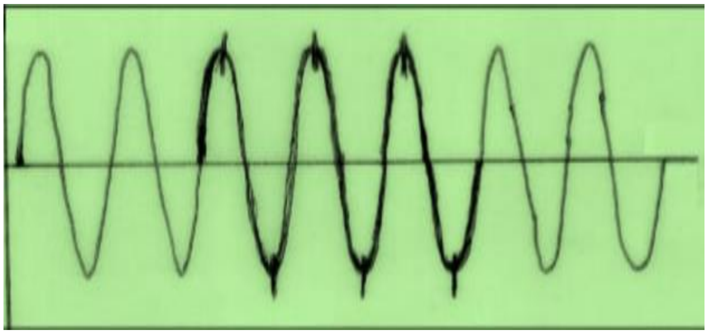


Figure 12: Noise

Solutions to Improve the Power Quality

An answer to the power quality problem may come from either the utility or consumer side. The two fundamental techniques for enhancing power quality are line conditioning and load conditioning. Both approaches can help to lessen power quality issues at various stages of the power system. When it comes to distribution systems, Flexible AC transmission systems (FACTS) can minimize a number of power quality issues and offer technical solutions to the current challenges facing power systems [6].

2.1.2. FACT DEVICES

A novel integrated concept called Flexible AC Transmission System (FACTS) uses power electronic switching converters to improve power quality of AC system [21], [5].

A power electronic-based system and associated static equipment known as the Flexible AC Transmission System (FACTS) offers adjustment of one or more AC transmission system parameters in order to improve controllability and boost power transfer capability. In electrical power systems, FACTS devices have been proposed for efficient power flow control and bus voltage regulation, resulting in greater transfer capability, minimal system losses, and improved stability [13], [11].

FACTS devices provide the controllers with the means to regulate a number of interconnected parameters, such as series and shunt impedance, current, voltage, phase angle, and damping oscillations at different frequencies below the rated frequency, that govern the functioning of transmission systems [12], [22], [23]. Modern voltage source converters are the main components of FACTS devices, which use more advanced technology. In accordance with the switching method used, the FACTS devices can be categorized into three groups: mechanically switched, thyristor switched, fast switched. [16], [7] Depending on the network connections, there are four different types of switches, which are:

- Series FACTS Controllers
- Shunt FACTS Controllers
- Combined Series-Shunt FACTS Controllers

- Combined Series-Series FACTS Controllers

2.3.1. Series FACTS Controllers

If the voltage injected by these FACTS Controllers into the connecting line is in phase quadrature with the line current, the series controller does nothing more than transmit or receive changeable reactive power [24]. A series controller could include a reactor or capacitor with variable impedance that operates at the fundamental frequency. A serial controller can only provide or consume reactive power if the voltage is in quadrature with the line current; any other phase angle solely reflects active power management. Members of this type of controller include SSSC, and TCSC.

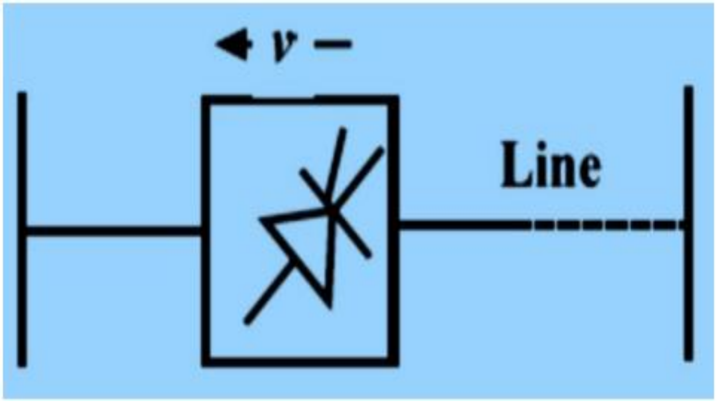


Figure 13 : Representation of Series FACTS Controller

According to IEEE definitions and standards, a thyristor-controlled series capacitor (TCSC) is a capacitive reactance compensator that consists of a series capacitor bank that is switched by a thyristor-controlled reactor to give a smoothly varied series capacitive reactance [25], [22].

The thyristor controlled series compensator controls the flow of power, reducing net loss, dampening power oscillation, and ensuring voltage stability across the power system network. The thyristor in the TCSC gadget offers adjustable flexibility with the ability to regulate continuous line compensation. The TCSC provides substantially faster response than standard control devices while providing smooth and flexible management of the line impedance. TCSC device consists of three main components, Capacitor bank, bypass inductor and bidirectional thyristor, as shown in figure 2.13.

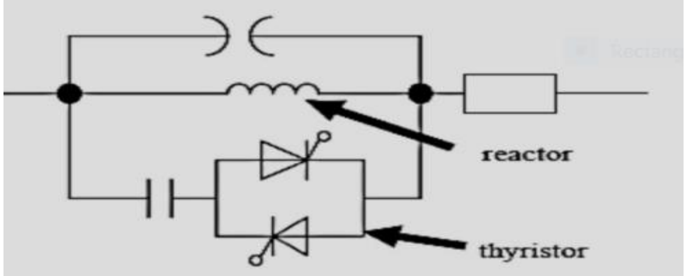


Figure 14: Thyristor Controlled Series Capacitor

Static Synchronous Series Compensator (SSSC):

static synchronous generator, dynamic voltage restorer, or series compensator with an output voltage that is in quadrature and controllable independently of the line current for the purpose of increasing or decreasing the overall reactive voltage drop across the line are all examples of devices that operate without the need for an external electrical energy source [19]. Moreover, it manages the electric power that is transmitted.

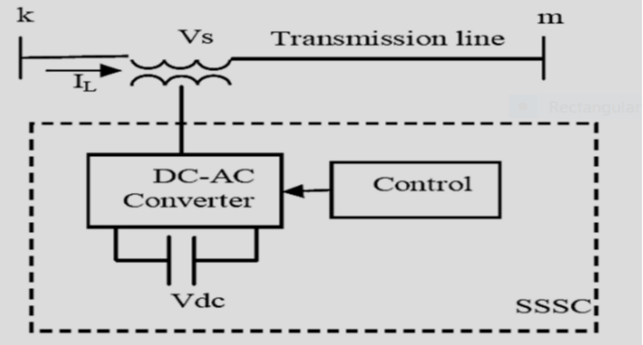


Figure 15: Static Synchronous Series Compensator

To enhance system performance, the SSSC has been used in numerous power system studies. There has been some work done to improve the stability of the power system by utilizing the SSSC's properties [1].

2.3.2. Shunt FACTS Controllers

The shunt FACTs controllers may be variable impedance-type devices, such as reactor or capacitor adjustable sources, that are shunt coupled to the line in order to inject variable current. Other than that, it operates effectively for the real power flow at any angle for voltage and current up until the point when the current is injected to the line voltage with phase quadrature. This gives the system fluctuating reactive power or absorbs it.

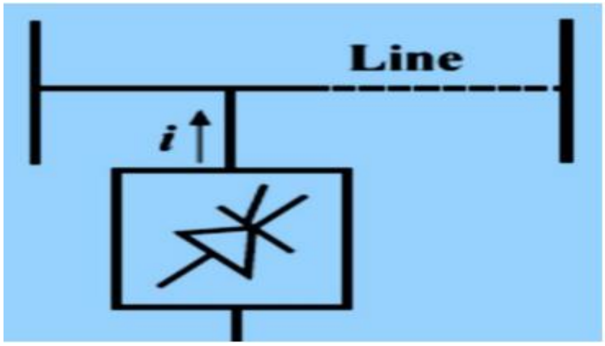


Figure 16: Representation of shunt FACTS Controller

Shunt controllers operate by adding current to the system in quadrature with the line at the point of connections. Variable electrical base, variable impedance or both are typically present. The current flowing through the variable impedance represents the current injected into the line. In other words, variable shunt impedance related to the line voltage may also be the root of the variable current. Included in this group of controllers are STATCOM, TCR, and SVC [7].

Here is a list of some shunt controllers.

- Static VAR compensator (SVC)
- Thyristor Controlled Reactor (TCR)
- Static synchronous compensator (STATCOM)

Static VAR Compensator (SVC):

The SVC is the first component of the FACTS controller. It is a shunt-connected static VAR generator or absorber whose output is modified to exchange capacitive or inductive current in order to maintain or control particular electrical power system parameters [26].

The voltage in the power system can be kept at the rated value by a static VAR compensator. To managereactive power quickly and increase power transfer over long distances, static VAR compensators with thyristor control are utilized. The SVC is a controller that has a fixed capacitor with a thyristor-controlled reactor (TCR) and a thyristor switched capacitor connected in shunt (TSC). With rapid acting voltage regulation, it can also increase stability in both steady-state and transient conditions [23]. Figure 17 depicts the SVC's fundamental structure.

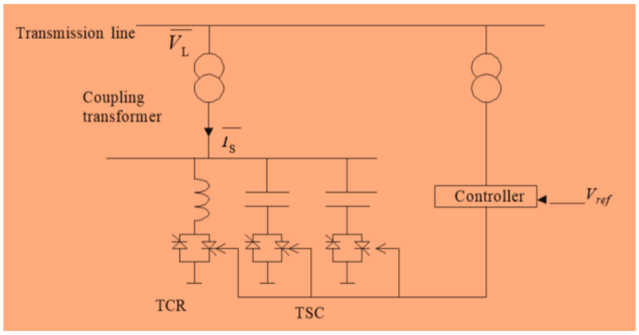


Figure 17: Basic structure of SVC

Thyristor Controlled Reactor (TCR):

TCR is a subset of SVC in which a thyristor-based AC switch with firing angle control regulates the conduction time and, consequently, the current in a shunt reactor. To swap capacitive or inductive current, output is changed. It is used to maintain or regulate particular electrical power system parameters [25].

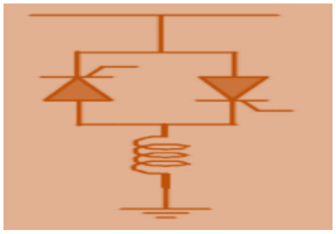


Figure 18: Thyristor controlled reactor

Static Synchronous Compensator (STATCOM):

STATCOM is a static synchronous generator that is used as a shunt-connected static VAR compensator [27]. STATCOM does not require passive components like inductors and capacitors. In order to improve power quality and stabilize the power system, transmission and distribution networks primarily use STATCOMs, which also provide dynamic voltage support. STATCOM also function as a system's active harmonic filter[28]. The static VAR compensator is a thyristor-controlled reactor and a thyristor switched capacitor, and STATCOM is a shunt-connected voltage or current sources convertor based VAR generator. Compared to SVC, STATCOM performs better overall and offers more flexibility. Figure 19 shows the STATCOM's fundamental construction.

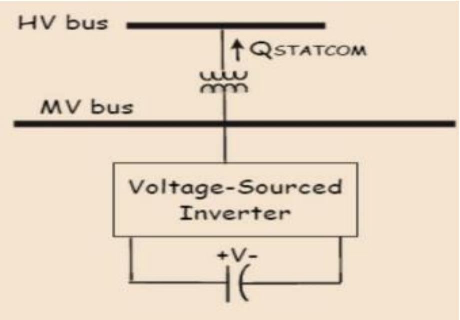


Figure 19: Basic structure for STATCOM.

The STATCOM Voltage-Source Inverter (VSI) provides the active and reactive power that the system requires by converting a DC input voltage into an AC output voltage [4], [9]. In order to control the voltage at the linked bus to the reference values, STATCOM is a shunt connected controller device that modifies the voltage and the angle of the internal voltage source. Whe voltage is low, high, under, or beyond the limit, STATCOM exhibits constant current characteristics. Due to the limitations of SVC, this enables the devices to produce constant reactive power. The STATCOM offers greater damping properties than the SVC from the perspective of stability of the power system since it can exchange active power with the system shortly.

2.3.3. Combined Series-Series FACTS Controllers

These may mix a variety of various series controllers. The setup of combined series-series FACTs controllers allows separate series reactive power compensation for each line in addition to distributing real power between the lines via a power connection. Since there is a power link between the series controllers, this system is referred to as a “unified series-series controller”. Feature of the Unified Series-Series Controller that transfer real power, is used to balance the flow of both real and reactive power through the line. The line feeder controller or the transmission capacity of the active power, which presents a unified serial controller, can both be used to balance the active and reactive power.

By properly connecting the dc terminals of the converters and controllers' controllers, the unified nature of the system makes it possible to achieve active power transfer between each other. Interline Power Flow Controller is a common illustration of a serial-serial controller.

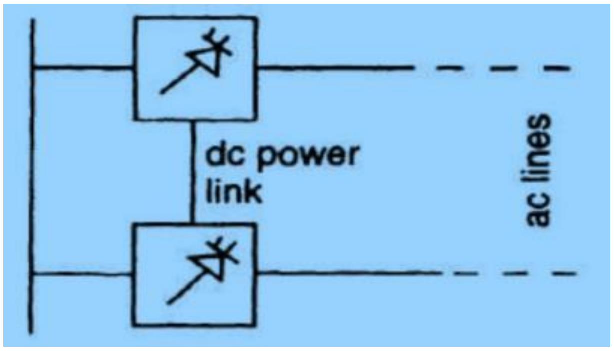


Figure 20: Schematic of a series-series FACTS Controller

Interline Power Flow Controller (IPFC):

It consists of two or more Static Synchronous Series Compensators (SSSC) coupled by a shared dc power link, which enables the bidirectional flow of actual power between the SSSC’s ac terminals [10].

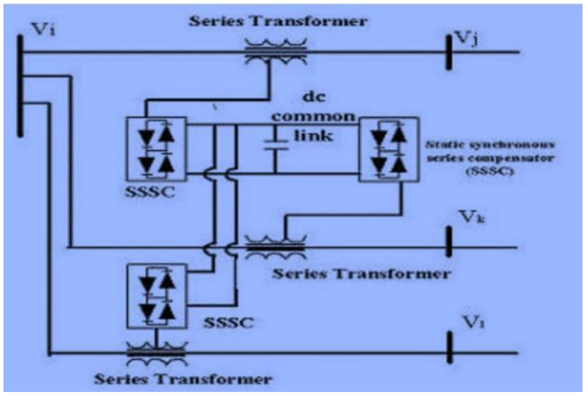


Figure 21: Basic structures of Interline Power Flow Controller

Two series VSCs that are injected into two different transmission lines make up the IPFC. A DC link connects the two VSCs so that they are side by side. The IPFC has four degrees of freedom in control since it can adjust the magnitude and phase angle of the injected voltage in both lines. The DC-link voltage is maintained at one degree, just like in the Unified Power Flow Controller (UPFC) [29], [30], while the remaining three degrees are employed to manage the real and reactive power in one line and the real or reactive power in another line. The series sources are split into two lines and by controlling the power flow in each line, the transmission capacity may be used more fairly. Additionally, without requiring any hardware changes, the individual VSCs of the IPFC can be detached and used as standalone Static Synchronous Series Compensators (SSSCs).

2.2.4. Combined Shunt-Series FACTS Controllers

These are separate arrangements of shunt and series controllers that are connected so that their controls are closely coordinated. When these controllers are connected to each other and to the line, the real power exchange occurs through the power dc link. They operate by introducing current into the system through the controller's shunt portion and voltage into the line through the controller's series portion. Thus, the series and shunt components of the controllers are combined. As a result, a suitable link can be used to enable real power exchange between the series and shunt controllers. UPFC and DPFC are two controllers that belong to this group.

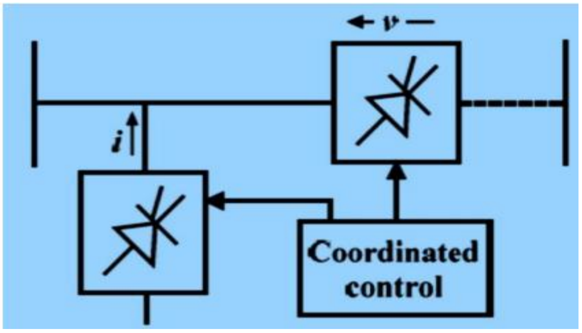


Figure 22: Organized series and shunt Controller

Some of shunt-series FACTS controllers are,

- Unified Power Flow Controller (UPFC)
- Distributed Power Flow Controller (DPFC)

Unified Power Flow Controller (UPFC):

UPFC is made up of STATCOM and SSSC that are connected via a shared DC power link to enable the bidirectional flow of actual power between the series output terminals of the SSSC and shunt output terminals of the STATCOM. FACTS concept's most promising gadget is a unified power flow controller (UPFC) [3], [19]. It can change all three-control parameters; bus voltage, line reactance and phase angle between buses simultaneously or separately. This is accomplished via a UPFC By controlling the shunt compensation, quadrature voltage, and in-phase voltage [31]. Figure 23 provides an illustration of the UPFC's general configuration.

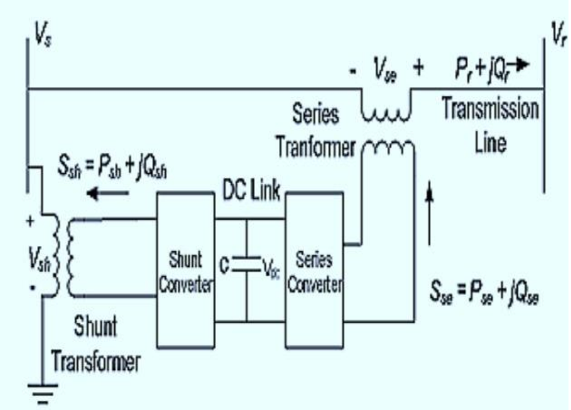


Figure 23: General configuration of UPFC

The DPFC is made up of a shunt converter and a number of tiny independent series converters, much like the UPFC. The series converter uses the D-FACTS, which uses several single-phase converters rather than a single three-phase converter. The shunt converter is comparable to the STATCOM.

Instead of using a DC-link to exchange power between converters, the transmission line is employed in the DPFC to connect the output of the shunt converter to the AC port of the series converters. Line parameters can be balanced by the DPFC, which has the same capabilities as the UPFC. Figure 24 depicts the DPFC's fundamental structure.

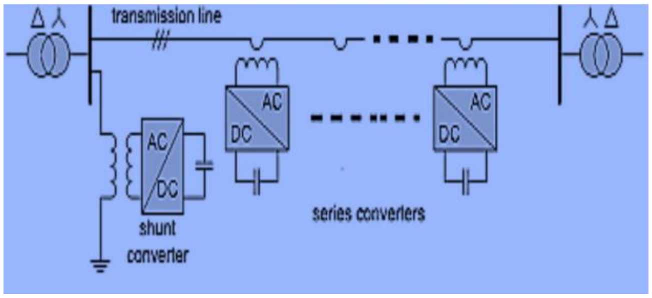


Figure 24: DPFC Configuration

FACTS devices has a number of benefits on power quality of transmission or distribution network, including power flow regulation, reduction of need for constructing new lines, reactors and capacitors and providing greater ability to transfer power between controlled lines [32], [24], [1].

2.2. LITERATURE REVIEW

Many people have worked on the topic of power quality. Thus, the following are the various published works that have been reviewed in relation to this research work.

In 2021, Yashoda R. Perkar et la [8] studied on improving the power quality of distribution network using compensation devices(custom power devices) to compensate load by correcting power factor, unbalance etc. or by improving the quality of supply voltage. The STATCOM-BESS control system is employed in this author's proposed approach to reduce the harmonic content of the load current. As a result, power quality is maintained at the common coupling point. For the fast dynamic response, the STATCOM employs a hysteresis current control method. It also ensures that voltage and current remain in phase. That means the source end maintains unity power factor. The findings reveal that the grid voltage and current are in phase, resulting in a power factor of one, implying that the reactive power demand of the Induction generator and load is now supplied by the STATCOM rather than the grid. In addition, the grid current has a nearly sinusoidal shape, and after adjustment, the percent THD has decreased from 11.08 percent to 5.78 percent. A low voltage grid connected wind powered IG system feeding a non-linear load has improved its power quality with the proposed control strategy.

In 2020, Miss. Shaikh Firdous Tarannum et la [33] reviewed STATCOM in improving power quality by gaining reactive power compensation and maintaining power factor in transmission and distribution networks. STATCOM is a dynamic and multitasking shunt compensator from the FACTS family that is highly preferred for practical usage in managing the transient behavior of the system under stressed conditions under acceptable economic constraints. This research focuses on control strategies as well as a variety of applications. The specified control strategies are extremely important in preserving the quality of the power system; therefore, STATCOM's versatility can help to increase power quality. It is a reactive power compensator that offers various benefits in a wide range of applications, and as a result, it has replaced many controllers. This compensator is a self-commuting SVC that is useful (both practically and economically) for both stand-alone and grid-connected systems. It can be used for load correction, HVDC integration, renewable energy, and many other things. STATCOM is a highly capable device for reactive power compensation, harmonics abatement, and power factor enhancement, or, to put it another way, it enhances the total power of a power system while also increasing system reliability.

In 2021, Divya Shende et la [30] used UPFC to clear the voltage sink and surges. The technology used to connect UPFC to the transmission line of the electrical system outperforms existing technology such as power stabilizers and automated voltage control. Studies on the relative variation of reactive power support, terminal voltage, and active power; UPFC has been shown to improve momentary stability and they get better volatility stability with UPFC than without it.

In 2021, Ibrahim M. Mehedi et la [1] had used Flexible AC transmission system(FACTS) in reducing the line losses, they proposes a fact-based method for minimizing the fault current in the system and improving performance of switchgear and protection equipment. As fault current limiters, many FACTS devices have been investigated. Several FACTS devices are being explored for their performance, including the SSSC, STATCOM, and UPFC. SSSC has little impact on fault current and voltage regulation, and instead focuses solely on reactive power flow. UPFC and STATCOM, on the other hand, can reduce fault current while also correcting voltage and regulating current. STATCOM and UPFC absorb reactive power from the system in such a way that fault currents are considerably reduced. UPFC outperforms STATCOM in terms of stability, transients, and voltage control. Because of the low fault current, the system's crucial clearing time will be extended. Because the switchgear and protection system will not need to be altered, more power can be sent. FACTS provides both economic and reliability benefits when used in a transmission and distribution system.

In 2020, SUNDEEP SIDDULA et la [34] did a comprehensive analysis on UPFC which is one of the FACTS devices. The significance of the FACTS device for the purpose of analysis is noted. The UPFC is one of the major FACT devices that are investigated, as well as the two compensations, series and shunt compensation. The performance of the UPFC with PI controller is also investigated. They suggest a Fuzzy logic controller for use with the Unified Power Flow Controller, and the results are evaluated. This is accomplished with the help of MATLAB/SIMULINK. Furthermore, this output is compared to the UPFC based on a PI Controller, and compensating values are extracted. In compared to the PI controller based UPFC, the introduced Fuzzy Logic Controller based UPFC has better compensatory values, according to this finding. As a result, it can be argued that the Fuzzy logic controller is an excellent controller for addressing Power Quality concerns.

In 2021, Kalpana Arunprasad et la [35] suggested four number of DSSCs for TTBDS to improve the voltage profile. Simulated TTBS with and without DSSC. The results show that the inclusion of DSSC improves voltage, real power, and reactive power. The increase in V, P, and Q is due to the installation of DSSC, which raises the voltage. The voltage sag in power and distribution lines can be compensated by DSSC. The disadvantage of DSSC is that it raises the cost of hardware. The current study examines TTBS with and without DSSC. In the future, studies on closed loop TTBS with PI and PR systems will be conducted.

In 2021, K. Naresh Kumar et la [25] measured the system's performance in the presence of TCSC using a range of strength machine variations, including voltage amplitude variance, weight turning on and off, generator output and grid synchronization, as well as voltage, energy glide, and impedance to enhance power quality. The usage of a thyristor switched collection capacitor to improve the electricity efficiency of the transmission network. In a series design, the TCSC is connected to the transmission line's two components. Various sorts of strength system disturbances have been established, including load switching on and off, outages, and generator grid synchronization, as well as metrics such as voltage, electricity flow, and impedance. The existence of TCSC was discovered in order to manage the strength system parameters in order to increase the device's durability. The results of the simulations suggest that the proposed TCSC is correct. The talk is on improving power quality in the power system's transmission system network. In series with the double portions of the transmission line, a thyristor-controlled series capacitor has been installed. Different types of power system disturbances, such as load switching, generator output, and grid synchronization, have been created. Voltage, current, power flow, impedance, and angle are the parameters that have been measured. The TCSC is in charge of the power system's parameters. As a result, the system remains more stable.

In 2021, D. Babu Rajendra Prasad et la [36] provided a series of novel technical approaches to reduce key power quality challenges. They provide thorough information on cutting-edge strategies for improving the power quality of distribution systems in both the DG and non-DG environments. The main power quality challenges (voltage and current harmonics, voltage and frequency changes) are thoroughly examined and mitigation solutions are divided into six categories: ODGP, CPD, Power converters, ESS, OLTC, and Hybrid filters. Each method's contribution to resolving PQ issues is tabulated. The contribution and capability of PQI devices are tabulated. The future research ideas in the power quality concern are outlined based on the major gap identification.

Chapter 3. DATA COLLECTION AND ANALYSIS

3.1. SITE DESCRIPTION

The case study area of this research is Kibuye distribution network connected to Karongi distribution substation, which is a part of Rwanda Energy Group located in western province, Karongi district. Kibuye distribution network has capacity of 30 Kv and is connected to 10MVA Karongi substation. Distribution substation step down 110 Kv to 30 Kv to distribute the power to the surrounding area through Kibuye and Mugonero feeder. The distribution substation is the source of distribution line data for this study. Currently, the distribution network is not supplying good quality of power due to power quality problems.

Figure 25: distribution substation

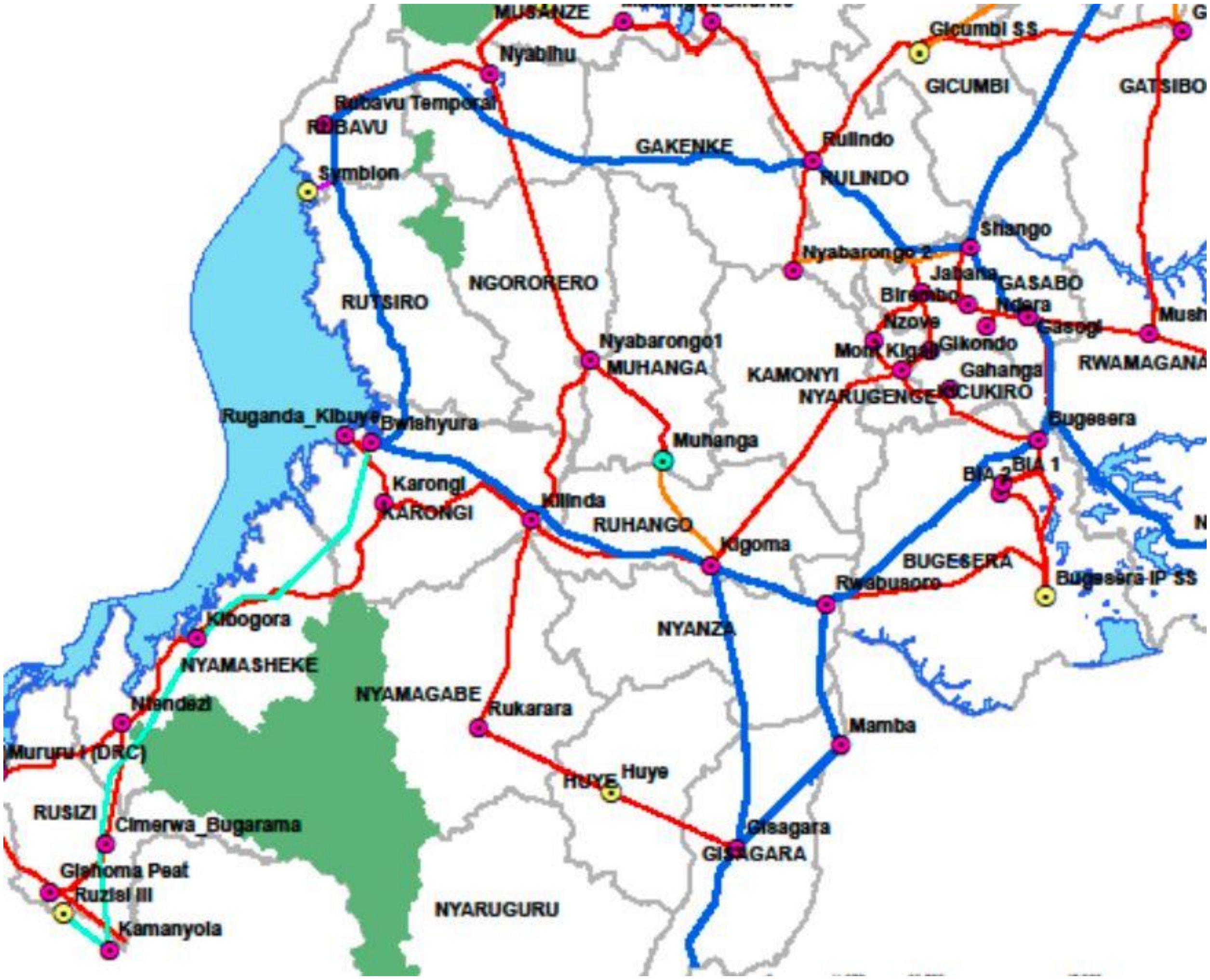


Figure 26: Karongi substation location

The single line diagram of proposed network is shown in figure 27

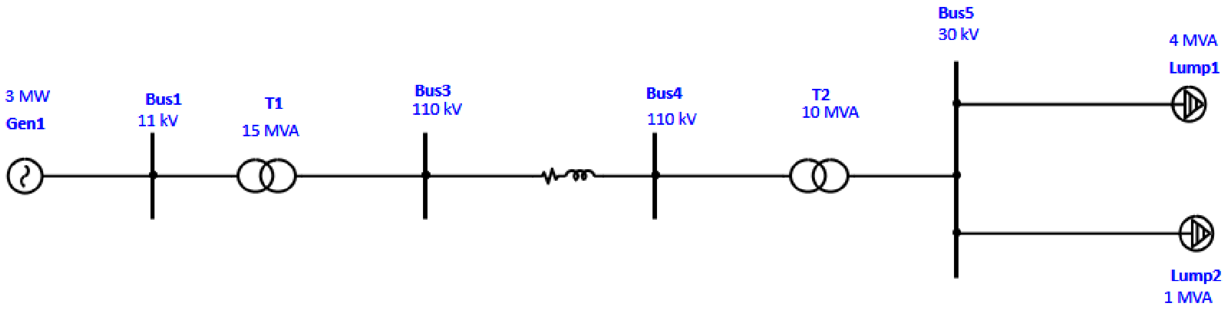


Figure 27: single line diagram

3.2. DATA COLLECTION

The data for the thesis are gathered from various day/night records at distribution substation from REG/EUCL at Karongi distribution substation as chosen site. Different collected data from the distribution substation are presented and analyzed. The collected data are different distribution line magnitudes and parameters like voltage, current, active power, apparent power, reactive power, frequency and power factor from Rwanda Energy Group (REG) Karongi substation. The distribution line voltage is 30 kV and the data has to be analyzed to evaluate the major power quality problem in the distribution network.

Table 1: Distribution substation data

DAILY DATA ON 24 JUNE 2022											
Hour	Current (A)			Voltage (kV)			Power			COSΘ	Freq.
	A	B	C	L12	L23	L31	S(MVA)	P(MW)	Q(MVAR)	Pf	F (Hz)
1:00	26	27	28	30.5	30.5	30.5	1.40	0.5	-1.40	0.34	49.7
2:00	27	27	28	30.3	30.3	30.3	1.40	0.52	-1.20	0.35	49.7
3:00	25	25	28	30.2	30.2	30.1	1.50	0.51	-1.40	0.33	49.4
4:00	28	28	29	30.4	30.4	30.4	1.50	0.5	-1.40	0.35	50.5
5:00	30	29	31	30.8	30.8	30.8	1.50	0.54	-1.50	0.32	50.3
6:00	29	28	29	30.6	30.6	30.6	1.40	0.33	-1.40	0.26	50.2
7:00	27	26	27	30.1	30.1	30	1.40	0.37	-1.20	0.29	50.2
8:00	24	24	25	30	30	30	1.30	0.55	-1.20	0.44	49.8
9:00	23	23	24	30.2	30.3	30.2	1.20	0.67	-0.91	0.55	49.1
10:00	23	24	24	30	30	30	1.30	0.7	-1.00	0.55	50.2
11:00	17	18	18	29.9	29.9	30	1.00	0.84	-0.58	0.81	49.5
12:00	19	19	19	30	30	30	1.10	0.94	-0.53	0.87	49.5
13:00	16	17	17	30.4	30.4	30.4	0.90	0.75	-0.50	0.85	50.3
14:00	21	22	21	30.7	30.7	30.7	1.10	0.8	-0.80	0.74	50.2
15:00	21	21	21	30	30.1	30.1	1.10	0.7	-0.90	0.62	49.7
16:00	25	26	26	30.1	30.1	30.1	1.30	0.92	-1.00	0.66	50.1
17:00	20	21	21	30.5	30.5	30.5	1.00	0.63	-0.83	0.55	50.2
18:00	21	21	21	30.2	30.2	30.2	1.10	0.63	-0.93	0.53	49.9

19:00	34	35	35	30.5	30.5	30.6	1.90	1.20	-1.50	0.64	49.7
20:00	42	42	42	30.2	30.2	30.2	2.30	0.83	-2.10	0.37	49.8
21:00	40	40	40	30.2	30.2	30.2	2.00	0.80	-1.90	0.37	49.9
22:00	32	32	32	29.9	30	30	1.70	0.60	-1.60	0.34	50
23:00	28	29	29	29.8	29.8	29.8	1.50	0.30	-1.50	0.17	50.1
0:00	25	26	26	29.9	29.9	29.9	1.30	0.32	-1.30	0.23	49.7

Table 1 contains data of different parameters like, voltage, current, frequency, power and power factor collected from Karongi distribution substation.

3.3. ANALYSIS OF THE DATA

Referring to Table 1, there is a variation in voltage, current, power factor and as well as frequency. The normal values are; 30kv for voltage, 50 Hz for frequency and 0.9 for power factor.

3.3.1. Load Variation

According to the collected data in table 1, Figure 25 shows daily current (load) variation of the three phase current for primary side of distribution network.

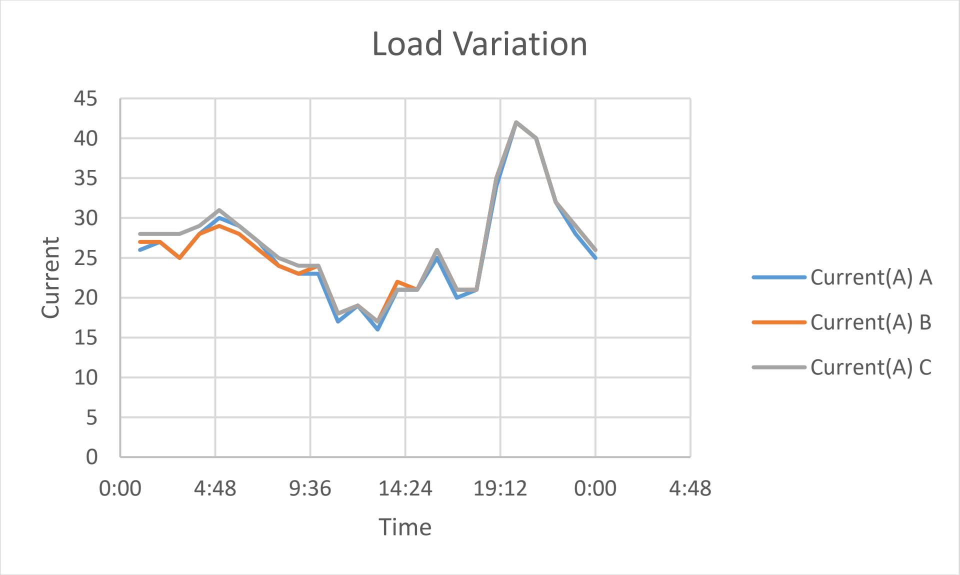


Figure 28: current variation

The current unbalance is computed for the maximum current deviation, as shown in Table 2 at the distribution substation for the current taken at 5:00 A.M.

Table 2: Maximum current unbalance values

Current	Values in A
I_A	30
I_B	29
I_C	31

According to the National Electrical Manufacturers Association of USA standard current unbalance is defined as the maximum deviation from the average of the three-phase currents, divided by the average of the three-phase currents, expressed in percentage, which is given by the following equation.

$$\%\text{current unbalance} = \frac{maximun\ deviation\ from\ mean(A,B,C)}{mean(A,B,C)} * 100 \qquad \text{(Eq.2)}$$

Where: mean=$\frac{30+29+31}{3}$=30 A

% current unbalance=$\frac{31-30}{30} * 100$ =3.33%

As can be seen from the result, the percentage of current unbalance is not beyond the acceptable limit imposed by the IEEE limit, which is 50%.

3.3.2. Voltage Variations

According to the collected data, Figure 26 shows daily voltage variation of the three phases for the primary side of the distribution system.

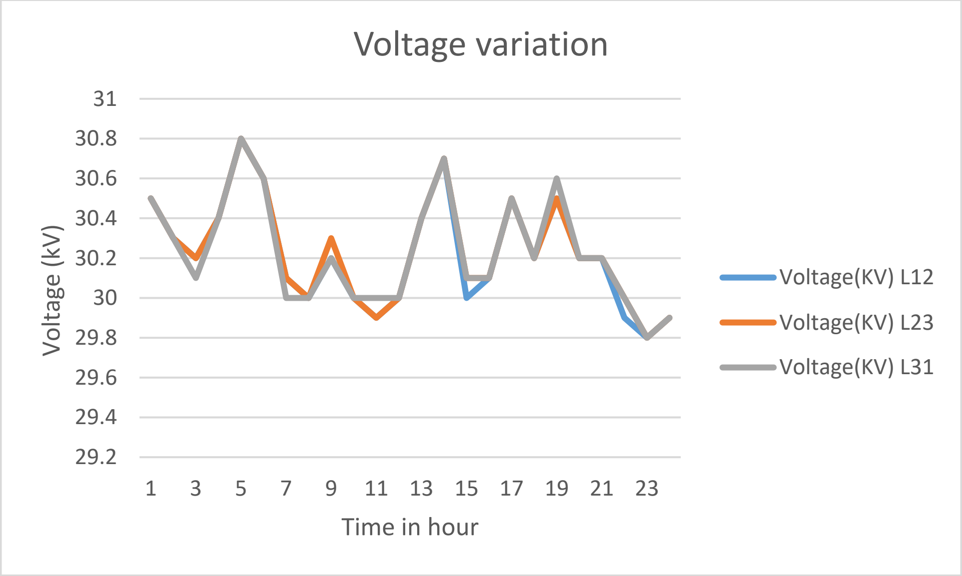


Figure 29:Three phase voltage variation

The nominal voltage of the distribution line is 30 kV. If the 30kv is the base voltage, the per unit voltage will be as follow (the measurement is taken at 9:00 AM):

Table 3: Three phase voltage measured

Voltage	value in kV	per unit value
V_{12}	30.2	1.006
V_{23}	30.3	1.01
V_{31}	30.2	1.006

From the per unit values, the percentage voltage unbalance is calculated using below formula

$$\%\text{voltage unbalance} = \frac{maximun\ deviation\ from\ mean(v_{12},v_{23},v_{31})}{mean(v_{12},v_{23},v_{31})} * 100 \qquad \text{(Eq.3)}$$

Where: mean=$\frac{1.006+1.01+1.006}{3}$=1.007 V

% voltage unbalance=$\frac{1.01-1.007}{1.007} * 100$ =0.29 %

As can be seen, the percentage of voltage unbalance is within the acceptable limit imposed by the IEEE limit of 2%. Therefore, the voltage unbalance is minimum.

3.3.3. Power factor variation

According to the data collected, Figure 27 shows daily power factor variation in the system for distribution substation.

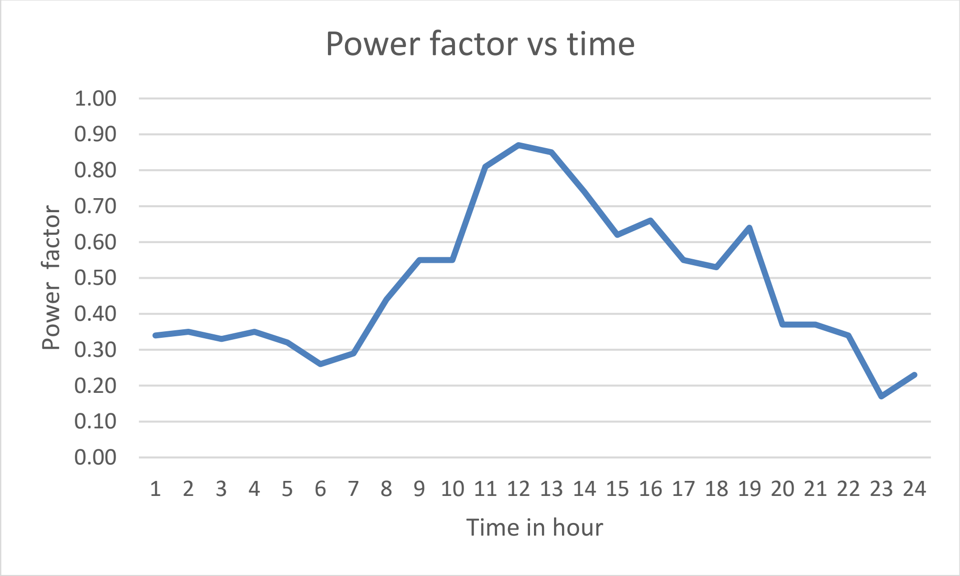


Figure 30: Power factor variation over a sample day

As can be seen from Fig. 3.3, the measured poor power factor varies between 0.2 to. 0.85, which is less than the standard value of 0.9; therefore applicable mitigation method should be implemented for its improvement.

3.3.4. Frequency variation

The maximum permitted frequency deviation is +5% or -5% of the nominal frequency.

5 % of 50 Hz is 5*50/100=2.5 Hz,

Therefore, the acceptable values are between 47.5 Hz and 52.5 Hz

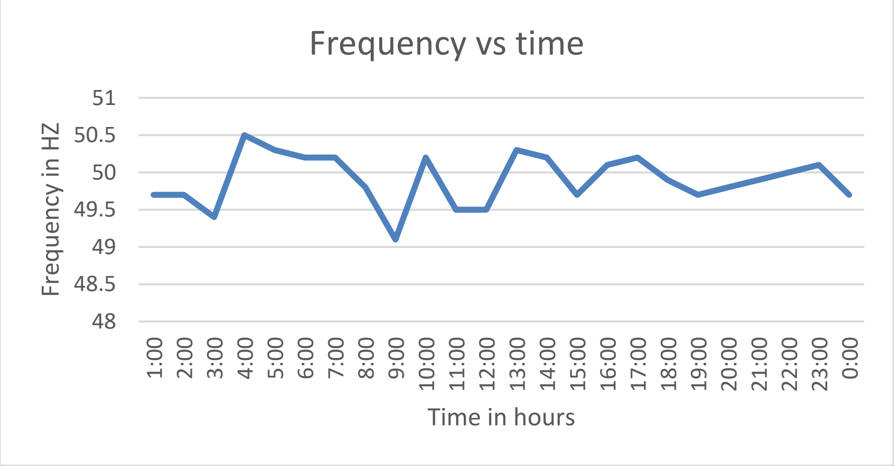


Figure 31: Frequency variation

As seen in Figure 31, the minimum and maximum values are not beyond 47.5 Hz and 52.5 Hz. This means that the frequency is within acceptable limit.

3.3.5. Power factor variation vs reactive and active power variation

Changes in the ration of active power versus reactive power has an effect on power factor of the system. When apparent power increases compared to the active power of the system, the power factor decreases. Eq. 4 shows the relationship between power factor, apparent, active and reactive power.

$$\cos\Theta = \frac{P}{S}\text{, Where } S = \sqrt{P^2 + Q^2} \qquad \text{(Eq.4)}$$

Therefore, to maintain the power factor to an acceptable value, we need to control the apparent power by controlling reactive power.

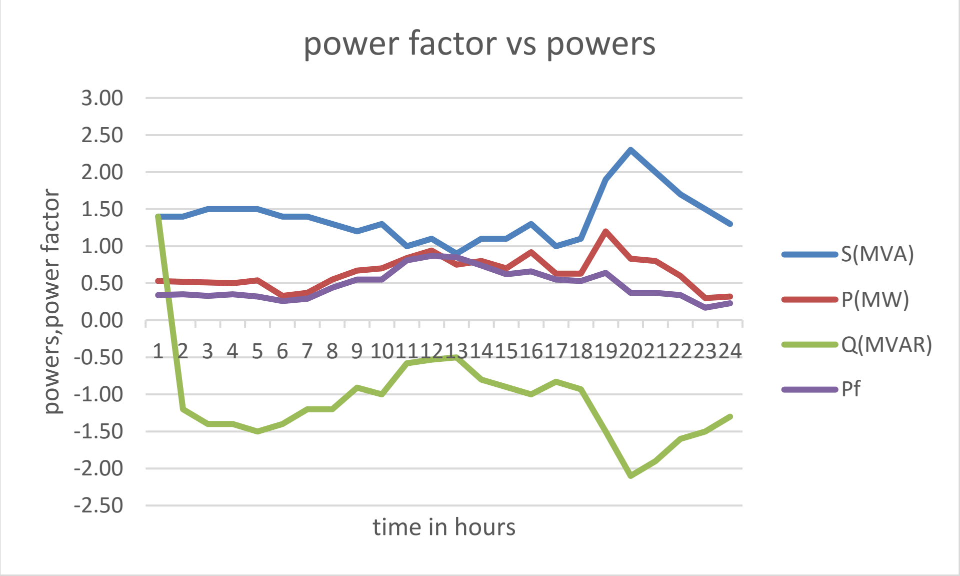


Figure 32: Power factor, active, reactive and apparent power variation

The increase of the reactive power of the system reduces the power factor of the system; hence by controlling the reactive power of the system, the power factor can be improved.

3.4. FACT DEVICES FOR IMPROVING POWR FACTOR

3.4.1. SVC

Reactive power is produced and absorbed by electrical loads. The transmitted load varies from hour to hour, which causes the reactive power variation. This may lead to voltage changes or a voltage depression. Under various network conditions, installing an SVC at one or more suitable points in the network can boost transfer capacity, cut losses, and provide a steady voltage profile. Additionally, SVC can reduce active power oscillations by modulating the voltage amplitude [14], [26]. The reactive power can be changed by coordinating the control of several of these branches. SVCs are a member of the Flexible AC Transmission System Device, which controls harmonics, power factor, voltage, and system stability. A static VAR compensator has minimal moving parts compared to a rotating electrical unit like a synchronous condenser. Power factor adjustment was previously only possible with huge spinning equipment like synchronous condensers or switching capacitor banks. The SVC is an automatic impedance matching tool created to nudge the system's power factor closer to unity and has some advantages on power system like, increasing of power transmission capability, improving transient, controlling the steady state and overvoltage, improving the load power factor and reducing line losses and improving system capability.

3.4.2. STATCOM

STATCOM is superior to the synchronous condenser in a number of respects, including better dynamics, reduced investment costs, and lower operating and maintenance expenses. [22], [33] The control characteristic for the voltage is determined by the slope of the static line between the current constraints. The benefit of a STATCOM is that it maintains its complete functionality even in the worst emergencies since the reactive power provision is independent from the actual voltage on the connection point. The STATCOM controls system voltage based on a voltage-sourced converter by creating or absorbing reactive power. [9], [37] STATCOM output current can be regulated independently of the AC system voltage, in contrast to a thyristor-based Static Var Compensator (SVC) [14], [38], [23]. STATCOM systems are divided into two categories: Transmission STATCOM and Distribution STATCOM, albeit sharing the same structure. A set of three balanced quasi-sinusoidal voltages is meant to be injected by Transmission STATCOM, which has a higher MVAR rating, to manage the flow of reactive power in the transmission system.

3.4.3. COMPARISON OF STATCOM AND SVC

Table 4: Comparison of STATCOM and SVC [21]**,** [32]**,** [14]

Device capability	SVC	STATCOM
Types of device	Shunt	Shunt
Main function	Voltage control	Voltage control
Controllers	Thyristor	IGBT, GTO
Cost	Low	Medium
Reliability	Low	Medium
Voltage stability	High	High

Response time	2 to 3 cycle	1 to 2 cycle
Transient behavior	Available before, during and after critical system condition	Self-protected at critical system fault
Space requirement	100%	40 to 50%
Availability	>99%	96 to 98%

From the comparison, due to better and greater flexibility and delivery of constant reactive power D-STATCOM is has better performance and is selected for improving the current unbalance and low power factor.

Chapter 4. MODELLING AND SIMULATION

4.1. Operation of STATCOM

STATCOM is a three phase shunt connected power electronic based devices, and is connected across the load at the distribution systems [39], [40]. Distribution line and STATCOM exchanges real and reactive power by controlling the voltage magnitude and phase angle of STATCOM [41]. The load absorb reactive and real power by a three-phase power supply due to it inductive nature.

The purpose of STATCOM is to control reactive power in phase with system voltage and to reduce voltage variance. It is capable of linearly and continuously compensating for inductive and capacitive current. The terminal voltage $\mathbf{V_{bus}}$ equals the addition of the inverter voltage $\mathbf{V_{STATCOM}}$, the voltage across the leakage reactance $\mathbf{V_L}$, and the resistance in the inductive and capacitive modes. This means that STATCOM will supply reactive power to the system if its output voltage $V_{STATCOM}$ is in phase with the bus terminal voltage $\mathbf{V_{bus}}$, and $V_{STATCOM}$ is greater than Vbus [42], [39]. If $V_{STATCOM}$ is less than $\mathbf{V_{bus}}$, the power system's reactive power is absorbed by STATCOM [40]. There will be no power exchange if $V_{STATCOM}$ and V_{bus} are equal; STATCOM will then function in floating mode [43].

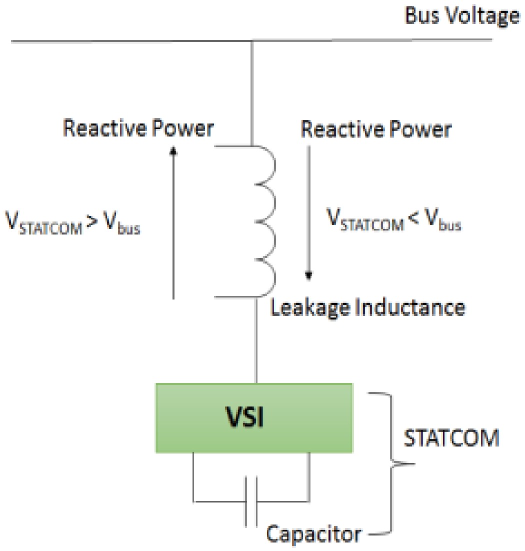


Figure 33: Operating principle of STATCOM

The terminal voltage V_{bus} is equal to the sum of STATCOM output voltage and voltage drop across line reactor and resistance.

V_{bus} = bus terminal voltage

$V_{STATCOM}$= output voltage of STATCOM

X_L= inductive reactance

V_{dc}= DC capacitor voltage

Mathematical equation of STATCOM for active power, reactive power and STATCOM output voltage [44] may be given as

$$P= (V_{bus}*V_{STATCOM}/X_L) \sin\alpha \qquad \text{(Eq.5)}$$

$$Q= (V_{bus}*V_{bus}/XL)-(V_{bus}*V_{STATCOM}/xl) \cos\alpha \qquad \text{(Eq.6)}$$

4.2. Mathematical modeling of D-STATCOM

The performance of D-STATCOM is demonstrated in this thesis work using the distribution system, resistance, leakage inductance, VSI, and a DC capacitor make up D-STATCOM. Inductance and resistance serve as the system's magnetic coupling. Constant voltage is provided by DC capacitor, which serves as source. It uses an IGBT with an anti-parallel diode. While a diode conducts rectification, an IGBT performs conversion. The system and STATCOM are both considered three-phase balanced system, voltage source V_{shunt} with a programmable fundamental frequency can serve as an analogous representation of the STATCOM [44].

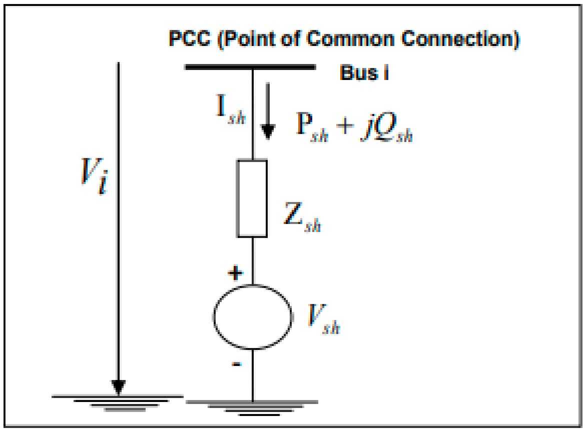


Figure 34: equivalent circuit of D-STATCOM

Based on the equivalent circuit, it can be accepted that V is the voltage at bus i, and **I**$_s$ the current through the STATCOM shunt converter [45]. **P**$_s$ and **Q**$_s$ are the shunt converter branches' active and reactive power flow. The power flow direction of **P**$_s$ and **Q**$_s$ is leaving the bus i. **Z**$_{\textbf{shunt}}$ is the equivalent STATCOM shunt coupling transformer impedance. Assume, based on the equivalent circuit.

$$P_{sh} = Vi^2 g_s - V_i V_s (g_s \cos(\theta_i - \theta_s) + b_s \sin(\theta_i - \theta_s)) \qquad \textbf{(Eq.7)}$$

$$Q_{sh} = -Vi^2 b_s - V_i V_s (g_s \sin(\theta_i - \theta_s) - b_s \cos(\theta_i - \theta_s)) \qquad \textbf{(Eq.8)}$$

Where $g_s + j\, b_s = \frac{1}{Z_s}$

Once the output voltage of STATCOM is the same as the voltage of the grid ($V_{STATCOM}$=Vi) then the exchange of reactive power between the STATCOM and the grid is equal to zero. In contrast, if STATCOM voltage is lower than the grid voltage at the point of common connection (PCC), the STATCOM absorbs reactive power. Reactive power is injected into the grid if the STATCOM output voltage is greater than the grid voltage at the PCC, $V_s > V_i$. Also, keep in mind that the maximum voltage and maximum current permitted by the semiconductors set a restriction on the ability to inject reactive power into the grid.

4.3. Simulation

Flexible Alternating Current Transmission Devices (FACTS) can overcome power quality issues. Therefore, the proposed system helps to solve the problems regarding with power factor, and some current unbalance. MATLAB Simulation model of distribution network is shown in Figure 31. Point of Common Coupling (PCC) is used to access the parameters from electrical distribution network. Static Compensator (STATCOM) is connected in parallel with the distribution network to improve the power factor. Powergui used to simulate the MATLAB Simulation Model is in discrete or phasor time.

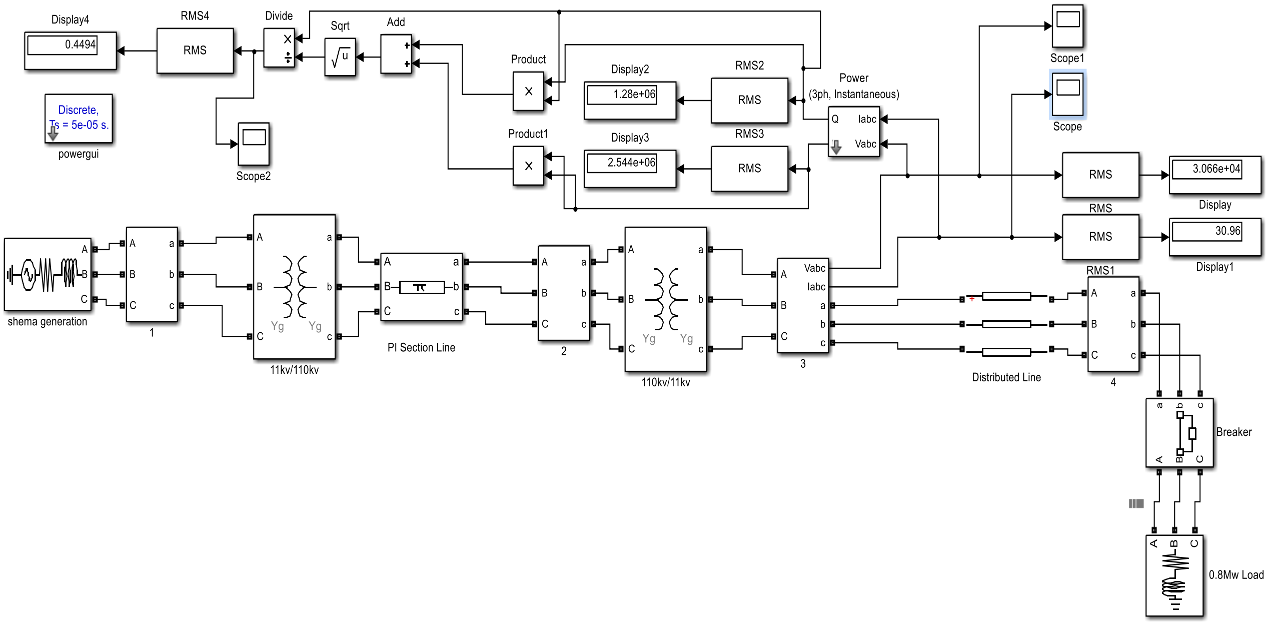


Figure 35: Matlab/Simulink model of distribution network without STATCOM

For the system proposed, Matlab Simulink software is used to model the system as shown in figure 32. STATCOM is connected to improve the power factor of the system by controlling the system reactive power. The power factor of distribution network has to be improved from 0.3 to at least 0.9 to have better performance of distribution network. The reactive power to be supplied by STATCOM to improve the power factor of distribution network is given by, P= S*PF (Eq.9)

P=1.5MVA*0.96= 1.44MW

Reactive power Q=$\sqrt{S^2 - P^2}$=$\sqrt{1.5^2 - 1.44^2}$= 0.42 MVar

Reactive power taken from the grid is given by

S=$\frac{P}{PF}$ and Q=Ssin ϴ (Eq.10)

S=$\frac{1.44MW}{0.44} = 3.27\ MVA$

ϴ=$\cos^{-1} 0.44 = 63.89^0$

Q= 3.27MVA*sin 63.89 = 2.936 MVar

To improve the power factor of distribution network from 0.4 to 0.9, the amount of reactive power needed to be injected by STATCOM is

Q_S= (2.936-0.42) MVar =2.516 MVar

The size of STATCOM to compensate reactive power of 2.516 MVar is

$Q_{STATCOM}$= Q_S +10%of Q_S (Eq.11)

as (IJETT)-volume 40 October 2016 says that the tolerance must be 10% of the reactive power needed by the system

$Q_{STATCOM}$= 2.516MVar +0.2516 MVar =2.7676 MVar

Considering 1% active power dissipation of STATCOM

The size of STATCOM is $P_{STATCOM}$= $Q_{STATCOM}$*1%=2.7676*0.01 MW= 0.027676MW equivalent to 27.676 kW

The apparent power of STATCOM is

$S_{STATCOM}$= $\sqrt{Q^2 + P^2}$= $\sqrt{2.7676^2 + 0.027676^2}$= 2.7677 MVA

Therefore, 2.7677 MVA rating of STATCOM is used to improve the power factor of distribution network from 0.44 to 0.96. The voltage of STATCOM is 30kv, and converter rating, DC link voltage of STATCOM are adjusted to 9.54 kVA and 25.083kV.

The capacitance of DC link is calculated as follow

Reactance (X_C) $=\frac{{V_{STATCOM}}^2}{0.15*Q_{STATCOM}}=\frac{30000^2}{0.15*2.7676*10^6}=2167.9\ \Omega$

Capacitance (C) $=\frac{1}{2\pi F*X_C}=\frac{1}{2\pi*50*2167.9}=0.000001468\text{ F}=1.468\mu\text{f}$

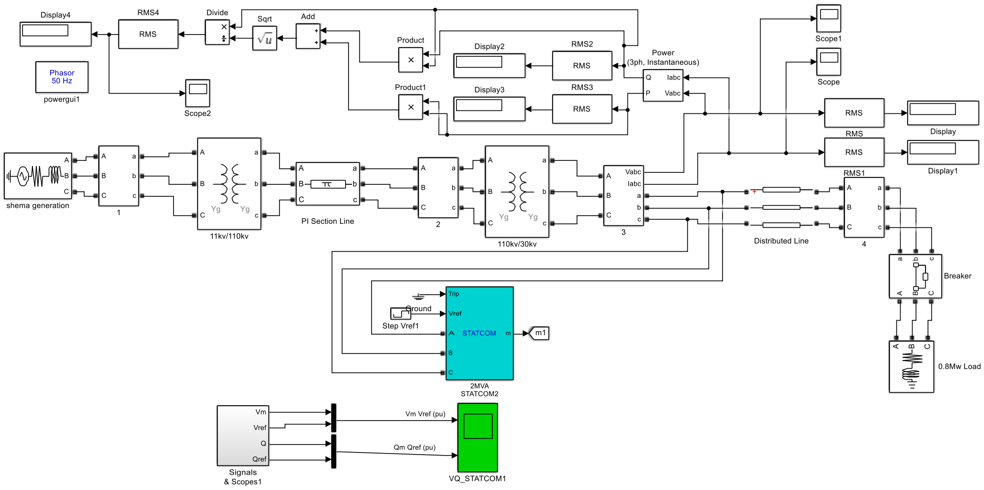


Figure 36: Matlab/Simulink model of distribution network with STATCOM

Power factor improvement is important for both consumer and utility. Figure 37 shows the simulation result without STATCOM.

4.4. Simulation result without STATCOM

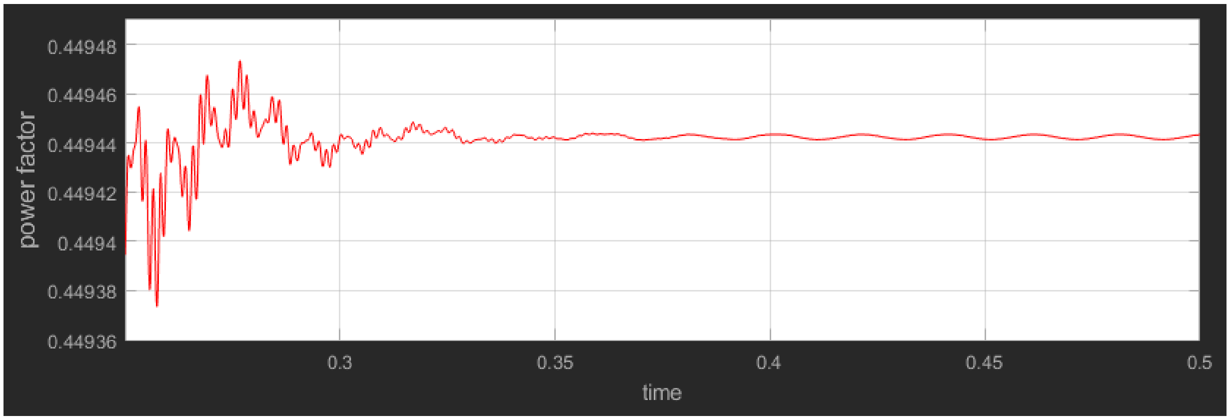


Figure 37: Power factor without STATCOM

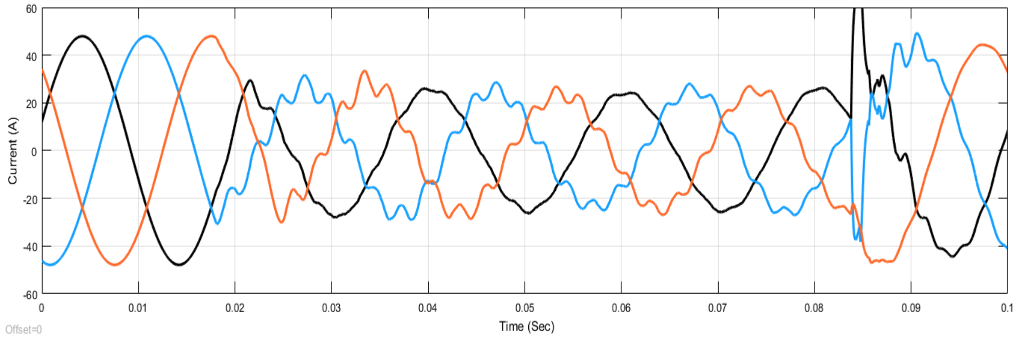


Figure 38: Current without STATCOM

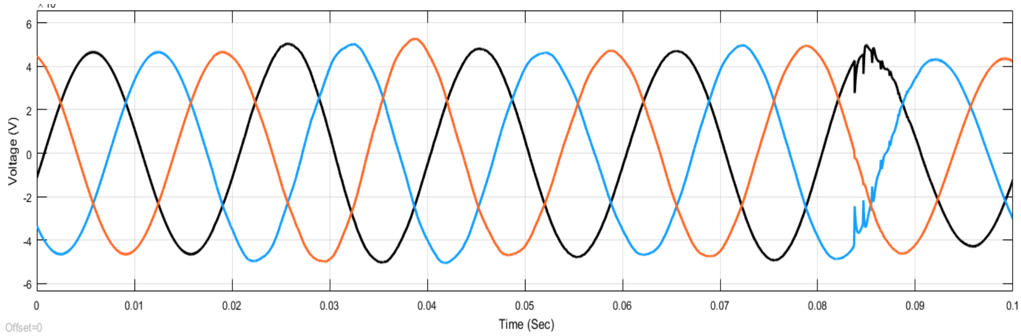


Figure 39: Voltage without STATCOM

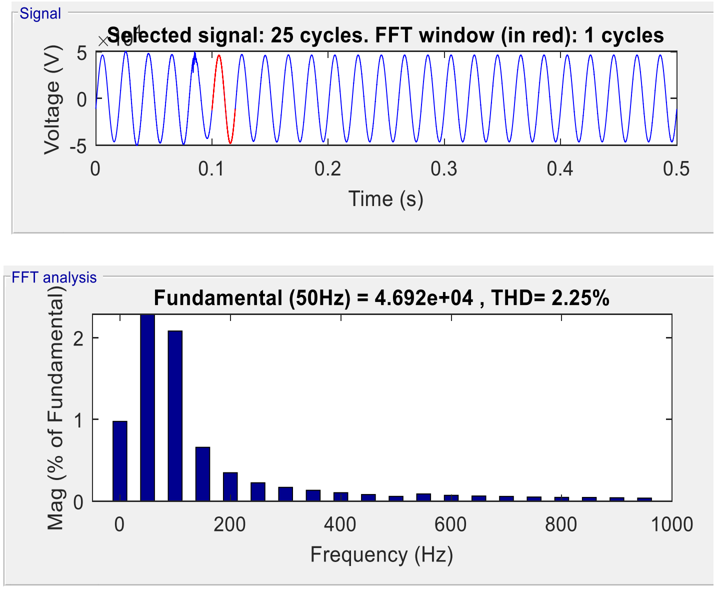


Figure 40: FFT analysis of voltage without STATCOM

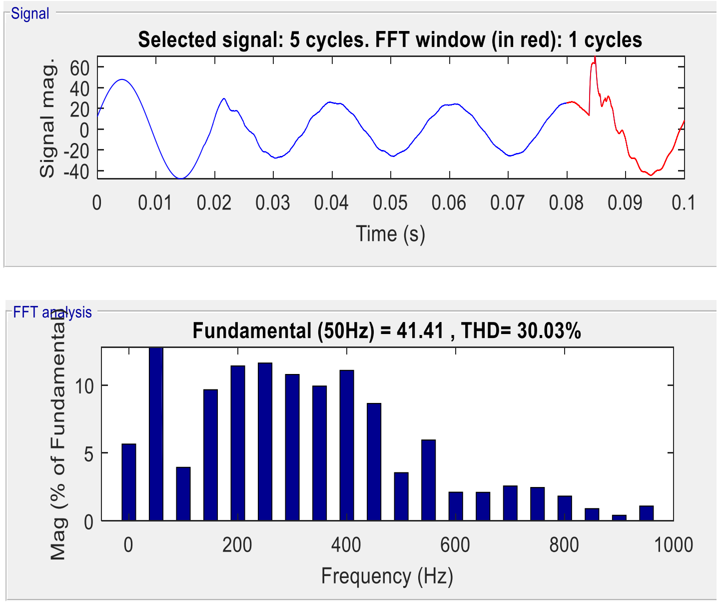


Figure 41: FFT analysis of current without STATCOM

4.5. Simulation result with STATCOM

The STATCOM measured voltage, Vm indicated by red line follows the reference value, Vref indicated by blue line for voltage regulation, and the reactive power generated or absorbed by the

STATCOM, Qm with red line and Qref with blue line as reference. The negative and positive means generation and absorption of reactive power by STATCOM. This shows that STATCOM supply or consumes reactive power to the system to maintain system voltage and improve power factor for power quality and system efficiency.

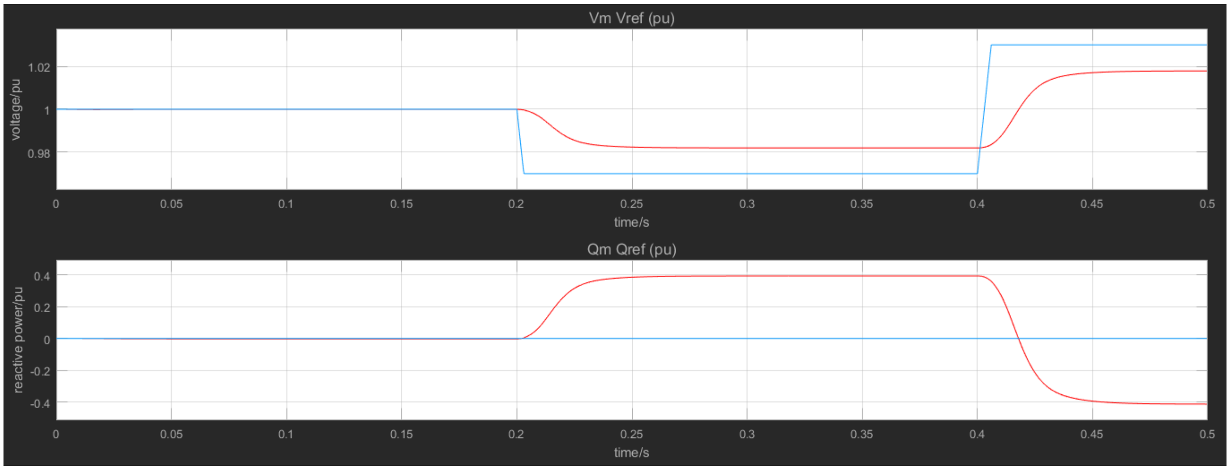


Figure 42: Voltage and reactive power supplied or consumed by STATCOM with reference values

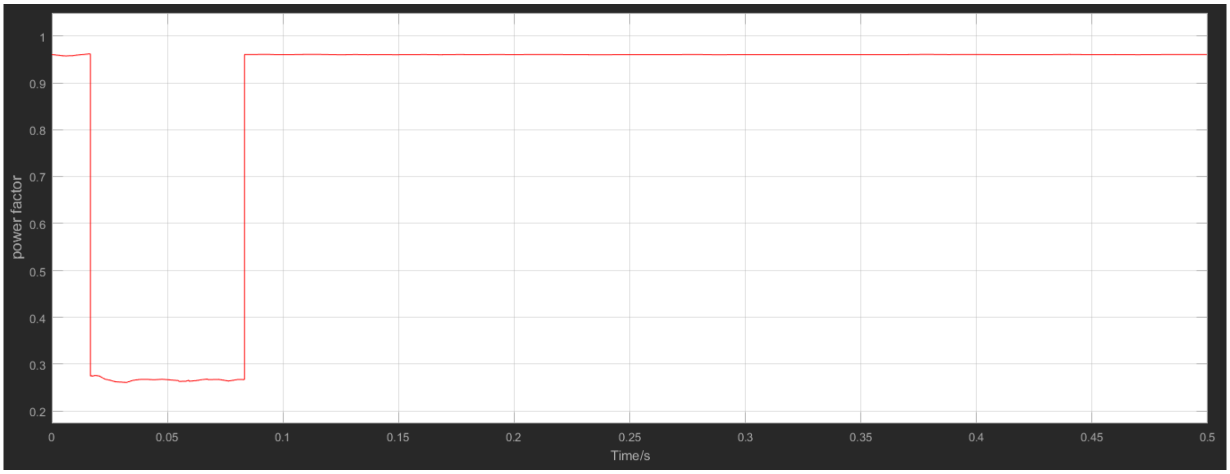
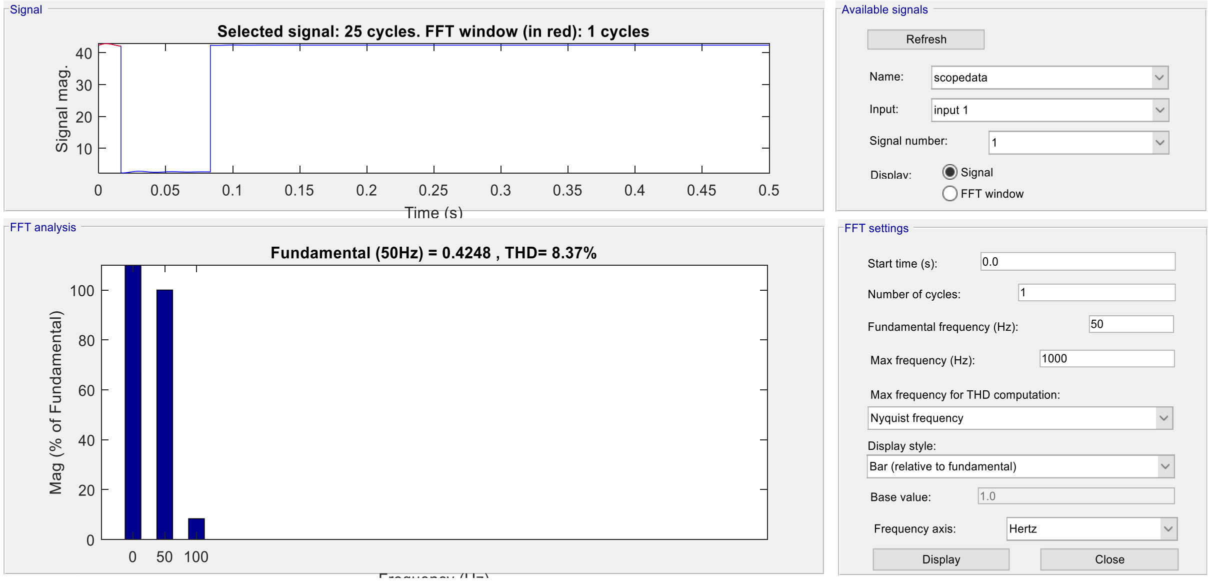


Figure 43: Power factor of distribution network with STATCOM



Selected signal: 25 cycles. FFT window (in red): 1 cycles

Fundamental (50Hz) = 0.4248 , THD= 8.37%

Name: scopedata
Input: input 1
Signal number: 1
Display: ● Signal ○ FFT window

Start time (s): 0.0
Number of cycles: 1
Fundamental frequency (Hz): 50
Max frequency (Hz): 1000
Max frequency for THD computation: Nyquist frequency
Display style: Bar (relative to fundamental)
Base value: 1.0
Frequency axis: Hertz

Figure 44: FFT analysis of current harmonics with STATCOM

The system power factor is improved to 0.96 and total harmonic distortion is improved to 8.37% after connecting STATCOM on a distribution network.

Chapter 5. CONCLUSSION AND RECOMMENDATION

5.1. CONCLUSSION

This thesis work aims to study the power quality issues in distribution network and provide factual device to improve the power quality problem. Power factor correction is presented in this work and is achieved by using Matlab/ Simulink model of a distribution line with fact device called static synchronous compensator (STATCOM), the performance and control of STATCOM for power quality improvement is presented. This is achieved by modification of the control scheme made in this work of adding reactive power with zero reactive power reference and Power factor of 0.96 is achieved not only that, total harmonic distortion (THD) is improves to 8.37%. From the simulation result, it is concluded that STATCOM control scheme shows the effectiveness of STATCOM for power factor correction in distribution network.

5.2. RECOMMENDATION

Currently, the use of power electronic based devices known as Flexible AC transmission devices (FACTS) is encouraged due to many advantages they provide. Utilities are encouraged to use FACTs devices which have the ability to maintain the power quality of the power system. These devices provide good quality of power by controlling the system voltage, active and reactive power. They are able to maintain the network parameters without changing the existing system, by simply connecting the device to the power system. For this research, distribution network was considered. However, with the integration of FACTs called STATCOM, the power quality (power factor) of distribution networks is improved. For this reason, flexible AC transmission devices (FACTs) will be considered for further research. Again, in the future research, I recommend that other categories of fact devices will be considered for better performance of power system.

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