# Enhancement of Voltage Stability and Loss Minimization Based on FACTS Devices Using Interline Power Flow Controller

(Case Study Area: Butajira Distribution Substation)

Sunemo Legese Delwato

A Thesis Submitted to

The Department of Electrical Power and Control Engineering,

School of Electrical Engineering and Computing

Presented in Partial Fulfillment of the Requirement for the Degree of Master's Science in Electrical Power and Control Engineering (Power System Engineering)

Office of Graduate Studies

Adama Science and Technology University

September, 2022

Adama, Ethiopia

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# DECLARATION

I hereby declare that this Master thesis entitled Enhancement of Voltage Stability and Loss Minimization Based on FACTS Devices Using Interline Power Flow Controller is my original work. It does not have been submitted for the award of any kind of academic degree, diploma, or certificate in any other university. The sources of materials that are used for this thesis have been properly acknowledged through citation.

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# RECOMMENDATION

I, the advisor of this thesis, hereby certify that I have read the revised version of the thesis entitled Enhancement of Voltage Stability and Loss Minimization Based on FACTS Devices Using Interline Power Flow Controller prepared under my guidance by Sunemo Legese submitted in partial fulfillment of the requirements for the degree of Master's Science in Power System Engineering.

Therefore, I recommend the submission of a revised version of the thesis to the department following the applicable procedures.

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## APPROVAL SHEET

I, the advisors of the thesis entitled Enhancement of Voltage Stability and Loss Minimization Based on FACTS Devices Using Interline Power Flow Controller and developed by Sunemo Legese, hereby certify that the recommendation and suggestions made by the board examiners are properly incorporated into the final version of the thesis.

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We, the signed, the members of the Board of Examiners of the thesis by sunemo legese have read and evaluated the thesis entitled Enhancement of Voltage Stability and Loss Minimization Based on FACTS Devices Using Interline Power Flow Controller and examined the candidate during the open defense. Therefore, to certify that the thesis is accepted for partial fulfillment of the requirement of the degree of Master's Science in Power System Engineering.

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Finally, approval and acceptance of the thesis is contingent upon submission of its final copy to the Office of Postgraduate Studies (OPGS) through the Department Graduate Council (DGC) and School Graduate Committee (SGC)

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# ABBREVIATION AND ACRONYMS

| | |
|---|---|
| AAC | All Aluminum Conductor |
| AC | Alternative Current |
| DC | Direct Current |
| DG | Distribute Generation |
| FACTS | Flexible Ac Transmission Systems |
| GTO | Get Turn Off |
| HV | Higher Side Voltage of Transformer |
| HVDS | High Voltage Distribution System |
| I | Current |
| IGBT | Insulated Gate Bipolar Transistor |
| IGCT | Insulated Gate Commutated Thyristor |
| IPFC | Interline Power Flow Controller |
| KCL | Kirchhoff's of Current Law |
| KV | Kilo Volt |
| KVL | Kirchhoff's of Voltage Law |
| LV | Lower Side Voltage of Transformer |
| PI | Proportional Integral |
| PID | Proportional Integral and Derivative |
| PLL | Phase Locked Loop |
| PU | Per Unit |
| PWM | Pulse Width Modulation |
| Ref | Reference |
| RES | Renewable Energy Sources |
| RMS | Root Mean Square |
| SCT | Saturation Current Transformer |
| SSR | Sub Synchronous Resonance |
| SSSC | Static Series Synchronous Compensator |
| STATCOM | Static Synchronous Compensator |
| SVC | Static VAR Compensator |
| SVS | Static Voltage Source |

| | |
|---|---|
| t | Time |
| TCPAR | Thyristor Controlled Phase Angle Regulator |
| TCR | Thyristor Controlled Reactor |
| TCSC | Thyristor Controlled Series Compensator |
| TCVR | Thyristor Controlled Voltage Regulator |
| UPFC | Unified Power Flow Controller |
| V | Voltage |
| V1 | Sending end voltage |
| V2and V3 | Receiving end voltage |
| Vs | Injected voltage |
| VSC | Voltage Source Convertor |
| Vseff | Sending effect voltage |
| VSI | Voltage Source Invertor |

# ***ABSTRACT***

*Power system is subjected with various type of interruption, due to rapidly increasing the demand of electricity, internal and external factors and interconnected power systems network complexity. Due to these challenges the power system stability has been affected and loss of the power system increase from generation to distribution system, and also difficulties to the system operation, planning and maintenances scheduling. These kind of problems are found in Butajira substation distribution network. To solve these kind of problems, building new distribution substation and network reconfiguration is difficult. Flexible Alternating Current Transmission System device can enhance voltage stability and loss minimization during disturbances. From the FACTS device in this thesis interline power flow controller is enhancing voltage stability and loss minimization for distribution network by controlling distribution network parameters. It compensate real and reactive power by injecting voltage to the line of distribution network with the quadrature of line current. Modeling and analysis of Interline power flow controller with and without faulted outgoing feeder line has been carried out based on proportional integral controller by using MATLAB Simulink software. From the simulation result the system at faulted condition without IPFC the voltage below 20kv and the current increased from 100A to 1500A at 33kv feeder also active and reactive power increased 4.8MW to 21MW and 2.736 to 48Mvar respectively. The system with IPFC during faulted condition the current increased from 100A to 200A at fault occurring line and remain constant all other outgoing lines. Also, active and reactive power increased 0 to 9MW and 0 to 8.04Mvar respectively. From this observed that system voltage has become more stable, the power transferability has increased from 5.4 to 5.88MW the system with IPFC and loss of the system also decreased.*



**Keywords***: - Flexible AC Transmission Systems, Interline Power Flow Controller, voltage stability and loss minimization.*

# CHAPTER ONE

# INTRODUCTION

## 1.1 Background

An Electrical power system has become a vast and more complex interconnected network, so it is subjected to sudden changes in load levels. The distribution system is part of a power system to distribute the power from the substation to the end-user. The distribution network is being faced with load demand. The load demand increase causes an increase in the burden at the feeder and changes the bus voltage profile level. An electric distribution system mainly delivers electric power from the high voltage transmission line level to the customer's load center. As a result, utilities should provide sustainable and cost-effective service while maintaining service voltages and power quality within defined limits. There are various power quality issues in electric power distribution networks due to different types of load available in varied ranges of energy consumption, over and under loading, equipment, and insulation failure. The load current supplied from the source would increase in a highly overloaded distribution network, and the stress would lead the system to losses a lot of power and have an inappropriate voltage profile. In this system network, the ratio of resistance to inductance is significantly higher than that of a transmission system (Ćalasan et al., 2020). Voltage stability enhancement and power loss minimizations analysis have become significant studies in the power system to keep its stability with some interruption.

In the power system, there are problems with keeping their operating and acceptable system parameters like bus voltage profile level active and reactive power during normal and abnormal operation. This problem occurs especially distribution side because the power system contact with the individual end-user customer. The system needs regulation and regaining steady operating system profile after overloaded and fault is created. Faults can cause reduce of voltage profile and loss of power. Insulation failure or compromise caused by lightning ionizing air, power cables blowing together in the wind, animals or plants coming into contact with the wires, salt spray, pollution on insulators, system overloading, far away from the substation with uncontrolled buses at the receiving end-user, and natural causes such as harsh weather conditions. To maintain acceptable values, reduce actual and reactive power losses by limiting the power flow of the lines loaded with more than the permitted limit and improving voltages for the bus network.(Salman, 2015).

Power electronics-based equipment, also known as flexible AC transmission systems (FACTS) devices, is being created in response to variation of active and reactive power flow control and the rapidly growing power electronic technologies. The management and operation of the power system have grown extremely complex as a result of rising power demand, the incorporation of prosumers, continual growth, a competitive market, and the inherent limits of alternating current. The employment of developing technology was unavoidable for cost-effective, dependable, and secure operations (Hussain et al., 2018). The FACTS devices used to control most parameters like voltage, inductance and phase angle of systems network which to improve the network's transmission and distribution capacities while also improving the system's security. This devices improve transmission and distribution system controllability while also boosting power transfer capacity (Shahgholian & Yousefi, 2019).

FACTS devices can be categorized into two classes based on their technical approach. In the first group, thyristor valve and tap changing transformer-based controlled such as /TCVR and TCPAR/, static VAR compensator/SVC/, thyristor controlled series capacitor/TCSC/, and etc. In the second group, self-commutated voltage source switching converters-based such as Static Synchronous Series Compensator (SSSC), interline power flow controller/IPFC/, unified power flow controller/UPFC/, Static Synchronous Compensator /STATCOM/, and etc. These devices are also divided into three classes based on how they link to the system: shunt compensators, series compensators, and mixed compensators. The shunt compensators are connected in parallel with the power system, and injected current into connected line of power system. Which include SVC and STATCOM, and etc. The series compensators are series connected with the power system and which injected the voltage to connected line of power system. Which include TSSC, TCSC and SSSC, and etc. The compensator which are made from the combination of both series and shunt compensating power electronic based components are called combined compensators. This may be series- series or series- shunt combination. UPFC and IPFC are the combined compensators from the above two groups. From the FACTS compensating devices, unlike other FACTS controllers' devices (STATCOM, TCSC, SSSC, UPFC and etc.), which are used to manage a single line, however IPFC could be controlled independently the active and reactive power flows to satisfies the suitable set value of the power system parameters and increase power transferability of multiline substation of power system. To improve system stability and loss minimization, series and combination compensators would be a preferable choice. As a result, an interline power flow controller (IPFC) is utilized to boost line power transfer capacity, manage power flow, adjust for reactive power, and avoid network overload. In addition to these, the tool's improved voltage stability, dynamic and transient stability correction, and used as a power filter in distribution and transmission systems have all turned it into a multifunctional device (Baddu Naik et al., 2021; Bhadoria & Bhadoria, 2013; Buraimoh et al., 2018; Okakwu et al., 2018).

If a system has at least one unstable bus, it is considered unstable. As a result, power engineers must identify the more loaded and disturbed buses and locations to design and manage active and reactive power and control voltage effectively. For this purpose, an approach for the appropriate modeling of the distribution system for the interconnected scheme with IPFC for the Butajira radial distribution power system network.

The Cause study would be carried out at Butajira distribution substations, which are found in the south nation nationality people representative /SNNPR/ region, Gurage zone at Butajira city. It is 135km away from Adis Abeba and connected with Adami-Tulu Substation, and it get power from Koka generating hydropower plant and distribute to deferent areas. The substation energized 1995 EC. It contains a 132KV bus bar with a three-phase winding power transformer. From these substations, 132KV to Buea substation and 132/33/15KV power transformer with three 33KV feeders and three 15KV feeders are fed to different areas. From which 33KV feeders are fed to Werabe, Witta, and idle and 15KV feeders are feeding to Butajira, industry zone, and Kella.

### 1.2 Statement of the Problem

Power system stability of distribution system is very important for the end-user customers and utility. An electrical power distribution system widely used customers in a deferent place which are found far away from substation. In Butajira distribution substation extends to a different separate location from a single supply source at the substation distributer. The demand for electric energy day today increase rapidly and it is a mismatch with the supply internal and external factors cause distribution systems disturbances like personal error, animal, plant growth, wind, and other natural factors. The power interruption of this distribution substation has become a serious problem. These factors are the cause for the interruption of electricity in the distribution system such as Human error factors, External factors, and Intrinsic factors are the main motivating factors to study in this area. The number of customers those were used this substation to get power at different palaces are rapidly increasing day to day. However, the power system facilities, particularly the distribution network, have not experienced proportionate expansion and have not been adequate for maintenance during system overloading, system losses due to mismatches between the power supply and demand received, unreliable power supply to consumers, transient behavior of the systems, overloading of feeder (conductors, resulting in overheating and insulation breakdown), and constant power outages leading to a shutdown of the system. Due to these problems voltage magnitude of the overloaded bus decreases and losses of the system increase. As a result the economic development, political and social effects on different towns and industry zone including Worabe, Kibet, and Butajira city. As a result, this thesis proposes employing the FACTS device interline power flow controller to stable voltage profile and minimize power loss at the Butajira substation for the 33kv and 15kv outgoing feeder networks.

## 1.3 The objective of the thesis

### 1.3.1 General Objective

The general objective of this thesis is to use an interline power flow controller to enhance voltage stability and loss minimization.

### 1.3.2 Specific Objective

The specific objectives are to

- Identify existing problem in the distribution substation
- Collecting the data required for system model.
- Model and simulate existing substation with and without IPFC in MATLAB/ Simulink software for controlling disturbances.
- Analyze the voltage stability with and without IPFC devices at 15kv and 33kv outgoing feeder line of distribution network.
- Compare distribution voltage and Power loss system with and without IPFC during three phase fault.

## 1.4 Significance of the study

The significates of this study is to enhance power system stability and increase power transferability by controlling power system distribution parameters during unwanted power system disturbance. As a result, limiting amount of fault current during power system with unwanted fault, loss minimization due to power system disturbance and remove unwanted blackout of power system are as a significances of this study.

Also this study has economical significances to prevent equipment's from being damage by some oscillation signal from system disturbance and economical advantage by preventing component damage and save energy, time cost, man power that used to solve unwanted power system disturbance problem.

## 1.5 Scope and Limitations of the Study

The scope of this thesis work was to enhance voltage stability and loss minimization by using an interline power flow controller, identification of bus voltage, and modeling and simulation of interline power flow controller with a distribution power system by using MATLAB Simulink show with and without IPFC during normal and fault condition. However, distribution power system voltage stability improved by using different compensating component like STATCOM, SVC, UPFC and TCSC the scope of this thesis is limited to study the voltage stability and loss minimization of distribution substation improved by using interline power flow controller in Matlab Simulink.

## 1.6 Organization of the Thesis

This thesis work has been organized into six chapters, which are listed below.

**Chapter one** contains the overall introduction to the thesis work, which includes the thesis's main categorized notation and directs the thesis's body, problem statement, objective, significant, and scope of the study. **Chapter two** states the theoretical background of the distribution system, classification of power system, the method of enhancing voltage stability and loss minimization the distribution system, and the overview of FACTS devices. It also contains a literature of study based on the preceding findings, which are related to the distribution system's power quality problem, specifically, reducing power loss and enhancing distribution line voltage stability. **Chapter three** deals with the Materials and Methods, the required data, and analyzing the collected data. **Chapter four** deals with design and analysis of distribution system, components of IPFC, mathematical modelling compensating component and Simulink modeling of with and without IPFC. **Chapter five** Results and Discussion of the simulation results, and discussion for outgoing feeder with and without installation of an interline power flow controller. **Finally, chapter six** deals with the conclusion and recommendations of the thesis work are discussed.

# CHAPTER TWO

# LITERATURE REVIEW

## 2.1 Theoretical Background

### 2.1.1 Distribution Power System

Generation, transmission, and distribution are the three basic components of an electrical power system. A transmission line connects the generating plant station to the distribution system, which is where the power is distributed. The power is transmitted from generating plant station to the distribution system interconnected by a transmission line. Using high voltage linkages between load centers, the transmission line transports a large quantity of voltage. The distribution systems were in charge of converting this large amount of voltage to a level adequate for the customer's load end-users. The final stage in the delivery of electric power is distributed, which transports electricity from the transmission system to individual consumers. Distribution substations connect to the transmission system via transformers, which reduce the transmission voltage to a medium voltage that ranges from 2 kV to 35 kV(Singh Tanwar & Choubisa, 2021).

Distribution substation, primary distribution, and secondary distribution are some of the sub-components of the distribution system. The power is received from the higher voltage transmission system and converted to a lower voltage level suited for the primary distribution system at the substation level, as well as transferring high voltage to another substation. As a result, a single substation will serve a large number of customers who are located far from the substation center. As a consequence, the distribution systems have several times the number of overhead lines as that of the transmission systems.

The primary distribution system was made up of the feeders that carry electricity from the distribution substation to the distribution transformer. A primary distribution system's voltage level is higher than its utilization voltage level. The primary distribution system is typically a three-phase, three-wire system with a voltage level between 3.3 kV and 33 kV. Large users including businesses, shopping malls, and other commercial complexes receive power from the main distribution system. The voltage level at the utilization level is reduced via a step-down transformer. This transformer is placed near the consumer premises.

Secondary distribution systems are part of electric power distribution which transfers electric energy from the distribution transformer to the end-user customer. The primary winding of this transformer is connected in delta connection and the secondary winding is connected in star connection to give a ground terminal, and the most common operating voltages are 11KV to 220 V. As a result, the secondary distribution system has a three-phase four-wire configuration. Single-phase supply is taken by using any one phase with a neutral terminal that provides a voltage magnitude of 220V, 230 V, or 120V depending on the standard of the country. For small shops and residential purposes, a single-phase supply is used. Some consumers require three-phase supply like small scale industries, flour mills, etc. This type of consumer uses a three-phase supply by using the R, S, T, and N terminal. (Islam et al., 2017)

In addition, most consumers are only linked to one of the distribution system's three phases. As a result, the power flow on each of the lines differs, and the system's stability and balance are often compromised. As a result, load flow models including distribution networks must account for this type condition.

A distribution feeder, distributor and service main are parts of distribution system.

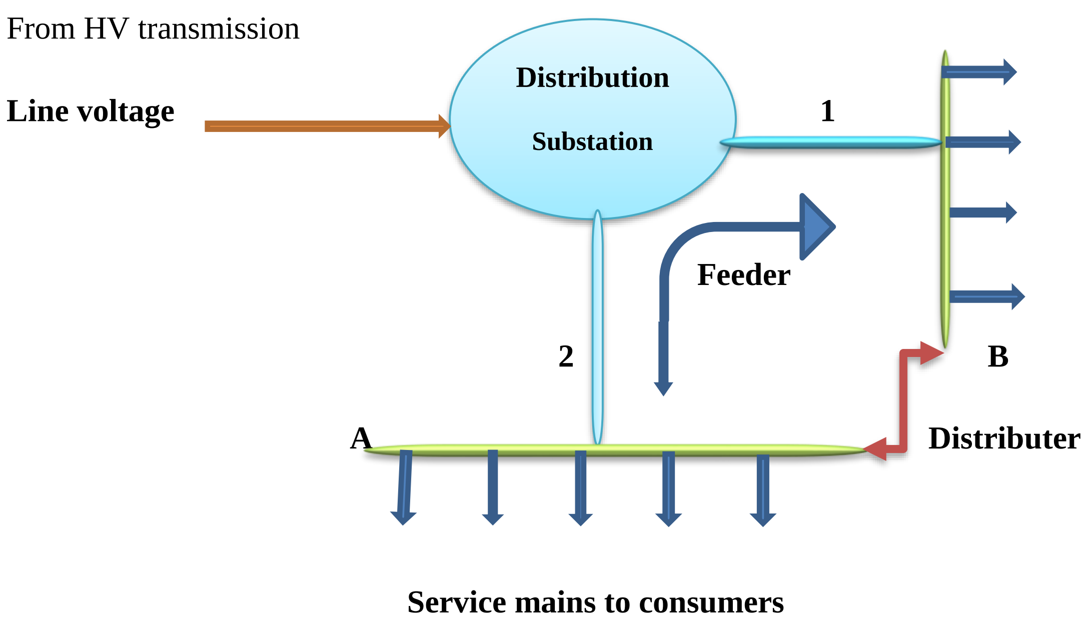


Fig. 2.1 Component of a single-line distribution system

A. Distribution feeder

A feeder is a conductor that runs from a substation or a localized producing station to the area where power is distributed. 1 and 2 in Fig. 2.1 are distribution system feeders. There are no toppings taken from the feeder, therefore the current in this area remains constant. The present current carrying capacity must be considered while designing a feeder ( R.Thakur, 2015).

B. Distributor

A distributor is a conductor from which taps for supply to consumers are obtained. In Fig. 2.1 A and B are the distributors. Because tapping is done at various points along the length of a distributor, the current through it is not continuous. Voltage drop along a distributor's length is a crucial factor to take into account when building one because the statutory limit for voltage fluctuations at consumer terminals is 10% of the rated value.

**C.** Service main

A service main is a small cable that links the distributor to the terminals of the customer. It is typically only a narrow pipe. The distributor is linked to the terminals of the consumer by this cable.

### 2.1.2 Classification of Distribution Power System

According to the several classifications that can be made for distribution power systems, which are listed below

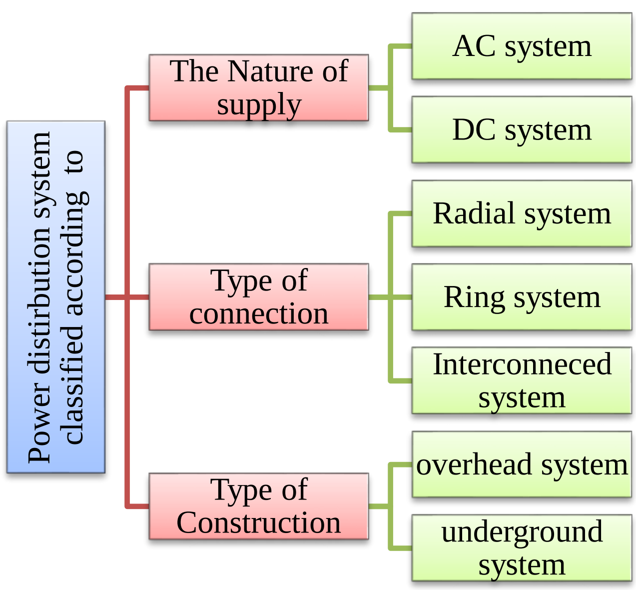


Fig. 2. 2 Classification of distribution power system

## I. The Nature of Supply

In an electrical power system, there are two types of electric power; depending upon the nature of electricity used in the distribution systems are AC distribution system and the DC distribution system. The AC distribution system and the DC distribution system have their own characteristics due to the nature of electricity used in the distribution system.

### A. AC Distribution System

The power consumer or load, in the majority of cases, demands AC power. As a result, AC power is used to generate, transfer, and distribute electric power. Because a transformer can easily step up and down an AC voltage. Transformers have made it feasible to transport AC electricity at high voltage and make it suitable for end-user use. To lower the current in the conductor as well as line loss, high voltage transmission and AC distribution have been adopted.

### B. DC Distribution System

The power system load with the most connections was an AC load. However, there was a situation where DC power was required and distributed. To fulfill these requirements, the customer used DC power in the distribution system, also referred to as the DC distribution system. In this case, the generated AC power is converted into DC electricity using a rectifier converter. Also DC distribution system is occurred during community renewable energy source like solar energy directly distributed to customers. DC electricity was required for propulsion, DC motors, battery charging, and other home applications.

## II. Types of Interconnection Power Distribution System configuration

According to network operational configuration distribution systems could be classified into three forms. Radial distribution system, Ring, and interconnected distribution system.

### A. Radial Distribution system

In a radial system, a separate feeder is used to feed power from the substation to each area and it feeds power to a distributor in one direction only. The design of the radial distribution system is simple and easy to implement in the system. The initial cost of this system is less compared to other systems. However, its reliability is low compere to others. If one feeder is out of step condition, the entire system will stop. This type of system is only used for a short-distance distribution system. The consumer far from the feeder may suffer poor voltage regulation and voltage fluctuation with a variation of load. Due to this advantage, this type of system is only used to supply the load which is near to the feeder. The power feeds from a unidirectional feeder due to this single direction the power flow fails at least one fault has occurred in the line. (Prakash et al., 2017). The single line diagram of a radial distribution system is shown in the following Fig. 2.3.

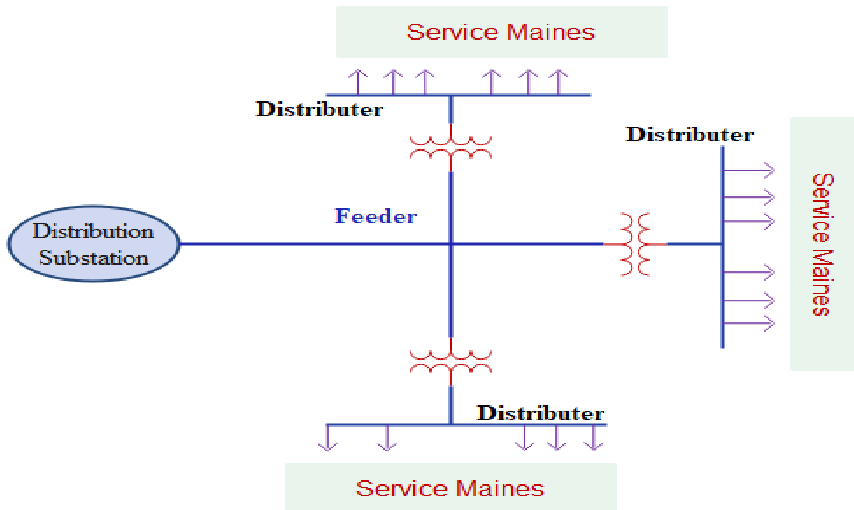


Fig. 2. 3 Radial distribution system

B. Ring or loop system

In the ring system, the distribution transformer is connected in a loop and supplied by a substation from one end. It means each distribution transformer has two different ways to connect with the substation. The following fig. 2.4 shows a simple line diagram of a ring-type of distribution system. The loop starts from substation bus bar and makes serve and return to substation.

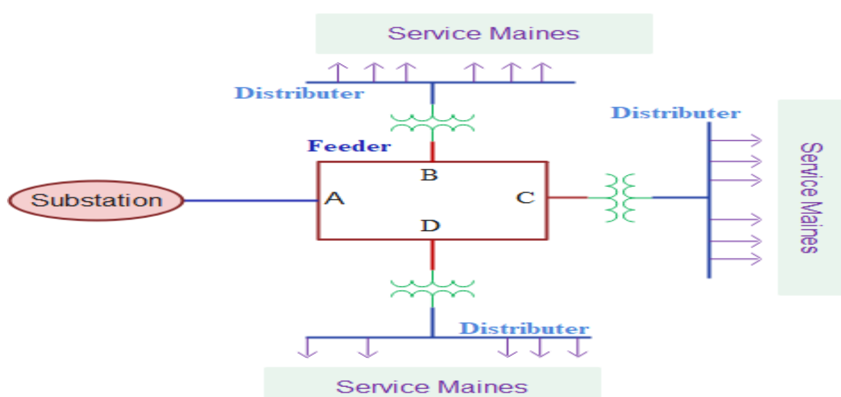


Fig. 2.4 Ring type of distribution system

From the Fig. 2.4 could be compare the loop arrangement ABCDA feeders connected each other. For example, if a fault occurs between B and C points. In this condition, the part between B and C will isolate from the system and substation supply power in another side is ADC and the customer still get power.

It makes the system more reliable at the consumer's end, there is less voltage fluctuation. Each part of the ring carries less current. So, less conductor material is required compared to the radial system. The most recent distribution power system has been made based on a radial distribution system which is unidirectional and as result inefficient in the case of feeder failure.

C. Interconnected system

A loop is fed by more than one substation at different places in a linked distribution system. A grid distribution system is another name for this technology.

A single line schematic of the connected distribution system is shown in Fig. 2.5 below.

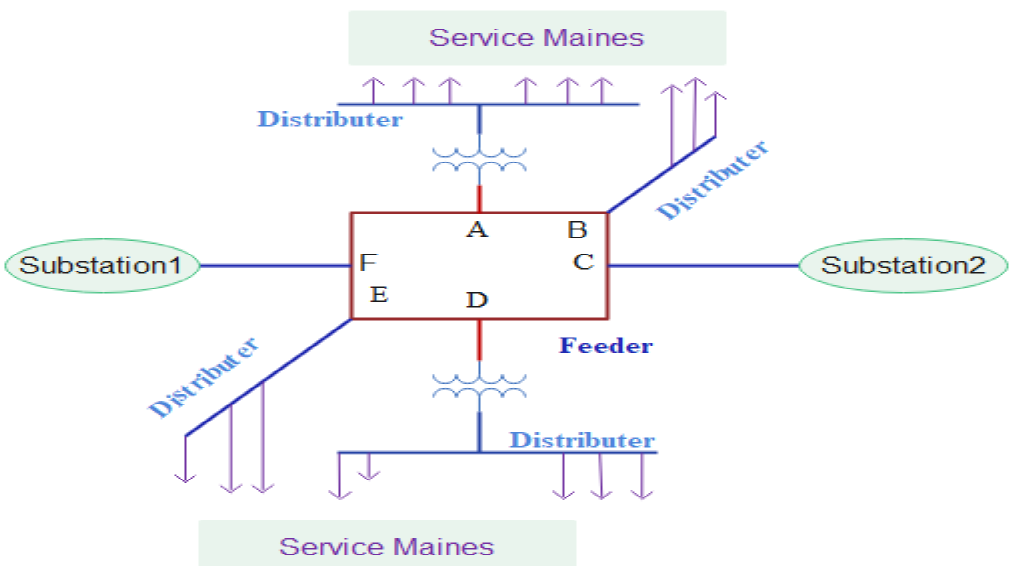


Fig. 2. 5 Interconnected system

As shown in the above figure, loop ABCDEFA is supplied by two substations at points C and F. Due to this type of arrangement, the reliability of the system increases compared to the Ring main and Radial system.

The design of the interconnected system is very difficult and the initial cost of the system is also high as a greater number of substations are required in a system. But this system has the advantage of good power quality and a more efficient system. This system reduces reserve power capacity (By, 2020; Dabbaghjamanesh et al., 2018; Faraby et al., 2021).

## III. Construction of distribution system

Depending on the placement of the distribution line configuration distribution system is classified into two underground and overhead distribution systems.

A. Underground Distribution System

In this kind of system, construction distributing line conductors are placed under the surface of stress or side wakes. It is safer than that of an overheated one because it does not has any physical contact with the prevailing issue. But the initial cost of the underground system is very high. Because it requires trenching, conduits, manholes, and special cables. In this system, the cables lie under the streets. Hence, there are fewer chances of the fault and it gives a good appearance as cables are invisible. When a fault occurs in the underground system, it is difficult to locate and also it is difficult to repair. The life of an underground system is longer than overhead and it is properly used for more than 50 years.

B. Overhead Distribution System

The power system is transmitted from one place to another place more commonly by using overhead methods than undergrounded in our country. In the overhead distribution system, the conductors are mounted on wooden, concrete, or steel poles. This system is also known as a conventional system for the distribution network. Dou to the facing of the conductor with hazards on the pole, this is more chance of faults compared to an underground distribution system. However, the initial cost of an overhead distribution system is less than an underground distribution system. It is more flexible compared to the underground system. Because this system is permanently placed once installed. Hence, it is easy to load expansion and lay a new line. The conductors are placed over the surface. So, the appearance of this system is not good as an underground distribution system.

In the overhead system, the conductors are placed with taking proper space. Hence, the air is used as an insulation medium. So, it does not require special insulated cables. The current carrying capacity of the overhead system is higher than compared to the underground system.

It is easy to install the overhead system and also, when a fault occurs, it is easy to locate and repair a fault. As a result, the overhead system has relatively low maintenance costs. There is a probability that a communication system will experience interference. An overhead system has a maximum 25-year functional life.

### 2.1.3 Distribution Power System Loss and Voltage drop

An Electric power system losses and voltage drops are secure at each stage of the power distribution process. Power system starts with step-up transformers from the power generating plant to the high voltage transmission system and ends with step-down transformer at secondary distribution at the customer service. The system consists of several key components: step-up transformers, transmission lines, substations, primary distribution system line, distribution transformers, and secondary distribution system networks that connect to individual homes and commercial (NACAA, 2015). As the demand for energy develops quickly, the transmission and distribution networks usually run under heavily loaded conditions, and distribution system loss has become a rising concern. It need the ways of loss and voltage minimization methods, as well as new operating processes, would be created in a very advantageous environment by delivering acceptable power quality and higher efficiency.

The power from generation to end user pass through large and complex network like transmission line, overhead line, cable, transformer and other equipment's to reach end user. The different between generated and distributed units are known as transmission and distribution line loss. These losses are not paid by end users. The power loss equivalent to the difference of energy input to the feeder and billed energy to customer in kwh divided by energy input to feeder and multiplied by 100. Resistance and inductance in the transmission and distribution network caused voltage drops and power losses.

As a result the primary and secondary distribution systems are should be planed within its limitation. Unexpected loads are increase than increase technical loss above the normal level and the losses are ones input to the distribution system electricity than it cannot be eliminated.

#### i. Types of distribution power loss

Generally, there are two main types of loss in power systems technical and non-technical losses. The amount of losses in a power system occurred in a distribution system is more than that of transmission power system. Because at distribution system the number of distributing networks are more and load unbalance occurrence more probable than transmission system. From this major losses that occurred at primary and secondary distribution lines.

**1. Technically occurring loss**

Physical qualities of power system network, such as energy or power dissipated in cables, equipment utilized for transmission and distribution networks, transformers, and magnetic losses in transformers, have occurred technical loss in a power system. The power is lost in a distribution network and transformers due to internal resistance and inductance of the distribution network and transformer. These losses cannot be eliminated due to the associated physical properties, but they can be minimized by using different methods of loss minimization technic in the distribution system network. Power systems typically have 22.5 percent technical losses and are highly dependent on network characteristics and operation mode. The following factors contribute to technical losses in distribution lines.

1. The size of the conductor in distribution is insufficient: - the size of conductor must be selected based on KVA* KM capacity of standard for required voltage regulation, rural loads are scattered and fed by radial type distribution feeder. Therefore the conductor size of this feeder is selected suitable size for the load.
2. Single and long distribution lines outgoing from single feeder: - at rural area the primary and secondary distribution extended to large and long area from single feeders of radial system. As a result the higher line resistance and increase $I^2R$ loss of the line. To minimize this loss the disorderly growth of distribution system into new area and large scale rural electrification system is used.
3. Existing transformer installation without keeping load center:- secondary distribution transformer is not keep load center of the customer, as a result the farthest customers get very low voltage level even if the secondary transformer have good voltage level. Line losses increase due to low voltage level at customer end. There for the transformer installed at load center of the customer.
4. The exiting Power factor is low: - the low power factor contribute for distribution power loss. So different method used for power factor adjustment like capacitor bank.

5. Balancing three phase loads: - balancing three phase load periodically throughout the overhead distribution network can minimize loss. It can be adjust simply overhead distribution network depending on scope for loss minimization and cost effective.
6. Switching off distribution transformer: - If a distribution substation needs two transformers of a specific size during peak hours, just one transformer is needed during off-peak hours to reduce fixed loss, and the other transformer is turned off.
7. Bad workmanship: The number of distribution system joints must be kept to a minimum and must be correctly joined by a qualified individual. Increased system loss is due to an increase in the number of joints.
8. Feeder phase current and load balancing: balancing the current along the three phase circuit is easiest mechanism of loss minimization in distribution system. Also feeder phase balancing tends to balance the voltage drop among phases giving the three phase customer less voltage unbalance.
9. Other factors like
   - ❖ Due to external and internal interruption, the line loads changed to overloaded,
   - ❖ Unbalance loads have occurred due to unequal load distribution among three phases in the long distribution system causing high neutral currents.
   - ❖ Distribution transformer work during abnormal operating conditions of the power system.
   - ❖ Due to inductive loads causing the higher value of current and low voltage profile on the customer side,
   - ❖ Low-quality equipment for a different purpose that used existing power in rural and urban working areas.

This technical loss is also divided into two type's fixed and variable technical loss

**Fixed losses** are losses that do not vary according to current. This loss takes place during transformer energizing in the form of heat and noise. From distribution networks, between 1/4 and 1/3 of technical losses are fixed losses. The common type of this losses is leakage current losses, corona loss, dielectric losses, open-circuit losses, and measuring and controlling continuous load loss.

**Variable Technical losses** are varied with the amount of electricity distributed and are more proportional to the square of the current passing through the line ($I^2 * R$ ). For this reason, a 1% increase in current leads to an increase in losses of more than 1%. Between 2/3 and 3/4 of technical losses on distribution networks are variable losses. By increasing the cross-sectional area of lines and cables for a specified load, losses will decrease. This leads to a direct trade-off between the cost of losses and the cost of capital expenses.(Bhatti et al., 2015; Moreira Rodrigues et al., 2021).

**2. None technical loss**

Non-technical losses occur as a result of energy theft, metering inaccuracies, unmetered electricity, faulty energy meters, profiling error, ignoring overdue bills, unpaid bills, Pressuring meter readers to take false readings, and dismiss past-due bills, and Stealing by bypassing the meter or making other illicit connections. These losses are not actually losses in terms of consumption loss. What makes them to be grouped under losses is that the consumption is not paid for. They can be evaluated on the basis of the difference between the generated and sold energy on one hand and the calculated technical losses on the other hand. Illegal energy consumption (theft), incorrect meter reading, energy meter failures, and shortfalls in billing are known sources of non-technical losses.

There are approximately 16.6% non-technical losses and the main reasons are the following:

- Stealing of power
- Meter inaccuracy
- Meter Reading fault
- Low load un mitering losses
- Supply of unmetered
- Distribution line sections have variant phases like 3-phase, 1-phase or 2-phase
- Limitation of data is required for model and analysis purposes because of limited monitoring and control (Jamil et al., 2019).

The loss of power at transmission and distribution is calculated by the square of current passing through the line multiplied by the resistance and inductance of the same line. This formula is written as Equation Chapter 2 Section 1

$$P_{loss} = \sum_{i,k}^{n} I^2 R_{ik} \tag{2.1}$$

$$Q_{loss} = \sum_{i,k}^{n} I^2 X_{ik} \tag{2.2}$$

$$S_{loss} = \sum_{i,k}^{n} I^2 (R + X)_{ik} \tag{2.3}$$

From equation (2.1 and 2.2) Ploss and Qloss the total active and reactive power loss; Iik = branch current flowing from node i to node k; Rik = line resistance between node i and node k; Xik = line reactance between bus i and bus k.

**ii. Voltage drop in the distribution system**

Ideally sending and receiving ends voltage should be equal at power transfer of transmission and distribution line, but in practice, there is voltage drop especially at distribution system due to effects of transferring component resistance(R) and impedance(x). In addition to the non-technical losses already listed, there are overhead line losses. Even though all equipment connected to the utility system is designed to be used in a specific way, it is virtually impossible to service every customer exactly to the same voltage.

### 2.1.4 Voltage Stability Improvement

The Stability of voltage has become one of the main concerns to maintain system security in power system operation and planning. Controlling modern power systems has become very difficult due to increased demand and consequential increases in power flow. Voltage stability is the ability of a power system to maintain acceptable power system parameters such as bus voltage, phase angle, and line inductance at all system buses under normal operating conditions (Steady State conditions) after experiencing a disturbance.

Enhancing voltage stability is currently one of the primary challenges in power system management and planning to preserve system security. A system is considered to be voltage unstable when a disturbance, increase in load demand, or change in system state causes a gradual and unpredictable reduction in voltage as a result of the network being unable to keep up with the growth in reactive power demand. Voltage instability, which occurs when the system's voltage drops to a level from which it is challenging to recover, is what leads to system collapse. Instability caused by voltage collapse events has recently resulted in a number of significant power system blackouts across the planet (Mathad et al., 2013)(Thannimalai et al., 2015) . Therefore, improving voltage stability appropriately is crucial for the effective management and planning of the power system.

The reasons of voltage stability problems are listed as below**:-**

- High reactive power consumption at load centers
- Generating stations located far from load centers
- A transmission of reactive power is difficult during heavy loads
- Due to the FACTS controllers' incorrect placement
- Ineffective communication between several FACTS controllers

The voltage instability has the following effects on the power system:**-**

- Energy drain in certain places
- distribution and transmission networks tripping
- Systemic voltage breakdown

The Voltage stability can be improved using any of the following techniques:**-**

- Placement of FACTS controllers
- Co-ordination of multiple FACTS controller
- Installation of synchronous condensers
- Placement of series and shunt capacitors/reactors

### 2.1.5 Methods of Enhancing Distribution Systems Performance

There are numerous ways to lower a distribution feeder's loss and voltage variation. Network reconfiguration, network re-conducting (conductor grading), distribution transformer locating and sizing, reactive power compensation, highly efficient transformers, high voltage distribution systems, distributed generation, and building new substations are a few of the techniques used to reduce power loss and voltage drop. The following explanations provide details on how to reduce power loss and voltage drop.

A. Reactive power compensation

By controlling of reactive power leads to improvement in the performance of ac power systems. The compensation has two aspects, (1) Load Compensation which increases the power factor, balances the real power drawn, compensates voltage regulation, and eliminates current harmonics of the system. (2) Voltage injection into the system to decrease the voltage fluctuation and low voltage at any given terminal of a distribution and transmission network line. Reactive power (VAR) compensation hence improves the active power that can be transmitted, which enhances the stability of the AC power system. Although reactive power is viewed as a crucial component of the power system, it is also recognized as a significant barrier to generating reliable power and a constant voltage (Nanda et al., 2017).

The source of reactive power can be anything from inductive loads, peak load, power theft, or connection of various distribution generation units to the grid. Hence, during day-to-day operations the voltage at different buses across the system increase or decreases during daily operation.

The compensation methods are applied by using the FACTS device and capacitor placement at the appropriate place. This device is used to increase the transferability and feasibility of the power system by controlling suitable set power system parameters.

B. Conductor grading

This method depends on the size and quality of the conductor in a distribution system. These parameters are important parameter as it determines the current density and the resistance of the line. If the size of the conductor has been lower than standard, then high losses and high voltage drop were takes place in the system. As a result, consumers' consumption is lower, and utility revenue is reduced. The assumption that the distribution feeders have a uniform cross-section has been made in the majority of distribution system planning methodologies. However, in actual systems, the cross-section of the feeders' sections will vary since the current carrying capacity of the feeders varies in various system parts.

The main causes of significant losses in developing countries like Ethiopia include stretching distribution lines past the capacity of load centers, irregular load growth, and an imbalance between generations and load that results in reactive power generation, and other factors. Therefore, careful conductor selection is very important for the distribution system since it affects the line's resistance and current density. Increasing the size of conductors will require additional investment, which may not payback for the reduction in losses.

C. DG allocation

DG allocation methods was depend on the availability of Distributed sources like solar, wind and other renewable energy source. It is described as the generating an electric energy to improve existing electric grid voltage profile. To enable connecting with existing power system at almost any location inside of that power system.

Power systems have been enhanced using distributed generation (DG), notably at the low voltage (LV) level, to increase their efficiency, security, and dependability. The system is simultaneously faced with new issues brought on by DG since it is not yet prepared to handle large levels of DG penetration. In this regard, voltage control concerns and problems with protective mechanisms are the two key challenges. Given that the integration of DG, particularly those based on Renewable Energy Sources (RES), is expected to rise in the electric power systems of the present and the future, a consideration of the effects of such generating technologies on distribution networks is necessary(Razavi et al., 2019).

There are various advantages for integrating DG with existing utilities, including

- Reduce environmental impact
- Increase the overall efficiency of the generating system
- relieved distribution congestion,
- Sporting voltage and line loss reduction.

D. Network reconfiguration

This technique, which uses a number of inter connected and radial power distribution system network, is a crucial way to conserve electricity. Most often, low voltage distribution networks were affected. By moving loads between feeds, switching operations can change the arrangement. In primary distribution systems, there are two different types of switches. They are either typically open switches or normally closed switches (sectionalizing switches) (tie switches). By replacing aging and collapsing poles, this technique reduces loss in the distribution system and improves system performance (Kalambe & Agnihotri, 2014).

The reconfiguration is applied as listen below.

- Service restoration under faulty conditions,
- Using load balancing to reduce network overload and enhance voltage profile
- planning outages for maintenance and

- loss minimization

E. High voltage distribution system

When the transmission and distribution of electric power transferred by high voltage was very important for loss minimization because the amounts of the voltage increase the current passing through the line decrease also economic advantage due to the cable size of the conductor. In order to configure HVDS, a large distribution transformer is changed out for a few smaller distribution transformers, which are installed close to the load. Improved voltage profiles and reduced power losses will arise from the adoption of high voltage distribution systems. The annual savings and payback times for high voltage distribution systems will also be advantageous from a non-technical standpoint. Therefore, the electric distribution system used high voltage above 33kv for long distribution primary network more favorable than 15kv, 380v, and 220v of secondary and primary distribution network.

F. Distribution transformer locating and sizing

Distribution transformers located at load centers and their caring capacity must be suitable and consider the next expanding new electric distribution line. In most, developing countries like Ethiopia distribution Transformers are installed without considering load centers, especially in the rural area. Due to this problem unbalancing of three-phase line voltage. Also, single distributed transformers expand to very long areas without keeping their center and unequal voltage at the line. As a result, the consumer’s usage is lower and unwanted loss happens and also revenue of utility is reduced. To solve this kind of problem installing distribution transformer and its size will be kept. Instate of using a single higher capacity distribution transformer for a long distribution network, using a number of distribution transformers with suitable load centers was more advantageous to minimize voltage drop and loss at the distribution network. The transformer effectiveness is also higher to get high efficient energy and loss minimize.

### 2.1.6 Overview of FACTS Device

Electric power system networks have a limitation of one or more factors, such as line impedance, and operating variables, such as voltages and currents, typically restrict the operation of an AC power transmission and distribution electric line. As a result, the power line is unable to direct power flow among generating stations and distribution substations until end user customer.

Therefore, other parallel transmission lines that have an adequate capability of carrying additional amounts of power may not be able to supply the power demand. The primary function of flexible ac transmission systems (FACTS), new emerged and developing technology, is to improve the controllability and power transfer capabilities of ac power systems. Switching power electronics are used by FACTS technology to move power in the range of a few tens to a few hundreds of megawatts.

FACTS devices integrated with controlling function to satisfy the steady state operating parameter is known as FACTS controller. These could be thyristor devices with gate turn-on turn-off functionality. FACTS controllers can increase the flexibility of a transmission line, allowing it to deliver power closer to its thermal rating. In the majority of applications, controllability is utilized to prevent expensive or environmentally unfavorable extensions of power systems, such as renovations or new substations and power lines.

FACTS devices enhance the use of existing installations and offer a greater response to changing operational conditions. The standard applications for FACTS devices are as follows:

- Power flow control,
- Increase the power transfer capability of the line,
- Voltage control,
- Reactive power compensation,
- Stability improvement,
- Power quality improvement,
- Flicker mitigation,
- Interconnection of renewable and distributed generation and storage.
- Power flow management and security purpose

Through switched or controlled shunt compensation, series compensation, or phase shift control, FACTS devices can be made to have an effect. Electrically, the device function as quick current, voltage, or impedance controllers. The power electronic enables extremely quick reaction speeds of much less than one second. An organized summary of FACTS devices is provided below. These devices are assigned to their various application fields.

From the Fig. 2.6, the left column shown below Thyristor valves/ switches and tap changing transformer is as controlling convertor. Due to low switching frequency per one cycle, this valve controllers have low loss compere to other controller.

The right column of this Fig 2.6 used self-commutated and more advanced voltage source based switching convertors such as Gate Turn Off (GTO), insulated gate bipolar transistor (IGBT) and Insulated Gate Commutated Thyristors (IGCT) Voltage Source Converters provide a free controllable voltage in magnitude and phase due to a pulse width modulation. High modulation frequencies allow to get low harmonics in the output signal and even compensate for disturbances coming from the network.

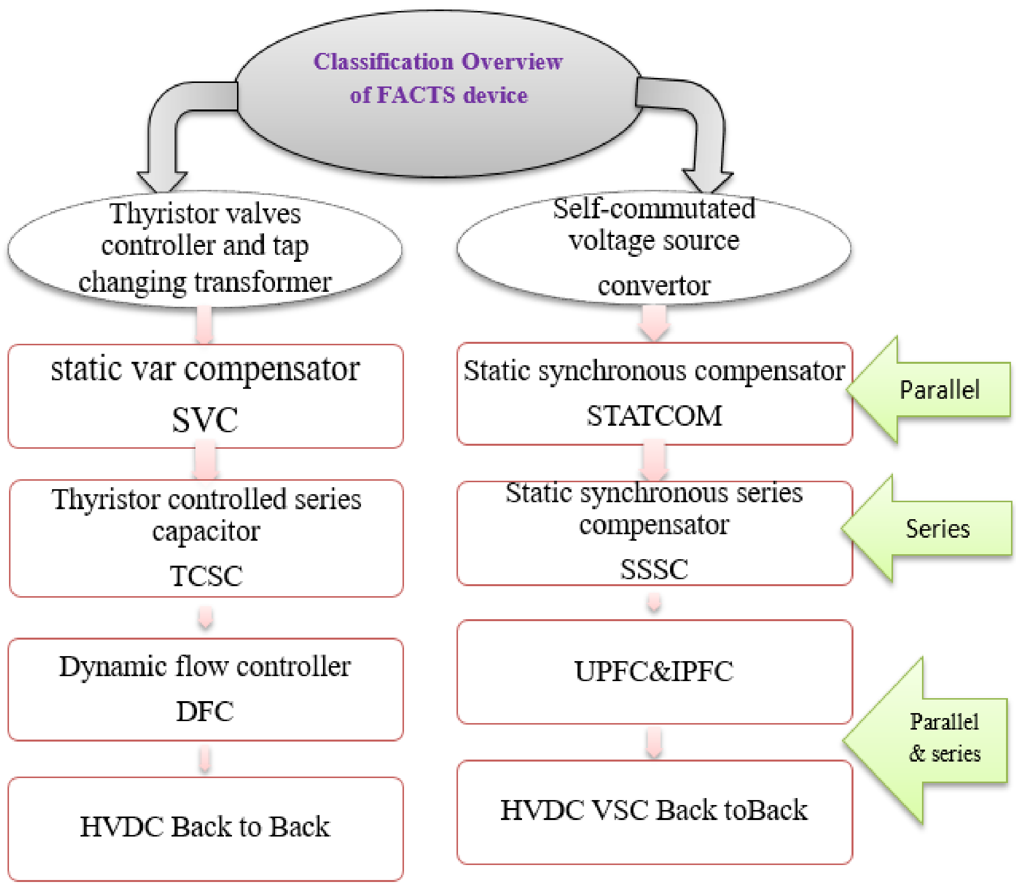


Fig. 2. 6 Classical overview of FACTS device

### 2.1.7 The Basic type of FACTS Controllers

Generally, FACTS controllers are divided into four categories depending on their connection to the power system (Aishvarya Narain & S. K. Srivastava, 2015).

- ✓ Series Controllers
- ✓ Shunt Controllers
- ✓ Combined series-series Controllers and
- ✓ Combined series-shunt Controllers

**1. Series controllers**

Series controllers are a type of controller that can be used to change a series impedance like capacitor, reactor and a power electronics-based variable source of main frequency, sub-synchronous and harmonic frequencies in order to meet the demands various application.

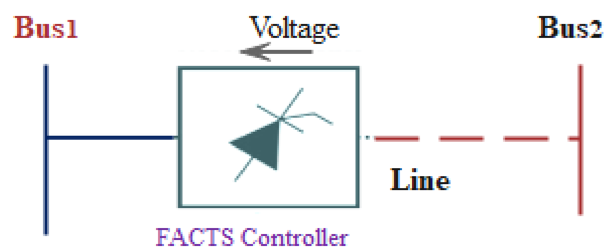


Fig. 2. 7 Basic structure series control configuration

In principle, all series controller injects voltage into power system at the connected point with series line. Any variable impedance will represent an injected series voltage in the line as the current flowing through it is multiplied. Only variable reactive power is supplied or consumed by the series controller as long as the voltage is in quadrature phase with the line current. The TCSC, SSSC, TSSC, etc. are examples of this type of series controller.

**A. Thyristor controlled series capacitor(TCSC)**

Thyristor Controlled Series Capacitor (TCSC) is a capacitive reactance compensator. It consists of a series capacitor bank connected in parallel with thyristor controlled reactor that provides smooth series capacitive reactance. It also addresses specific dynamical problems in transmission systems. Firstly, it increases damping when large electrical systems are interconnected. Second, it is capable of resolving the issue of Sub Synchronous Resonance (SSR), which is a phenomena caused by the interaction of massive thermal generators and series compensated transmission systems. The TCSC's high-speed switching capability provides a way for controlling the flow of line power, enabling greater loading of the current transmission lines as well as rapid modifications of the flow of line power in response to various circumstances. To reduce effective reactive power loss, increase the maximum transmittable power, and account for the line's inductive reactance, it is connected in series with transmission lines. As long as it stays within the parameters of its rating, it can also manage steady-state power flow. (Movahedi et al., 2019).

From a practically technological standpoint, the TCSC is similar to a traditional series capacitor. The Thyristor valve that regulates the operation of the main capacitor bank is among the power equipment that is installed on a separate steel platform. Likewise, along with other auxiliary systems, the control and protection are placed on ground potential. The basic configuration of a TCSC and its operational diagram are shown in Figure 2.8. The operational diagram's borders are established by the firing angle and thermal limits of the thyristors.

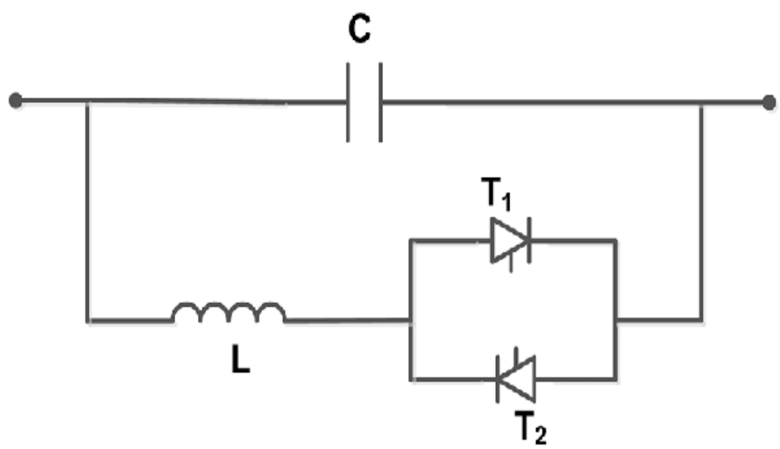


Fig. 2. 8 Structure of TCSC (M. T. Khan, 2015)

The principles of the TCSC have two main aspects firstly, to changing the reactance of a specific interconnecting power line by electromechanical damping between overloaded electrical power systems, i.e. the TCSC will provide a variable capacitive reactance. Second, the TCSC must modify its apparent impedance for sub-synchronous frequencies (as determined by the line current) in order to prevent a potential sub-synchronous resonance. The TCSC's control algorithms are used to accomplish these goals. The main capacitor becomes a variable capacitor at fundamental frequency but a "virtual inductor" at sub-synchronous frequencies when the controlling function on the Thyristor circuit is parallel with the main capacitor bank, adding controlled charges to the main capacitor.

## B. Thyristor Switched Series controller (TSSC)

Another type of capacitive reactance compensator is the Thyristor Switched Series Capacitor (TSSC), which consists of a series capacitor bank that is switched by a thyristor switched reactor to give step-wise control of series capacitive reactance. The TSSC utilizes the thyristor switch in the capacitor bank and it has a faster response than the compensator that is mechanically switched. The TSSC as shown in the Fig. 2.9 below can only inject capacitance into the line; it cannot limit the line current. The degree of compensation depend on number of injected series capacitor to the transmission line (Survey, 2021).

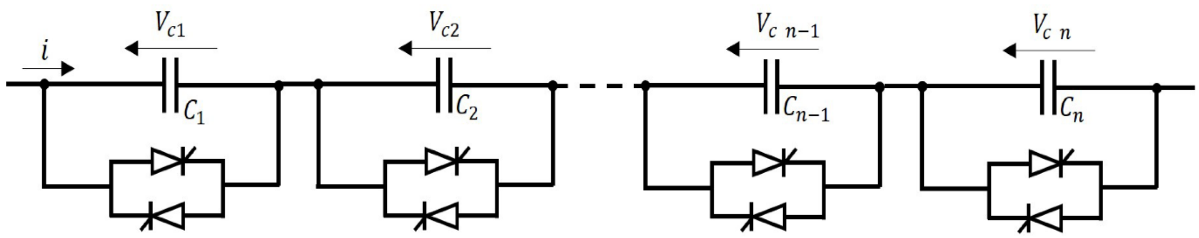


Fig. 2. 9 Schematic diagram of TSSC (C. A. Ordonez 2021)

## C. Static Synchronous Series Compensator (SSSC)

A solid-state voltage source converter (SSSC) produces a controllable AC voltage and connects it in series with power transmission and distribution lines in a power system. By injecting controlled voltage in series with the transmission line, SSSC effectively compensates for practically all transmission and distribution line impedance. When computing more in an inductive or capacitive reactance to affect the power flow in transmission lines, voltage sources should be in quadrature with the line current. Independent of the magnitude of the line Current, the virtual reactance introduced by V affects the flow of electric power in distribution lines. A VSC attached to the secondary side of a coupling transformer is used to change the value of V. A capacitor attached to the VSC's DC side serves as a source of DC voltage(Ingole & Gohokar, 2017). In order to increase or decrease the overall reactive voltage drop across the line and thereby regulate the transmitted electric power, a static synchronous generator is used without the support of an external electric energy source as a series compensator with an output voltage that is in quadrature with and independently controllable from the line current.

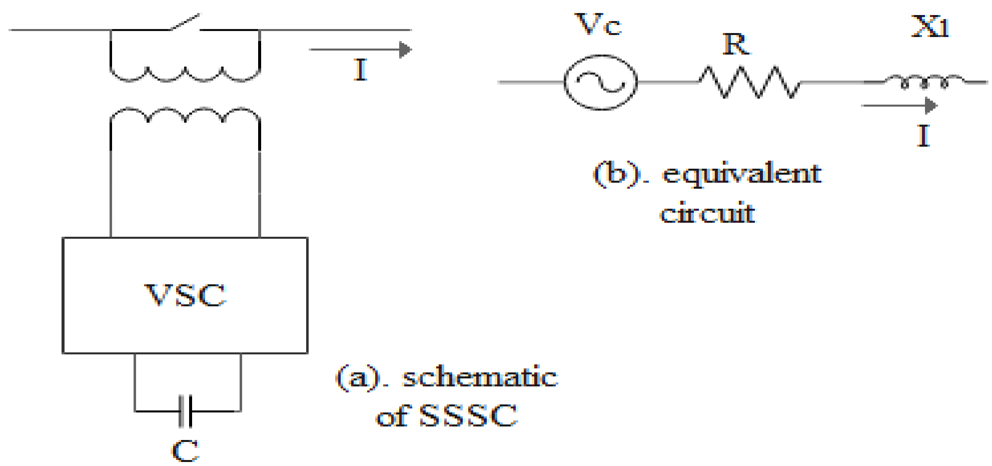


Fig. 2.10 Schematic and equivalent diagram of SSSC (I. Lal Yadav 2015)

**D. Thyristor Controlled Series Reactor (TCSR)**

A series reactor is shunted by a thyristor-controlled reactor in an inductive reactance compensator to create a smoothly changing series reactance. Uncontrolled reactor act as fault current limiter and stop conducting when the firing angle of the thyristor-controlled reactor is 180 degrees.

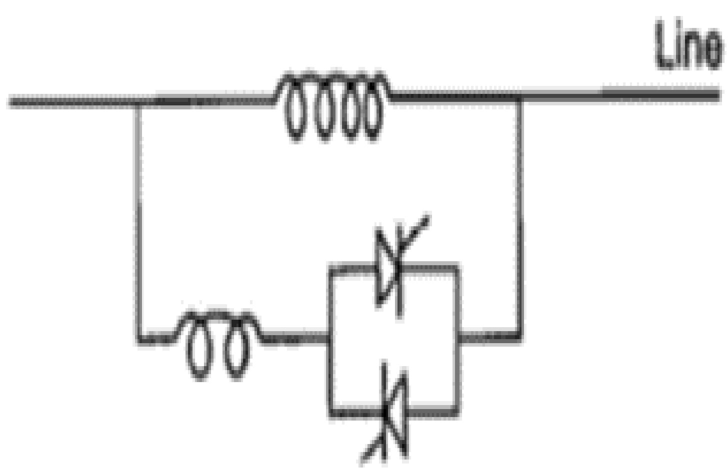


Fig 2.11 Configuration of thyristor series reactor

**2. Shunt controllers**

Shunt controllers can be variable impedance, variable source, or a combination of these, just like series controllers.

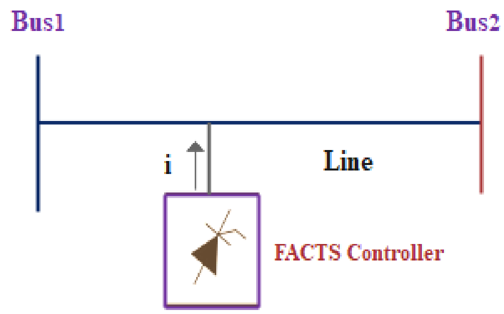


Fig 2.12 Basic configuration of shunt controller

In principle, all shunt controllers inject current into the power system at interconnected point. Even a voltage of shunt connected system have the same, varying it by variable shunt impedance connected to the line voltage and possible to get a variable current flow. Hence represents the injection of current into the account line of distribution and transmission system network. The shunt controller only produces or consumes variable reactive power as long as the injected current is in quadrature phase with the line voltage.

**A. Static Var compensator**

The SVC is a FACTS device controller that is connected in parallel with transmission lines. It is composed of a series controllers. From this TCR and TSR are used as reactive power observation, and TSC is used for reactive power injection to the power system when it required (AL Ahmad & Sirjani, 2019).

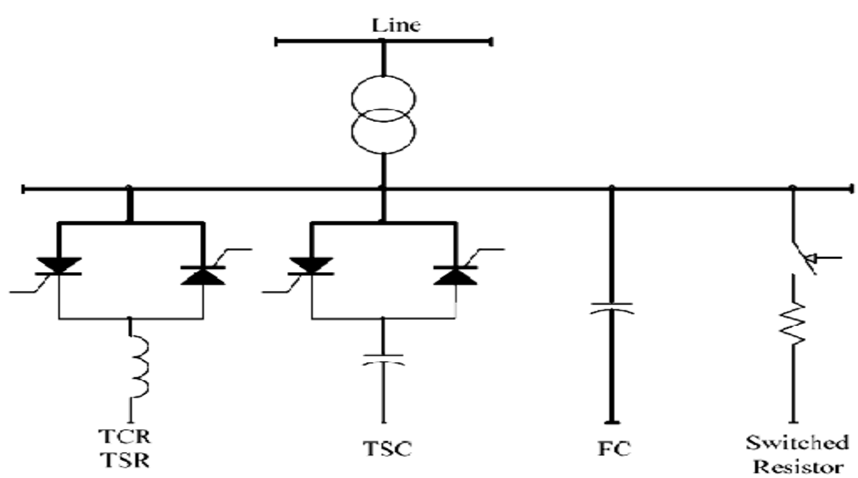


Fig. 2.13 Schematic diagram of svc (Ahmed Nasser alsammak, 2017).

**Thyristor Control Reactor TCR: -** A Shunt-connected, thyristor-controlled inductor whose effective reactance is varied by controlling the thyristor valve's partial conduction in a continuous manner. TCR is a subset of SVC in which a thyristor-based ac switch with firing angle control regulates the conduction time and current in a shunt reactor.

**Thyristor Switched Reactor (TSR):-** Another subclass of SVC is a shunt-connected, thyristor-switched inductor whose effective reactance is adjusted gradually by full- or zero-conduction operation of the thyristor valve TSR. Without any firing angle adjustments, TSR consists of a number of shunt-connected inductors that are turned on and off by thyristor switches. In order to make the required step adjustments in the power system's reactive power usage. Using thyristor switches without a firing angle control leads in less costs and losses even if there is no continuous control.

**Thyristor Switched Capacitor (TSC):-** a shunt-connected, thyristor-switched capacitor whose effective reactance is adjusted stepwise by the thyristor valve operating in full-or zero-conduction.

**B. Static synchronous compensator STATCOM**

The Static Synchronous Compensator (STATCOM) is a power electronics-based Synchronous Voltage Generator (SVG) compensator. It is a FACTS device with a shunt connection that offers capacitive or inductive output current for reactive power compensation to address various voltage stability and fluctuation conditions in the power system without relying on the AC system. It can be based on a converter that uses current or voltage as its source.

The main function of a STATCOM is to control and regulate the voltages at the weak bus in the transmission system and it supplies the desire reactive Power by varying the phase angle and magnitude. (Anyaka et al., 2020; Mahmood et al., 2017).

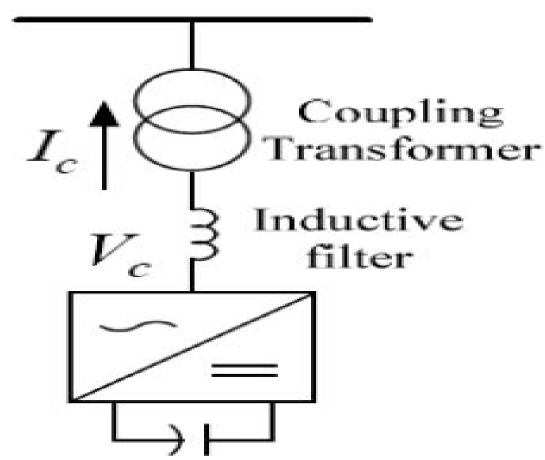


Fig 2.14 Structure of STATCOM (Haidar-Samet 2015)

### 3. Combined Shunt -series compensating controller

These are devices that combine independent series and shunt controllers in a coordinated manner. The combined series and shunt controllers inject voltage in series in the line with the series part, and current into the systems with the shunt part. The series-shunt device is shown in Fig. 2.15.

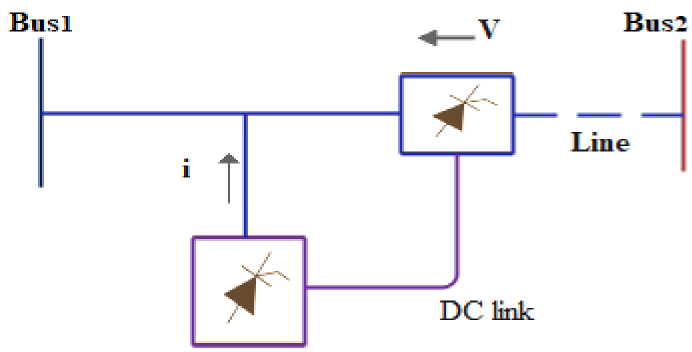


Fig. 2.15 Basic structure of shunt-series combination

### A. Unified Power Flow Controller (UPFC)

Active power can flow in both directions between the series and shunt output terminals of the Static Synchronous Compensator (STATCOM) and Static Synchronous Series Compensator (SSSC), which have DC link make up the Unified Power Flow Controller. This allows real and reactive series line compensation to be provided simultaneously without the need for an external electric energy source. Due to multipurpose of the UPFC device, the power flow can be controlled by changing three parameters of power transmission lines, namely the transmission magnitude voltage, impedance, and phase angle as represented in Fig. 2.16 (Raghav & Asim, 2015)(Nasser & Adnan, 2018).

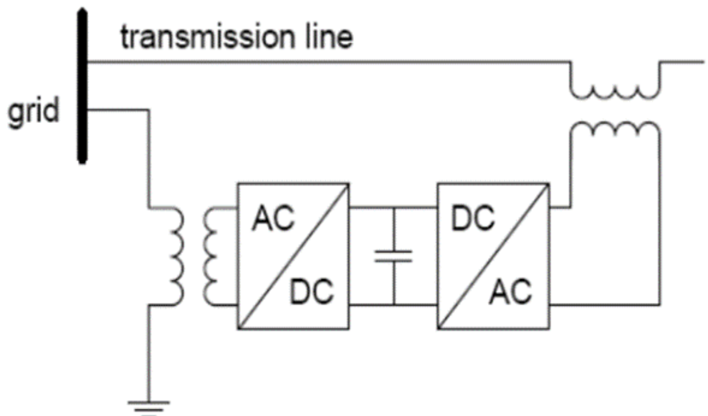


Fig. 2.16 Basic structure of UPFC

The shunt converter meets the second converter's actual power needs at the shared DC connection using the AC power supply. In addition to transferring active power to the DC terminal, it can also generate or absorb reactive power at its AC terminal. It can implement indirect voltage stability at the UPFC input terminal with the right control by supplying reactive power to account for the transmission line.

The series-connected booster transformer injects the voltage source produced by the series converter into the AC transmission line at the basic frequency with variable amplitude and phase angle. As a result, direct series compensation, voltage control, and phase shift can be accomplished by adding the converter voltage output in series with the line.

**4. Series-Series combination devices**

A combined series-series FACTS device is a combination of two different series FACTS devices in a coordinated manner. The series-series controller has two circuits. The first One is consists of series controllers working in a coordinated manner in a multiline distribution and transmission network and the other provides independent reactive power control for each line of a multiline transmission network and, at the same time facilitates active power transfer between the power link. This type of devices is Interline Power Flow Controller (IPFC) which balances active and reactive power flows at distribution and transmission line. These series Controllers provide independent series reactive compensation for each line but also transfer real power among the lines via the power link dc power link.

The unified series-series controller, also known as the interline power flow controller, has active power transfer capabilities that allow active and reactive power flow in the lines to be balanced maximizing the use of the distribution and transmission system.

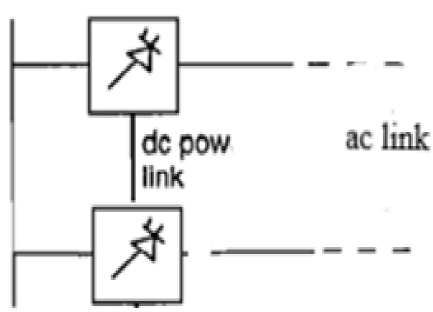


Fig. 2.17 Basic structure of series- series combination

### A. Interline Power Flow Controller (IPFC)

The Interline Power Flow Controller (IPFC) consists of two series converters in different lines that are interconnected by a common DC link. It is an apparatus that offers thorough power flow control for a multi-line transmission substation and is made up of a number of DC to AC converters, each of which offers series compensation for a distinct distribution and transmission line. The converters are connected to one another at their DC terminals, and their series coupling transformers are used to connect them to the AC systems. With this configuration, it offers series reactive compensation in addition to allowing any converter to be controlled to supply active power from its own transmission line to the common DC connection. (Muntjir, 2021). Unlike other FACTS controls and compensate power flow in a multiple outgoing line systems as shown in figure 2.18

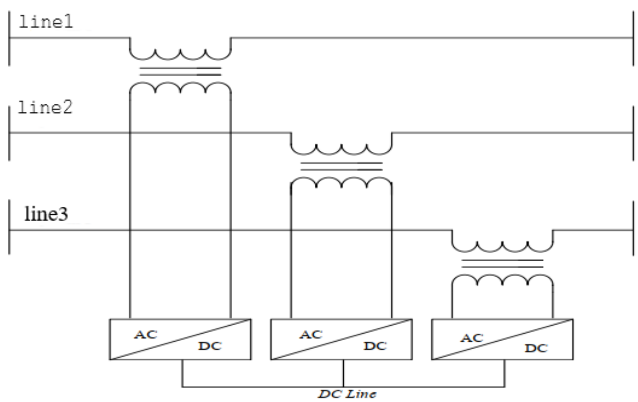


Fig. 2.18 Schematic diagram of IPFC for three outgoing line

## 2.2 Related literature review

From related review work, the ability of supplying and absorbing real and reactive power principal and devices, to improve the voltage stability and loss minimization based on FACTS device, power flow analysis, and to maintain steady state operation of the system when subjected to a large disturbance. To study this field area reviewed the following related open journal papers.

(Thippana et al., 2019) proposed that fault current limits the capability of interline power flow controller in a low-level distribution network. As a result, the IPFC device is suitable and effective for reducing fault current, with this effectiveness reduction of fault current could be avoided by replacing the existing L.V switchgear also the parallel operation of the transformer with single switchgear load distribution for economic advantage. However, injected voltage is limited by the reference design fault current of the switchgear.

(Shahgholian & Yousefi, 2019) proposed that Among FACTS UPFC controllers is the combination of series and shunt compensation to power flow control and enhancing the dynamic stability of power system by using phasor model.

(Gebru et al., 2021) proposed that network reconfiguration and capacitor bank placement In order to improve the performance of radial distribution systems, this research simultaneously proposes radial distribution network reconfiguration and switching capacitor bank allocation. Modified particle swarm optimization is used to select design variables depending on both the optimal network reconfiguration and optimal capacitor sizing. The algorithm is efficient in terms of reducing both real and reactive power losses as a result the active and reactive power.

(Abd al hassan & Tuaimah, 2020) proposed that Investigates one of the most promising FACTS device, the researchers used UPFC during investigation to achieved fundamentals like voltage regulation, reactive power, and power flow controller to make the system more efficient and reliable. The result can show the number of UPFC is increase with increased load at (15% and 20%) because one UPFC cannot reduce overload in lines loss so using two units of UPFC devices in a different position can improve maximum load ability and minimum line losses.

(Oukennou et al., 2018) Proposed that Coordinated Placement and Setting of FACTS in Electrical Network based on Kalai-smorodinsky Bargaining Solution and Voltage Deviation Index by using TCSC and SVC compensating FACTS devices which is teste investigation in IEEE-14 bus system which has been simulated in MATLAB.

(Pradesh, 2011) Proposed that the comparison of the Two most recent flexible AC transmission systems (FACTS) controllers used to regulate power flows across numbers of power lines are unified power flow controller (UPFC) and the interline power flow controller (IPFC). The regulation of power flow in the power lines are installed and where electricity flows, this model is incorporated into the Newton-Raphson (NR) power flow algorithm. During comparison the IPFC more performance.

(Suliman, 2020) Proposed that the FACTS device STATCOM is power electronics components which have the capability for enhancing voltage profile by injecting controllable voltage to the distributed system. By using FLC at load side during normal and abnormal condition at

MATLAB for enhancing voltage profile, and also increasing stability and controllability of distribution system.

The above literature reviews network reconfiguration, placing capacitor and FACTs devices TCSC, STATCOM and UPFC are compensate single line of transmission and distribution line, and IPFC injected voltage is limited by switchgear current rating. This thesis proposed the enhancement of voltage stability and loss minimization by using an interline power flow controller for two outgoing distribution line in Butajira 132 kV substation and Without injected voltage limitation of switchgear current to compensate for two distribution outgoing line.

# CHAPTER THREE

# MATERIALS AND METHODS

## 3.1 Materials

The materials used to identify the voltage profile and loss of each bus in butajira distribution substation system using MATLAB Simulink, Edrawmax, mathwork, interline power flow controller, power transformer, Bus Bar, voltage source converter, and capacitors.

The programming environment MATLAB was created mainly for engineers and scientists to evaluate and create the systems and technologies that will change the world. It contain matlab Simulink tool that used to measuring, displaying, transforming abc to dq0, power computation, and etc.  EdrawMax is diagram designing software which are integrated functional library to draw all the products.  To study the proposed butajira distribution network power problem, the primary data have been collected for one year monthly power loaded and faulted interruption from September 2020 to August 2021.

### 3.1.1 Description of the case study area within and outgoing feeder

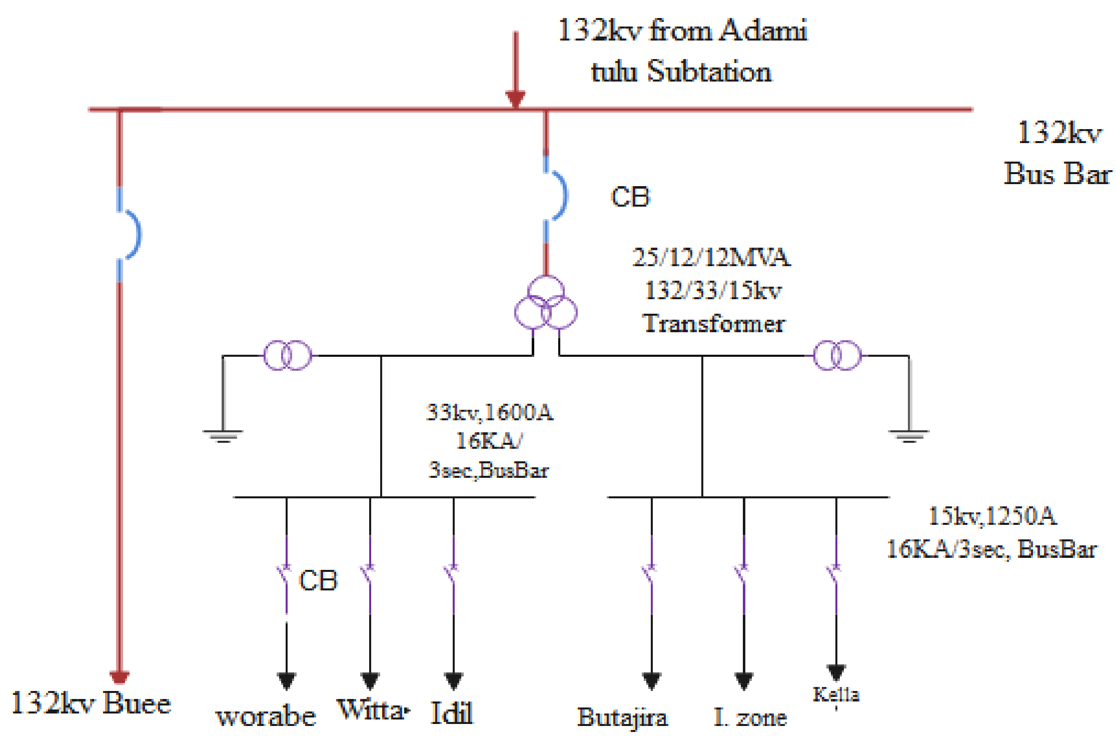


Fig. 3.1 Single line schematic diagram of Butajira substation

From the above figure Butajira distribution substations, which is found in south nation nationality people representative /SNNPR/ region, Gurage zone at Butajira city. The substation is 134k.m away from Adis Abeba and get power from Koka generating hydropower plant by Adami Tulu substation and distribute to deferent sub-areas and it was energized 1995 EC. It contains a 132KV bus bar with a three-phase winding power transformer. From these substations, 132 KV to Buea substation and 132/33/15 KV step down power transformer with three 33 KV feeders and three 15 KV feeders are fed to a different area. 33 KV feeders are feeds to Worabe, Witta, and idle, and 15 KV feeders are feeds to Butajira, industry zone, and Kella.

**Worabe outgoing feeder** feeds 33 KV from Butajira to Wurib, Senena, Gerbiber, Garora, Kibet Hospital, Asano, Menahriya, and Worabe twons. After reaching the distributed transformer, an area the secondary distribution system could be started with their own step-down 33 KV to 380 and 220-volt transformers.

**Witta outgoing feeder** feeds 33 KV from Butajira distribution substation to Desta garment, Ali plastic factories, Water pump, and Witta towns.

**Butajira outgoing feeder** feeds 15 KV from the substation to Butajira, Agoda, Mikayllo, Haro-Sheytan, Boza, Kibet and Adber Woleya.

Each outgoing feeder contains a number of transformers found after secondary electric power distribution systems that transfer to the end-user customer side. The secondary distribution side of this distribution system low-level voltage by a step-down transformer that is suitable for end-user usage. The commonly used voltages are 220 volts for the single line and 380v for the three-phase line to end-user customers.

For this thesis, only primary voltage data were used which means 33KV and 15KV outgoing lines from the substation with their loads which has been recorded in the substation for each day out of the year. Also, convertor size was considered the rating of this outgoing line feeders rating capacity.

### 3.2 Methods

The block diagram of methodology could be shown as the Fig.3.2 below with it’s description

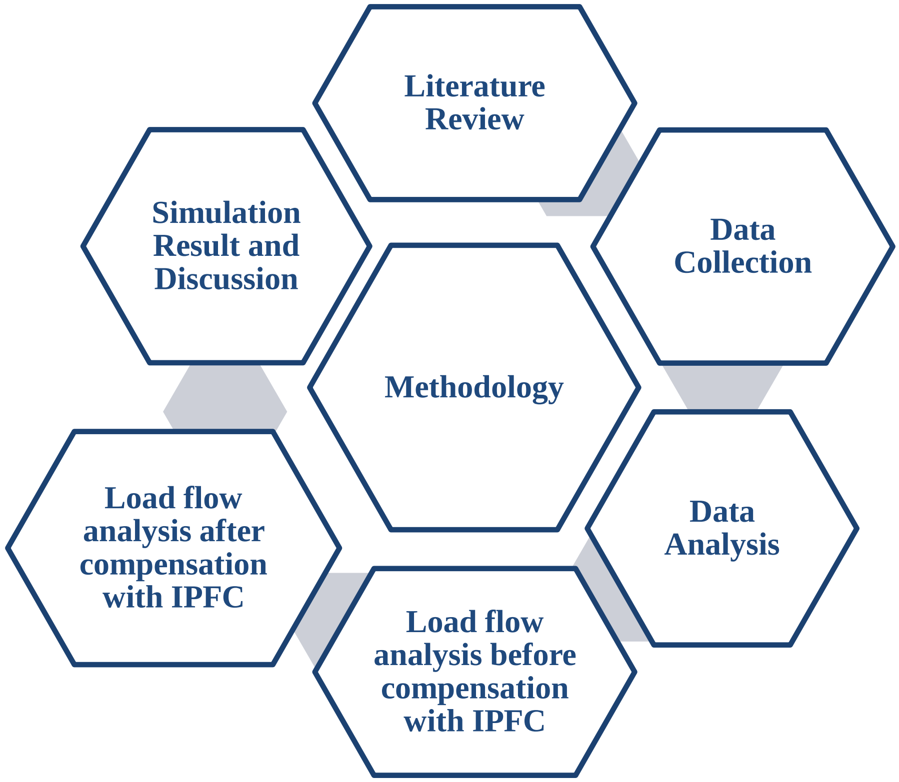


Fig. 3.2 Block diagram of methodology of the thesis

**Literature review: -** Numbers of published related research papers were reviewed in literature which are books, journal articles, thesis, and conferences. The related paper works are discussed for compensation.

**Data collation: -** The Primary data were collected through interviews and direct observation from Butajira distribution substation and Butajira utility. The secondary data were collected from literature and datasheets of electric distribution substation.

Data collected from collecting methods are

- Rating of distribution power transformers,
- The rated voltage of each feeder,
- Ratings of power transformer,
- Distribution line length from the substation to end customers, and Maximum, minimum, and peak loads are collected.

**Data analysis: -** The collected data were analyzed by tables using peak loads and line parameters of the distribution lines and the transformer ratings.

**Load flow Analysis before compensation with IPFC: -** Analyze voltage, current, active and reactive power of existing substation during normal and fault condition by using MATLAB Simulink.

**Load flow analysis after compensation with IPFC:-** After mathematical modelling of components to model IPFC, Analyze the simulation result after the applying of IPFC for both faulted and normal condition by MATLAB Simulink.

**Simulation result and discussion: -** finally Compere and Analysis the simulation result in

✓ MATLAB Simulink

### 3.3 Data collection and analysis

### 3.3.1 Transformer data

The distribution substation contains a three-phase winding power transformer with 132/33/15KV caring capacity and which has contained the following parameters.

Table 3. 1 Transformer data

| | |
|---|---|
| Transformer Id | SFSZ10-25000/132 |
| Rated power | 25/12/12MVA |
| Rated voltage | 132/33/15KV |
| Frequency | 50Hz |
| No-load current | 0.13% |
| No-Load Loss | 17.840KW |
| Load Loss | 38.421/ 39.224/ 40.612 KW |
| Impedance | 10.65/17.95/6.65% |

### 3.3.2 Yearly Peak Load and Minimum Load of the Outgoing Line

During the analysis of the power system distribution network, the value of the monthly peak, average, and minimum load of the feeder must be considered to determine the reason for power loss and weak voltage profile-related problems. The most habituated cause of power line loss and poor voltage profile in a distribution system is feeder overloading due to different load and fault cases. The following table 3.2 illustrates the peak and minimum load of the outgoing line of the Butajira substation for one year. However, the peak and minimum load of each feeder are from recorded data in each month during 2020 and 2021 which are tabulated in Appendix A in detailed.

Table 3. 2 Yearly peak and minimum load of the substation from Sep. 2020 to Aug.2021

| No. | Name of In/outgoing line | Peak load (MW) | current (A) | Minimum load(MW) | Current (A) |
|---|---|---|---|---|---|
| 1 | Adami tulu | 15.1 | 76 | 0.1 | 7 |
| 2 | 33kv feeder | 5.7815 | 119 | 0.5345 | 11 |
| 3 | Worabe | 5.7815 | 119 | 0.5345 | 11 |
| 4 | Witta | 0.243 | 5 | 0 | 0 |
| 5 | 15kv feeder | 8.3476 | 378 | 0.1988 | 9 |
| 6 | Butajira | 4.571 | 207 | 0.354 | 16 |
| 7 | Industry zone | 1.281 | 58 | 0.0884 | 4 |
| 8 | Kella | 2.783 | 126 | 0.0884 | 4 |

From the table, it can be seen that the outgoing line of Worabe and Butajira has more peak load demand than the other outgoing distribution line. That means these lines are more loaded and power interruption due to overloading of the system. This peak load of each outgoing line, the highest peak load is taking place on the feeder 33KV Worabe line and the minimum load value occurs at 33KV at Witta outgoing line. Therefore selected compensating components are between this two outgoing line.

### 3.3.3 Primary and secondary distribution line conductor type and impedance of the substation

The distribution conductors of overhead line should be symmetrically arranged and has been equidistant from each other to maintain that each phase's flux linkages and inductance are equal. Even if the currents in the conductors are balanced, if the conductor structure is asymmetrical, the inductance would be different, resulting in unequal voltage drops in the three phases. As a result, the voltage at the receiving end will be different for each steps. To ensure that voltage drops are equal in all conductors, it is common practice to arrange the conductors symmetrically or to interchange the location of the conductors at regular intervals along the line such that each conductor occupies the original position of any other conductor over an equal distance.

The overhead line of a Butajira substation from substation to end users have three type of all aluminum conductor AAC at primary and secondary distribution network. It has a very low specific mechanical resistance, is utilized for short lengths rather than long spans, and mostly employed in urban areas to provide perfect cable support, takes up less space, and simple to install. The primary substation conductor size is AAC 95 mm2 and secondary side of distribution connected by AAC 50 mm2 and AAC25 mm2. As shows in the table below the standard of the conductor impedances per/km with each outgoing line of the substation.

Table 3. 3 Standard of conductor type and their size.

| No. | Conductor type | Nominal area | Real area | Resistance Ω/km | Reactance Ω/km |
|---|---|---|---|---|---|
| 1 | AAC | 95 | 93.5 | 0.31 | 0.324 |
| 2 | AAC | 50 | 49.5 | 0.68 | 0.362 |
| 3 | AAC | 25 | 24.2 | 1.338 | 0.38 |

The resistance and impedance of each outgoing line per kilometer for Butajira distribution substation shown at the following table 3.4

Table 3. 4 Inductance of outgoing line

| No | Started from | Conductor type | End | R Ω/km | X Ω/km | Distance in km | Resistance Ω | Reactance Ω |
|---|---|---|---|---|---|---|---|---|
| 1 | B.DS | AAC95 | Worabe | 0.31 | 0.324 | 58 | 17.98 | 18.792 |
| 2 | >> | AAC95 | Witta | 0.31 | 0.324 | 15 | 4.65 | 4.86 |
| 3 | SD.TF | AAC50 | Awaye | 0.68 | 0.362 | 30 | 20.4 | 10.86 |
| 4 | >> | AAC50 | Kella | 0.68 | 0.362 | 15 | 10.2 | 5.43 |
| 5 | >> | AAC50 | Industry zone | 0.68 | 0.362 | 12 | 8.16 | 4.344 |

For this thesis analysis the primary bus data with necessary load data were used. Therefore the outgoing line data of primary distribution substation tabulated above table. Also resistance and inductance with their length of the distribution system only considered primary side of secondary distribution transformer. For 33KV outgoing feeder line considered AAC95 conductor and for 15KV outgoing feeder line used AAC50 conductor type consideration of primary distribution substation for analysis of the system.

## 3.4 The FACTS device which is selected to compensation

### 3.4.1 Interline power flow controller

The objective of express this component is to solve the problem of compensating a number of distribution and transmission lines witch are connected at a substation. The application of a TCSC and SSSC to be reducing impedance of the line, as a results in the reduction of net series reactance of the line.

The Interline Power Flow Controller offers the capacity to interchange actual power directly across the compensated lines of the system, in addition to being suited for individually adjustable reactive compensation for each individual line of the power system. To do this, all of the DC capacitors of each individual converter are linked in parallel, linking the series connected VSCs at separate lines on the DC side. This is possible because all the series converters are near to one another inside of the substation. An IPFC with two converters compensating two lines as shown in Fig.3.3 is similar to that UPFC in that the magnitude and phase angle of the injected voltage in the prime system line 1 can be controlled by exchanging real power with the support system and also a series converter in the line 2.

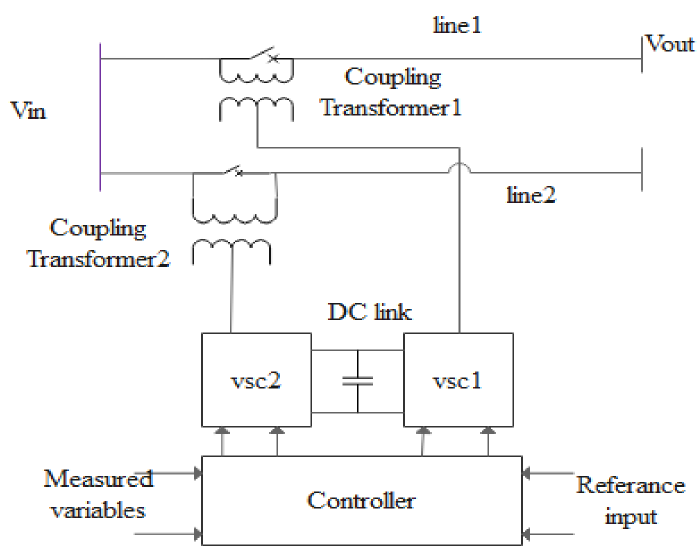


Fig. 3.3 Two voltage source convertor interline power flow control with controller schem

The main difference between IPFC and UPFC is that UPFC constructed in the form of shunt to inject the system instance of series convertor injection of IPFC.

The IPFC's prime system series converter is referred to as the master converter, and the support system's series converter is referred to as the slave converter. The slave converter controls the DC voltage across the capacitor and the amount of the reactive voltage, while the master converter controls both active and reactive voltage up to a certain limit.(Sharan et al., 2019).

### 3.4.2 Working principal of interline power flow controller

In generally principal of series controller of FACTS devices are injecting voltage to the connected point of series network with quadrature of line current. In the case of interline power flow controller in addition a number of AC to DC converters each providing series compensation for a different line. Another way, the IPFC comprises a number of Static Synchronous Series Compensator's (SSSC). During compensation the voltage source convertors are act as invertor to inject the voltage to the line or as reactor to observing voltage from the line depending on line parameter value. The simplest IPFC consists of two AC to DC converters placed back-to-back, coupled in series with two lines using series coupling transformers, and their DC terminals linked by a single DC connection.

The control variables like reference, measured and parameter settings are input to controller for adjusting voltage source converter to injecting suitable magnitude to distribution line as shown below Fig. 3.3. The IPFC structure have been possibility to transfer reactive power, as well as to exchange active power with the line. On the other hand, the transmitted power in each line depends on the line's series impedance, the sending and receiving buses' phase shift, and the voltage amplitude of the sending and receiving buses.

The two back-to-back voltage-source converters (VSCs) based on the use of gate turn off (GTO) thyristor valves. The voltage source converters (VSC) produce voltages that vary in magnitude and phase angle. These voltages are inserted in series with the managed distribution and transmission lines using series transformers. The active power exchanged at the ac terminal is transformed into dc power by the associated VSC, which manifests as a positive or negative demand at the dc link. As a result, each VSC's actual power negotiation across the dc lines must be equivalent to the active power negotiation made by the other VSC. As a result interline power flow controller (IPFC) can maintain the flow of active and reactive power in multiple line system even when a failure occurs(Becker et al., 2015).

### 3.4.3 Operating principle of series convertor

In generally, the operating principals of series compensation method is injecting voltage with series line current quadrature depending on desired input. The operating modes of series convertor depends on the magnitude of injected voltage, relative phase angle and variation of active and reactive power flow at distribution line with in specified region. The series convertor controls the magnitude and phase angle of the voltage injected in series with the line as invertor and reactor depending on the magnitude of the Bus voltage and angle. The magnitude of the injected voltage to the line is influence the power flow with in line. Operating mode of series convertor for IPFC determine as flow.

A. **Direct voltage injection: -** The series converters act as reactor to observe and act as invertor to generate a voltage vector with magnitude and phase angle requested by reference input. When the injected voltage is kept in quadrature with the line current to provide entirely reactive series compensation, this is a specific example of direct voltage injection. In order to phase shift the voltage with respect to the voltage by the amount indicated by the reference input, the series inverter injects the necessary voltage.
B. **Automatic Power Flow Control: -** The reference input determine the required real power and the reactive power at a specified location in the line. The real power and reactive power can be controlled independently of each other in a feasible region determined by the satisfaction of various constraints. Interline power flow controller has the capability of independently controlling both the real power flow at a specific point. This capability can be appreciated by interpreting the series injected voltage, Vse as a controllable two-dimensional vector quantity. Automatic power flow control refers to the process of creating a matching power flow using an adequately determined injected voltage vector to force any desired current vector that is within its limit to flow on the line. To guarantee that the necessary actual power and reactive power are maintained during the various system changes, the series injected voltage is automatically and constantly calculated by a vector control system.
C. **Line impedance reduction: -** Line impedance reduction mode where the series injected voltage is controlled in proportion to the line current. The desired impedance is specified by reference input. In general, it may be impedance with resistive and reactive components of either polarity. The impedance is get from injected voltage divided by the line current is

determined by the reference inputs. It is essential to avoid instability or resonance power system. A resonance can be formed from large value of the capacitive (negative) reactance of the line.

**D. Shifting Phase Angle: -** The reference input is phase displacement between the sending end voltage and the receiving end voltage

# CHAPTER FOUR

## DESIGN AND ANALYSIS OF DISTRIBUTION SUBSTATION SYSTEM

### 4.1 Interline power flow controller

The existing distribution substation data were mentioned above portion with their necessary primary bus data. To design and analysis the existing distribution substation with selected component interline power flow controller to stable the power system and loss minimization will be discussed in this portion.

Interline power flow controller is a combination of two and more convertor's which are act as synchronous series compensator's (SSSCs) with combined a common DC voltage link. At this combination there is no energy storage system installed for storage purpose in state of DC voltage battery usually modelled DC capacitor as voltage source storage. From the connection that offers the IPFC a route for exchanging active and reactive electricity between various distribution network lines. The VSC of IPFC can be modeled as a series voltage source injecting an essentially sinusoidal voltage with adjustable magnitude and angle in both steady-state analysis and rotor angle stability analysis.

### 4.2 The Components to design interline power flow controller

Interline power flow controller combination of two and more than two convertor, but in this thesis it consists two convertor, coupling transformer and dc source.

#### a. Convertors

The most important parts of IPFC systems are convertors. They play the role of converting AC power to DC power or DC power to AC power. The converter valves are built with GTO power semiconductors(Akther et al., 2019). Methods of reducing the harmonic in higher power system that produced by convertors are harmonic neutralization utilizing by using magnetic coupling, multilayer converter designs, and innovative pulse-width modulation (PWM) switching techniques. By merging two or four (12-pulse) VSI with the required phase shift between each converter, the 24 and 48 pulse converters are produced. A 24-pulse convertor could be adequately used in most application, but in the case of 48- pule convertor could be ensured low power quality problem and harmonic resonances. A 48-pulse Gate Turn-Off thyristor voltage source converter is included in the combined reactive power compensation and voltage stabilization of the electricity supply network. They are provided with R-C snubber and series

R-L elements to reduce dv/dt and di/dt stresses that occur during ON/OF transitions. Also it has low harmonics relative to other convertors (Chennakesavulu & Panthagani, 2015; Profile, 2017).

The same work is done by the back-to-back voltage sourced converters, but they have the added benefit of being able to independently adjust the ac voltage on the connection bus on each side. This is due to the fact that each voltage supplied converter's reactive power created on the ac side is largely unrelated to the real power being transferred from one converter to the others(Das et al., 2018).

**Convertor size:** To design the size of converters in IPFC systems depends basically on the steady performances requirements, i.e. on scheduled active power transport and voltage support requirement. During steady state operation the voltages at the equipment terminals, e.g. converters, shall be within the pre-defined limits. Typical limits are 95% to 105% and 90% to 110%. Strictly speaking, the limits are only applicable to the equipment terminals. However the way power systems are currently designed and operated requires voltage to be kept within limits in the whole power system.

**b. Transformers**

Power electronic components are needed to be suitable for their working or operating capacity. For this purpose the transformers are used for converting the system voltage to a value suitable for the converter. For IPFC application standard transformers are used. The leakage reactance of the transformer is usually in the range 0.1-0.2pu. In this thesis work IPFC distribution line system development, the converter transformers convert the injected voltage which is suitable for the converters.

**c. Dc voltage source**

Capacitor is an important part of the converter for maintaining the DC voltage at constant value. Hence, designing the dc capacitor is very importance. A little ripple in the DC voltage is achieved by the capacitor's design. The time constant, which is the ratio of the DC powers stored on the converter's DC side to its nominal apparent power, serves to describe the size of the DC capacitor.

1. **Dc operating voltage**

At distribution substation there are higher side of voltage from high transmission line input and lower side of voltage from the output of distribution power transformer at substation. The cost of IPFC is higher due to the cost of the converter bridges. Higher voltage levels, which usually chosen for large power transfer capability. Thus the choice of the voltage levels mainly touches economic issues. Due to this reason, the selection of operating voltages constitutes one-part economic optimization of interline power flow controller in distribution line installations. Fundamental frequency component voltage output of the converter can be related to the DC operating voltage by the following Equation Chapter 4 Section 1

$$V_{dc} = V_{do} \cos\alpha \qquad (4.1)$$

$$V_{do} = \frac{3\sqrt{2} * V_{ll}}{\pi} \qquad (4.2)$$

- Where, Vdo and Vll no load voltage and line to line voltage of the line and α delay angle15°, By using (4.2) can be get
- $Vdo = \frac{\mathbf{3\sqrt{2} * 15\ kv}}{\boldsymbol{\pi}}$

  $= 20.26kv$

  Where,

  15kv is secondary side of coupling transformer which is suitable for the outgoing feeder’s magnitude. From this no load voltage of secondary side of transformer calculate Vdc as $V_{dc} = V_{do} \cos\alpha$
- $Vdc = 20.26\,V\cos\alpha$
- $Vdc = 20.26\cos 15$

  =19.57kv which used for calculating capacitor value of secondary side of coupling transformer.

2. **DC capacitor value**

A large DC capacitors are used to get a small ripple in dc voltage. But large DC capacitors results in slow the changes of the DC voltage in response to changes in the power exchanged at the DC side of the converter. On the other way, the application of small DC capacitors results in fast response to changes in instantaneous power exchanged but case of large ripple in the dc voltage. Capacitor sizing is determined from energy storage of capacitors principle which states that energy store in a capacitor is proportional to the capacitance of the capacitor and the supply voltage to it.

Mathematically,

$$E = \frac{CV^2}{2} \tag{4.3}$$

$$\frac{E}{t} = \frac{CV^2}{2t} \tag{4.4}$$

Dividing both side by time to get electrical power Sn than, the total capacitance of the dc capacitors can be approximated by

$$C_{DC} = \frac{tS_n}{0.5V^2{}_{dc}}$$

Where,

E is energy stored in the capacitor in joule.

Sn is the power rating on the capacitor 12 MVA

C is the capacitance of the capacitor in farad.

V is the secondary side voltage of the series transformer.

t is the time duration that the capacitor stores in second usually from 0.1ms to 0.6ms.

Let $t = 6ms$, Sn=12MVA, Vdc=19.57kv

Cdc $= \frac{6ms * 12 * 10^6}{0.5 * (19.57kv)^2}$ = 0.38mf

**4.3 Placement of selected compensating component**

By utilizing IPFC, the overall losses in the power system network's transmission lines are decreased, and bus voltages are boosted. The fitness function of average power loss is used to pinpoint the precise placement of the IPFC within the algorithm. The power flows in the transmission lines are also markedly improved after IPFC is positioned correctly(Vishnu Charan et al., 2020). Interline power flow controller effective voltage support at connected bus and to improves power transfer capability at distribution line. For this purpose the IPFC placed at lower side of Butajira substation in this thesis work. It is placed at lower voltage side of the transformer because of the cost convertor low due to low DC operating voltage and consequent power loss in distribution line associated with the reactive power flow.

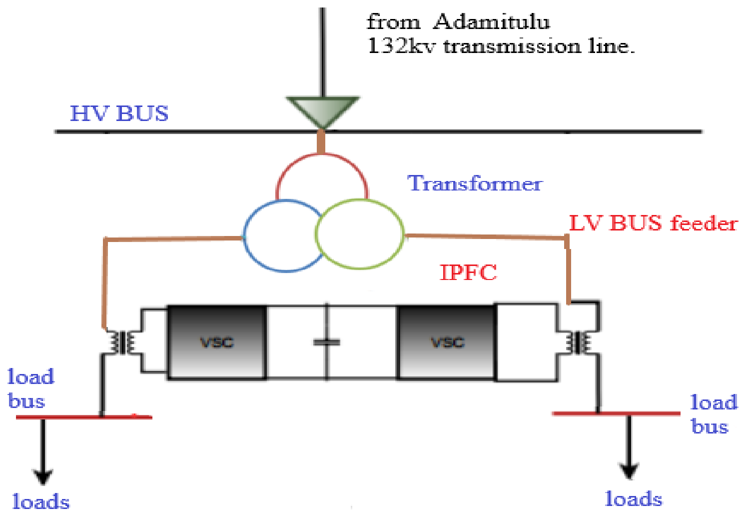


Fig. 4.1 Schematic diagram of substation with the placement of IPFC

### 4.4 Mathematical Modeling of Interline Power Flow Controller

Mathematical analysis of interline power flow controller is derived from equivalent circuit. Each interline power flow controller is composed of several VSCs, each of this VSC located in series with the lines their DC sides connected via a common capacitor. For the purpose of modelling the IPFC, it is considered in the form of several VSCs which have common DC connections(Ghorbani et al., 2018; Sreenivasachar, 2001). To model IPFC to this thesis considering only two VSC with common DC for two outgoing distribution line.

As explained at Fig.4.2 a phasor diagram of voltage source convertor which controlled by one converter of IPFC defines the relationship between sending-end voltage as V1 and receiving end Voltage as V2, the voltage across line impedance X (Vx) and inserted voltage Vs1 with a controllable magnitude as well as phase angle. The receiving end voltage V2 could be enhance its voltage profile by controlling injected voltage Vs1 to the system. During sending time a Vs1 added to the sending end voltage of V1 an effective sending end voltage becomes as

$$V_{seff} = V_{s1} + V_1 \tag{4.5}$$

Then the voltage difference between Vseff and V2 Set as compensating voltage. Angle ρ is varied over its full 360 degree range, the end of voltage Vs1 moves along a circle with its center located at the end of voltage V1. The operating region were the area covered by Vs1 overall the circle.

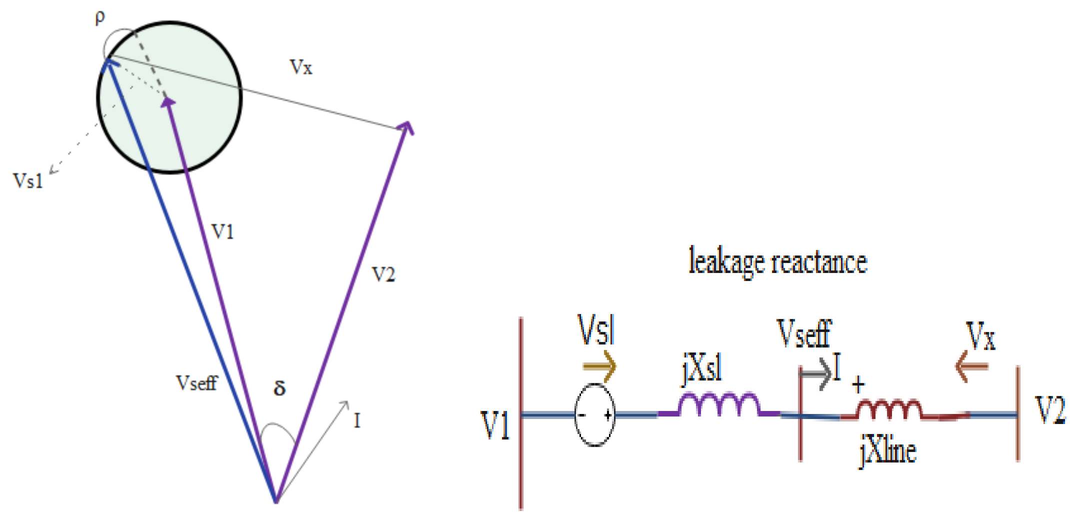


Fig 4.2 Phasor diagram of voltage source convertor

The mathematical modelling for three bus distribution substation with IPFC shown below fig 4.3 from the figure the load current at line one is represented by Il1 and the load current at line two represent by $Il2$ and V1, V2 and V3 are the three Bus voltage from which V1 as input bus voltage and V2 and V3 are output Bus voltage of Bus1, Bus2 and Bus3 respectively. Vseff1 and Vseff2 represents effective sending voltage of IPFC at line one and line two.

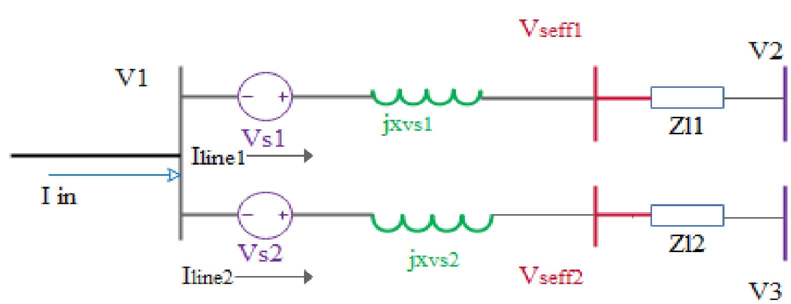


Fig. 4.3 Single line equivalent circuit diagram of IPFC with input and output bus of the substation.

Vs1 and Vs2 are the two series injected voltage by the two convertors, jxvs1 and jxvs2, Zl1 and Zl2 are impedance of injecting convertor and distribution line.

$$V_1 + V_{s1} = jX_{s1}I_{l1} + V_{seff\,1} \tag{4.6}$$

$$V_{seff\,1} = V_1 + V_{s1} - jX_{s1}I_{l1} \tag{4.7}$$

$$V_{seff\,1} = Z_{l1}I_{l1} + V_2 \tag{4.8}$$

From equation 4.7 and 4.8 gets

$$V_1 + v_{s1} - jx_{sl1}I_{l1} = Z_{l1}I_{l1} + V_2 \tag{4.9}$$

$$V_2 = V_1 + V_{s1} - I_{l1}(jx_{s1} + z_{l1}) \tag{4.10}$$

$$V_3 = V_1 + V_{s2} - I_{l2}(jx_{s2} + Z_{l2}) \tag{4.11}$$

From equation 4.10 and 4.11 understand the proposed solution V2 and V3 increased by additional injected voltage add with V1.

IPFC is composed of three components, each component has their own mathematical modeling. As discussed before the three components are, two series converter and DC link capacitors. Therefore, mathematical modeling for each component will simplify the design procedure.

i. Mathematical modelling of the convertor

Mathematical modeling the series convertor very important part to model IPFC. Therefore to model of the two convertor as flows.

Voltage stored on the resister convertor is given by I*Rs and the voltage stored in inductor is given by $V = l\frac{di}{dt}$. Therefore, from the figure 4.3 the voltage stored on the series converters can be formulated using the circuital theory of KVL equation.

In multi network line of power system and determining interims of voltage could be analysis the modelling equation of IPFC by using Kirchhoff's current law (KCL) and Kirchhoff's voltage law (KVL) from as follows(Parvathy S. & Thampatty, 2015).

For the first convertor Vs1

$$V_1 = L_{s1}\frac{di_{l1}}{dt} + R_{s1}I_{l1} + V_{s1} + V_2 \tag{4.12}$$

$$\frac{di_{l1}}{dt} = \frac{-R_{s1}I_{l1}}{L_{s1}} + \frac{V_1}{L_{s1}} - \frac{V_2}{L_{s1}} - \frac{V_{s1}}{L_{s1}} \tag{4.13}$$

For the second convertor Vs2

$$V_1 = L_{s2}\frac{di_{l2}}{dt} + R_{s2}I_{l2} + V_{s2} + V_3 \tag{4.14}$$

$$\frac{di_{l2}}{dt} = \frac{-R_{l2}I_{l2}}{L_{s2}} + \frac{V_1}{L_{s2}} - \frac{V_{s2}}{L_{s2}} - \frac{V_3}{L_{s2}} \tag{4.15}$$

Where,

- Ls and Rs are the series inductance and resistance of convertor, respectively.
- Il is the current through the distribution line.
- Vs, V2 and V 3 are series injected, sending end, and receiving end voltages.

The equation 4.14 and 4.15 could be written as in matrix form as below.

$$\frac{d}{dt}\begin{bmatrix} I_{l1a} \\ I_{l1b} \\ I_{l1c} \end{bmatrix} = -\frac{R_{s1}}{L_{s1}}\begin{bmatrix} I_{l1a} \\ I_{l1b} \\ I_{l1c} \end{bmatrix} + \frac{1}{L_{s1}}\begin{bmatrix} V_{1a} & -V_{s1a} & -V_{2a} \\ V_{1b} & -V_{s1b} & -V_{2b} \\ V_{1c} & -V_{s1c} & -V_{2c} \end{bmatrix} \tag{4.16}$$

$$\frac{d}{dt}\begin{bmatrix} I_{l2a} \\ I_{l2b} \\ I_{l2c} \end{bmatrix} = -\frac{R_{s2}}{L_{s2}}\begin{bmatrix} I_{l2a} \\ I_{l2b} \\ I_{l2c} \end{bmatrix} + \frac{1}{L_{s2}}\begin{bmatrix} V_{1a} & -V_{s2a} & -V_{3a} \\ V_{1b} & -V_{s2b} & -V_{3b} \\ V_{1c} & -V_{s2c} & -V_{3c} \end{bmatrix} \tag{4.17}$$

Controlling three elements is difficult so convert the equation 4.16 and 4.17 in to two element equation form to solve easier. This Equation has three voltage dependent currents and controlling this element is a more difficult. To reduce the complexity of the three-phase system control, reducing it into two-phase (d-q) frame of reference can minimize some work. Park's transformation rule can transfer three-phase system in two-phase system and this two phase system in other words called as d-q axis. How to converting and modeling the abc component to dq0 detailed explained with inductor, resistor and capacitor(Levron & Belikov, n.d.)(Fahima et al., 2018). So to reduce the complexity and to increase the performance of IPFC, mathematical modelling of IPFC is converted to dq0 from abc component for series convertor1 and convertor2 as below.

Three-phase signals in the abc reference frame are transformed into new values in the rotating dq0 reference frame via the dq0 transformation seen at appendix C.

For convertor1

$$\frac{di}{dt}\begin{pmatrix} I_{l1d} \\ I_{l1}q \end{pmatrix} = \begin{pmatrix} \frac{-R_{s1}}{L_{s1}} & \omega \\ -\omega & \frac{-R_{s1}}{L_{s1}} \end{pmatrix} \begin{pmatrix} I_{l1d} \\ I_{l1q} \end{pmatrix} + \frac{1}{L_{S1}} \begin{pmatrix} V_{1d} - V_{s1d} - V_{2d} \\ V_1 q - V_{s1q} - V_{2q} \end{pmatrix} \tag{4.18}$$

$$\frac{di}{dt}\begin{pmatrix} I_{l1d} \\ I_{l1}q \end{pmatrix} = \begin{pmatrix} \frac{-R_{s1}}{L_{s1}} & 0 \\ 0 & \frac{-R_{s1}}{L_{s1}} \end{pmatrix} \begin{pmatrix} I_{l1d} \\ I_{l1q} \end{pmatrix} + \frac{1}{L_{S1}} \begin{pmatrix} V_{1d} - V_{s1d} - V_{2d} + \omega L_{s1} I_{l1q} \\ V_1 q - V_{s1q} - V_{2q} - \omega L_{s1} I_{l1d} \end{pmatrix} \tag{4.19}$$

For convertor2

$$\frac{di}{dt}\begin{pmatrix} I_{l2d} \\ I_{l2}q \end{pmatrix} = \begin{pmatrix} \frac{-R_{s2}}{L_{s2}} & \omega \\ -\omega & \frac{-R_{s2}}{L_{s2}} \end{pmatrix} \begin{pmatrix} I_{l2d} \\ I_{2q} \end{pmatrix} + \frac{1}{L_{S2}} \begin{pmatrix} V_{1d} - V_{s2d} - V_{3d} \\ V_1 q - V_{s2q} - V_{3q} \end{pmatrix} \tag{4.20}$$

$$\frac{di}{dt}\begin{pmatrix} I_{l2d} \\ I_{l2}q \end{pmatrix} = \begin{pmatrix} \frac{-R_{s2}}{L_{s2}} & 0 \\ 0 & \frac{-R_{s2}}{L_{s2}} \end{pmatrix} \begin{pmatrix} I_{l1d} \\ I_{l1q} \end{pmatrix} + \frac{1}{L_{S2}} \begin{pmatrix} V_{1d} - V_{s2d} - V_{3d} + \omega L_{s2} I_{l2q} \\ V_1 q - V_{s2q} - V_{3q} - \omega L_{s2} I_{l2d} \end{pmatrix} \tag{4.21}$$

From equation no. (4.19) and (4.21) mathematical modelling of convertor1 and convertor2 respectively. Let as control variable for convertor one injecting voltage to distribution line 1 depending on equation no. (4.19).

$$\begin{pmatrix} V_{s1d} \\ V_{s1q} \end{pmatrix} = \begin{pmatrix} k_{ps1} + \frac{k_{is1}}{s} & 0 \\ 0 & k_{ps1} + \frac{k_{is1}}{s} \end{pmatrix} \begin{pmatrix} I_{l1dref} - I_{l1d} \\ I_{l1qref} - I_{l1q} \end{pmatrix} + \frac{1}{L_{S1}} \begin{pmatrix} V_{1d} - V_{2d} + \omega L_{s1} I_{l1q} \\ V_1 q - V_{2q} - \omega L_{s1} I_{l1d} \end{pmatrix} \tag{4.22}$$

Where, Kps1 and Kis1 are proportional and integral gain for the PI controller,

Il1drefnd Il2qref are direct and quadrature axis reference current of real and reactive power,

Il1d and Il1q are measured current of series convertor1 for d-q component, Vs1d and Vs2q are injecting voltage of series convertor to the distribution line,

V1d and V1q, V2d and V2q are d-q component of sending and receiving end voltage of line1.

From power computation, the power flow at bus2

$$s_2 = v_2(I_{l1}*) \tag{4.23}$$
$$= (v_{2d} + jv_{2q})(I_{l1d} - jI_{l1q})$$

$$= v_{2d}I_{l1d} + v_{2q}I_{l1q} + j(-v_{2q}I_{l1d} + v_{2d}I_{l1q}) \tag{4.24}$$

Active power of series convertor1 at bus two

$$P_2 = v_{2d}I_{l1d} + v_{2q}I_{l1q} \tag{4.25}$$

Reactive power of series convertor1 at bus two

$$Q_2 = -v_{2q}I_{l1d} + v_{2d}I_{l1q} \tag{4.26}$$

Reference current can be calculated from equation (4.25) and (4.26)

$$I_{l1dref} = \frac{P_{ref}v_{2d} + Qrefv_{2q}}{v^2{}_2} \tag{4.27}$$

$$I_{l1qref} = \frac{P_{ref}v_{2q} - Qrefv_{2d}}{v^2{}_2} \tag{4.28}$$

Where, $v_2{}^2 = v^2{}_{2d} + v^2{}_{2q}$ Iref, Pref and Qref reference current, real and reactive power at bus2 and V2d and V2q are active and reactive components of bus 2 at receiving end voltages.

Controlling variables for convertor2 by using equation 4.21

$$\begin{pmatrix} V_{s2d} \\ V_{s2q} \end{pmatrix} = \begin{pmatrix} k_{ps2} + \frac{k_{is2}}{s} & 0 \\ 0 & k_{ps2} + \frac{k_{is2}}{s} \end{pmatrix} \begin{pmatrix} I_{l2dref} - I_{l2d} \\ I_{l2qref} - I_{l2q} \end{pmatrix} + \frac{1}{L_{S2}} \begin{pmatrix} V_{1d} - V_{3d} + \omega L_{s2}I_{l2q} \\ V_1 q - V_{3q} - \omega L_{s2}I_{l2d} \end{pmatrix} \tag{4.29}$$

The direct axis of convertor two depends on Dc line capacitor storage voltage. Therefore, the reference current of convertor2 real component is

$$I_{l2dref} = (K_{ps2} + \frac{K_{is2}}{s})(V_{dcref} - V_{dc}) \tag{4.30}$$

And quadrature axis of convertor2 depends on the real power pass through convertor2 and it can be calculated as

$$I_{l2qref} = (K_{ps2} + \frac{K_{is2}}{s})(V_{1ref} - V_1) \tag{4.31}$$

ii. DC link modeling

The power flow maintain in a capacitor, controlling the net input power should instantaneously meet the charging and discharging rate of energy in the capacitor. The input power to capacitor comes through converter one and output power pass through converter two. Thus by applying the power balance equation, the net power in DC link capacitor becomes the difference between power in the converter one and power in the second converter.

The power in capacitor given the different of the two power line.

$$P_{dc} = p_{dcs1} - p_{dcs2} \tag{4.32}$$

Where,

Pdc is the power stored in DC capacitor

Pdcs1 is the power coming to DC link capacitor from series convertor one

Pdcs2 is the power injected to connected line from series convertor 2

$$P_{dcs1} = V_{s1d} I_{l1d} - V_{s1q} I_{l1q} \tag{4.33}$$

$$P_{dcs2} = V_{s2d} I_{l2d} - V_{s2q} I_{l2q} \tag{4.34}$$

The current in dc link capacitor is calculated as

$$I_{dc} = c \frac{d}{dt} V_{dc} \tag{4.35}$$

$$P_{dc} = V_{dc} I_{dc} \tag{4.36}$$

$$P_{dc} = V_{dc} c \frac{dV_{dc}}{dt} \tag{4.37}$$

$$V_{dc} c \frac{dV_{dc}}{dt} = \left(V_{s1d} I_{l1d} - V_{s1q} I_{l1q}\right) - \left(V_{s2d} I_{l2d} - V_{s2q} I_{l2q}\right) \tag{4.38}$$

Where,

$$V_{dc} c \frac{dV_{dc}}{dt} = \frac{1}{2} c \frac{dV_{dc}^{\ 2}}{dt}$$

$$\frac{1}{2} c \frac{dV_{dc}^{\ 2}}{dt} = \left(V_{s1d} I_{l1d} - V_{s1q} I_{l1q}\right) - \left(V_{s2d} I_{l2d} - V_{s2q} I_{l2q}\right) \quad (4.39)$$

$$V^2{}_{dc} c \frac{dvdc}{dt} = \frac{2}{c}\left[\left(V_{s1d} I_{l1d} - V_{s1q} I_{l1q}\right) - \left(V_{s2d} I_{l2d} - V_{s2q} I_{l2q}\right)\right] \quad (4.40)$$

Calculating the fault current with and without IPFC of outgoing distribution system network

$$V_1 = I_{f1l} * Z_{l1} + V_2 \quad (4.41)$$

$$I_{fl} = \frac{V_1 - V_2}{Z_l} \quad (4.42)$$

Where

$I_f$ for fault current

$Z_l$ for impedance of outgoing line of distribution line

From equation 4.41 and 4.42 were input voltage and current during the fault condition of outgoing line of fig.4.3 without IPFC. During this time there is no injecting voltage and the fault current in to the line is very high.

Interline power flow controller is connected at the low Voltage side of the distribution substation transformer. It is installed with two coupling transformers at the common low voltage bus and it is used to balance the load in normal operation. Controller senses the Bus voltage during the fault condition and it injects voltage from its voltage source convertor. The equation with IPFC during fault condition as flows.

$$V_1 = I_{fl} z_{l1} + V_{s1} + I_{f1} X_{s1} + V_2 \quad (4.43)$$

$$I_{fl} = \frac{V_1 - V_{s1} - V_2}{X_{s1} + z_{l1}} \quad (4.44)$$

From equation 4.44 understand fault current during the outgoing distribution line network with IPFC is reduced due to injected voltage.

**Power flow equation including IPFC**

The equivalent circuit of the IPFC in steady state is shown in Figure 4.3 consisting of two voltage sources in series with the two distribution lines via the coupling transformers and linked together by DC link. The IPFC is installed between buses 1 - 2 and 1 - 3. Each VSC injects a series voltage Vsl = Vsl∠$\delta$ to provide series compensation to the respective distribution line. Vs is the magnitude and $\delta$ is the phase angle of Vsl. The power injected to Bus 1 can be derived as flow.

The current away from Bus 1 is $$I_1 = I_{12} + I_{13} \quad (4.45)$$

$$\begin{aligned} I_1 &= \frac{v_1 - v_{s1} - v_2}{z_{l1}} + \frac{v_1 - v_{s2} - v_3}{z_{l2}} \\ &= (v_1 - v_{s1} - v_2)y_{12} + (v_1 - v_{s2} - v_3)y_{13} \\ &= (v_1 - v_{s1} - v_2)(g_{12} + jb_{12}) + (v_1 - v_{s2} - v_3)(g_{13} + jb_{13}) \end{aligned} \quad (4.46)$$

Where y=1/Zl=g1n+jb

$$S = V_1 I_1{}^* = P_1 + jQ_1 \quad (4.47)$$

Where I* complex conjugated of I, substitute equation 4.46 in to 4.47 separate real and imaginary part and obtain the power flow at bus 1 as flows.

$$\begin{aligned} P_1 &= V_1^2 g_{11} - \sum_{n=1,2} V_1 V_n (g_{1n}\cos(\delta_1 - \delta_n) + b_{1n}\sin(\delta_1 - \delta_n)) \\ &- \sum_{n=1,2} V_1 V_{s1n} (g_{1n}\cos(\delta_1 - \delta_{s1n}) + b_{1n}\sin(\delta_1 - \delta_{s1n})) \end{aligned} \quad (4.48)$$

$$\begin{aligned} Q_1 &= -V_1^2 b_{11} - \sum_{n=1,2} V_1 V_n (g_{1n}\sin(\delta_1 - \delta_n) - b_{1n}\cos(\delta_1 - \delta_n)) \\ &- \sum_{n=1,2} V_1 V_{s1n} (g_{1n}\sin(\delta_1 - \delta_{s1n}) - b_{1n}\cos(\delta_1 - \delta_{s1n})) \end{aligned} \quad (4.49)$$

iii. Simulink model of series convertor

The Simulink modeling of a series convertors are get from mathematical modeling equation of a convertor. It depends on d-q axis component of the equation. The figure below shows the Simulink block of series voltage injection with line.

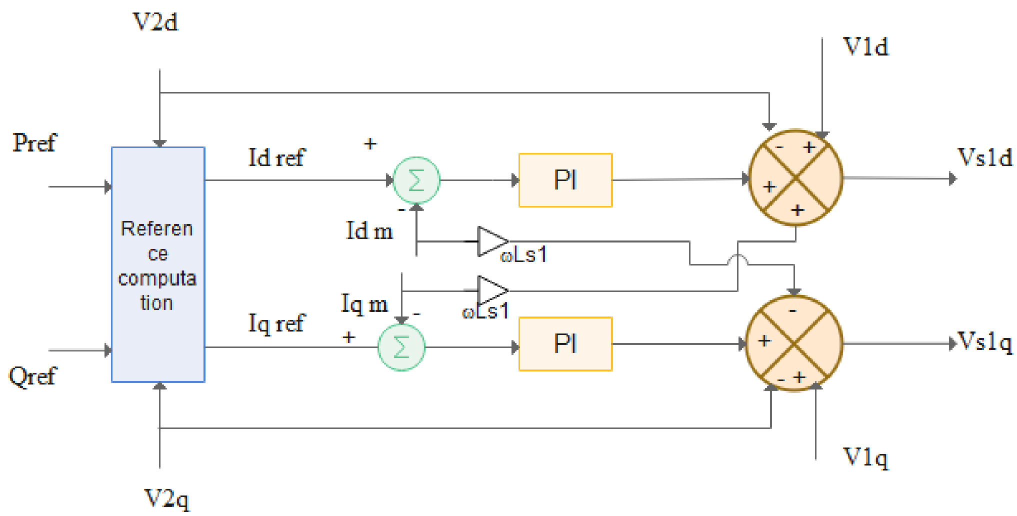


Fig. 4.4 The Simulink block diagram of series convertor

The reference computation get from equation (4.27) and (4.28) with its d-q axis component and voltage injection of series convertor get from equation (4.22).

**Controller**

There are different type of controller like PI, PID, FLC, and etc. These controller desired output depending on input signaled relative with adjusted controlling point. The controller used to control the parameter variation during the power system operation. When the reference and measured values are different than the error obtained and applied to controller. To the injection voltage during line interruption were used PI controller. From the Fig.4.4 shown that PI controller compare the reference value with corresponding measured value bus voltage and the error obtained. The V error is applied to PI control block. Than the limiter output V is applied to the PWM generator. The PWM generator output is compared with the carrier signal using a comparator, to get desired gate pulses which are used for IPFC (Parvathy S. & Thampatty, 2015). For this thesis to get suitable and desired output integral gain and proportional gain is 4 and 0.025 respectively.

### 4.5 Simulink modeling of existing substation with and without IPFC

As shown in the figure below there are two MATLAB Simulink modelling of the Butajira distribution substation power system networks represented. From this figure 4.5 Simulink modelling of existing distribution substation without compensating component IPFC and figure

4.6 shown Simulink modelling exiting substation with IPFC. During this time interline power flow controller placed two outgoing 33kv distribution line of the substation to the system stability and loss minimization.

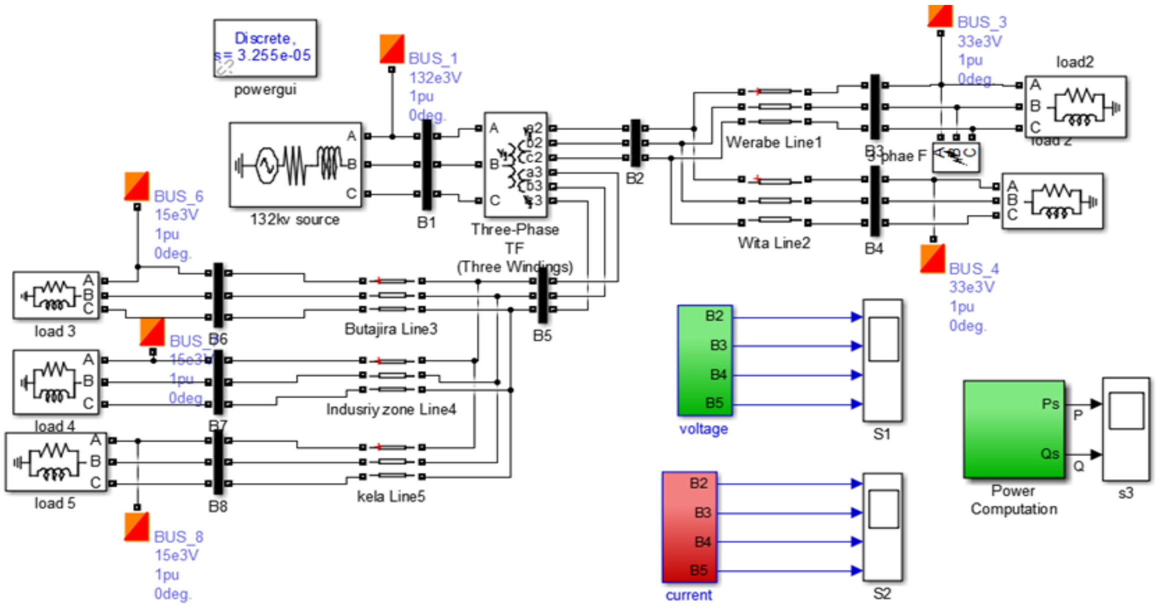


Fig. 4.5 MATLAB Simulink model of Butajira distribution substation.

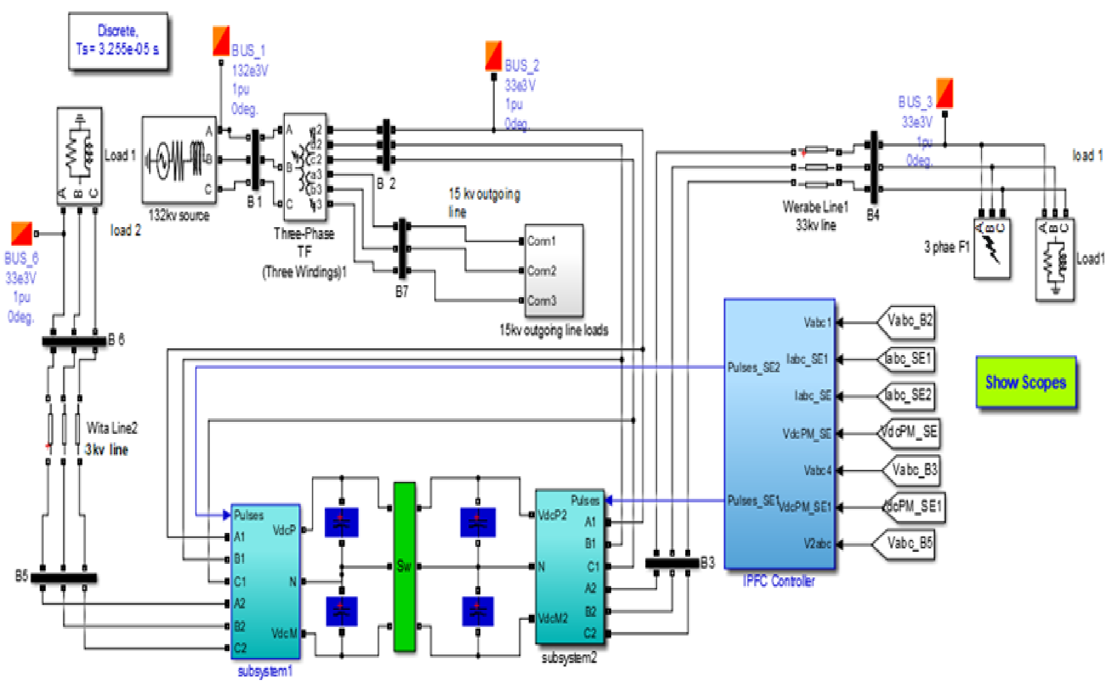


Fig. 4.6 MATLAB Simulink model of Butajira distribution substation with IPFC

# CHAPTER FIVE

# RESULTS AND DISCUSSION

## 5.1 Simulation Results with its Discussion

From the Fig. 4.5 and 4.6 MATLAB Simulink model for the Butajira distribution substation with and without IPFC shown at the end of chapter four. The simulation results of those figures has been explained and tested as the flowing cases.

- When the distribution power system is without fault
- When the three phase fault is applied for the distribution power system.
- When the IPFC  device is installed for distribution substation

The simulation results run MATLAB Simulink from 0 to 0.5 sec. for during normal and abnormal condition. From this simulation result the time interval of the interruption from 0.15 to 0.2. The characteristics of the substation system parameters are shown below and discussed for normal and abnormal magnitude.

### 5.1.1 The distribution system without any disturbance

For the first case the substation system without any interruption its bus parameters are at normally operate. During this condition Bus voltage at the Fig. 4.5, B2 and B5 are 33kv and 15kv line to line voltage of the outgoing line from Butajira substation. The simulation result of this bus without any interruption shown below Fig 5.1. When the system is without disturbance, large loads, no load is removed, and no fault is occurred, than the power system is stable. There is a balance between the input voltages, frequency to the load and the simulation results shown below as voltage and the current wave forms without the application of the three phase faults at Fig 5.1. For this case the input voltage is constant and the system is delivering pure and balanced sinusoidal voltage and current.

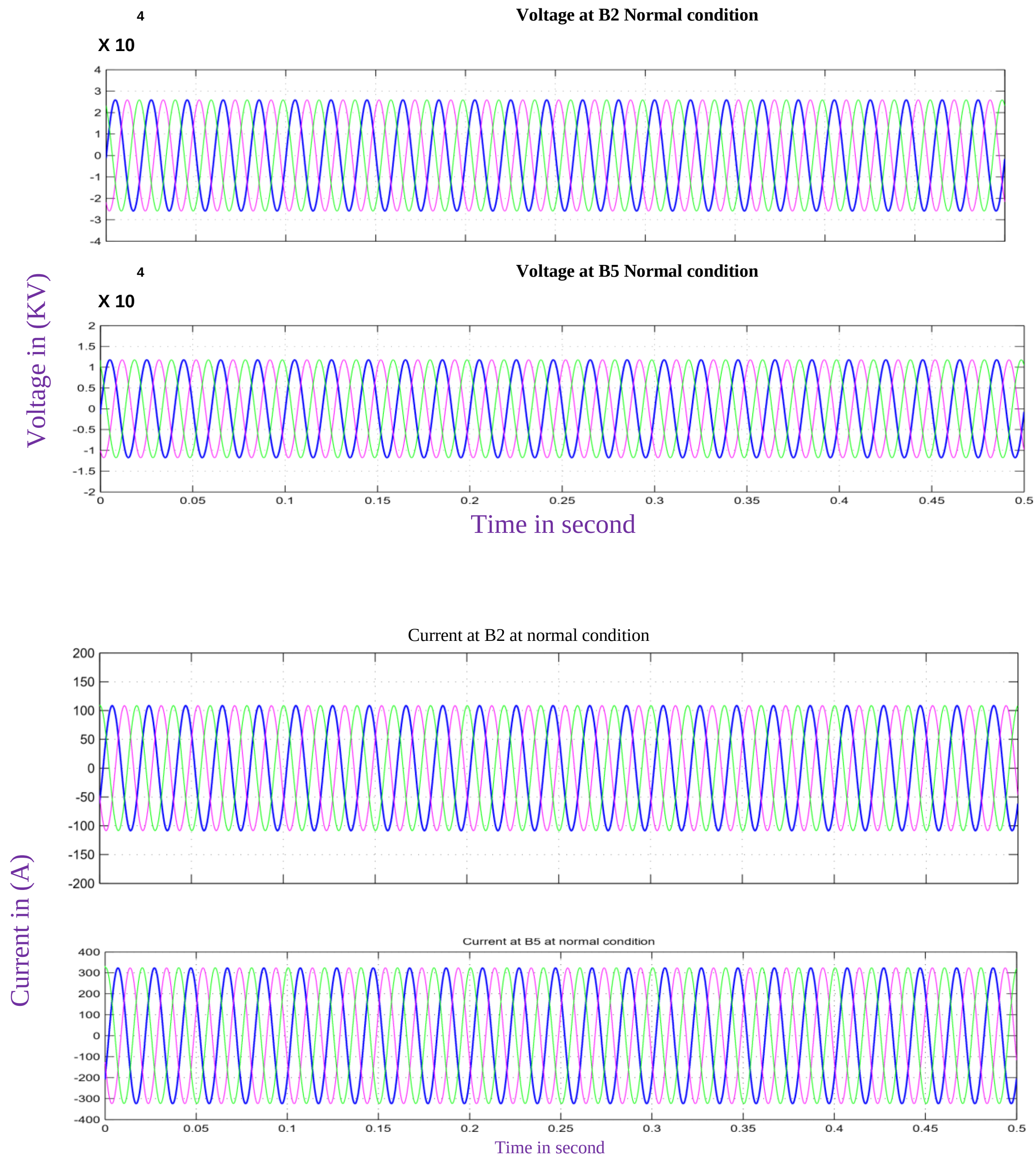


Fig. 5.1 Simulation result of voltage and current at bus B2 and bus B5 distribution system without any fault interruption

### 5.1.2 The power distribution system with three phase fault without IPFC

The three phases fault is applied at list one of outgoing line of the distribution power system, than the power system also disturbed and the power system does not gain its stability until the disturbance removed. The voltage sag happens and the current increase which, creates some disturbance on the distribution power system parameters. If this disturbance is not avoided until the fault is removed by using compensating device like IPFC and the system becomes unstable. When the three phase fault is applied at the outgoing line of B3 and B4 at Fig. 4.5 than the simulation result voltage and current with and without IPFC explained as below.

**a. The Voltage of the distribution system when the three phase fault is applied**

The three phase fault occurred outgoing line from Bus B3 at Fig 4.5, the simulation result of voltage at B2, B3 and B4 are shown below Fig.5.2. During this condition the disturbed power system voltage decreased from 33kv approach to zero at faulted line and lower than 20kv at B2 during the fault time interval of 0.15 to 0.2 sec.

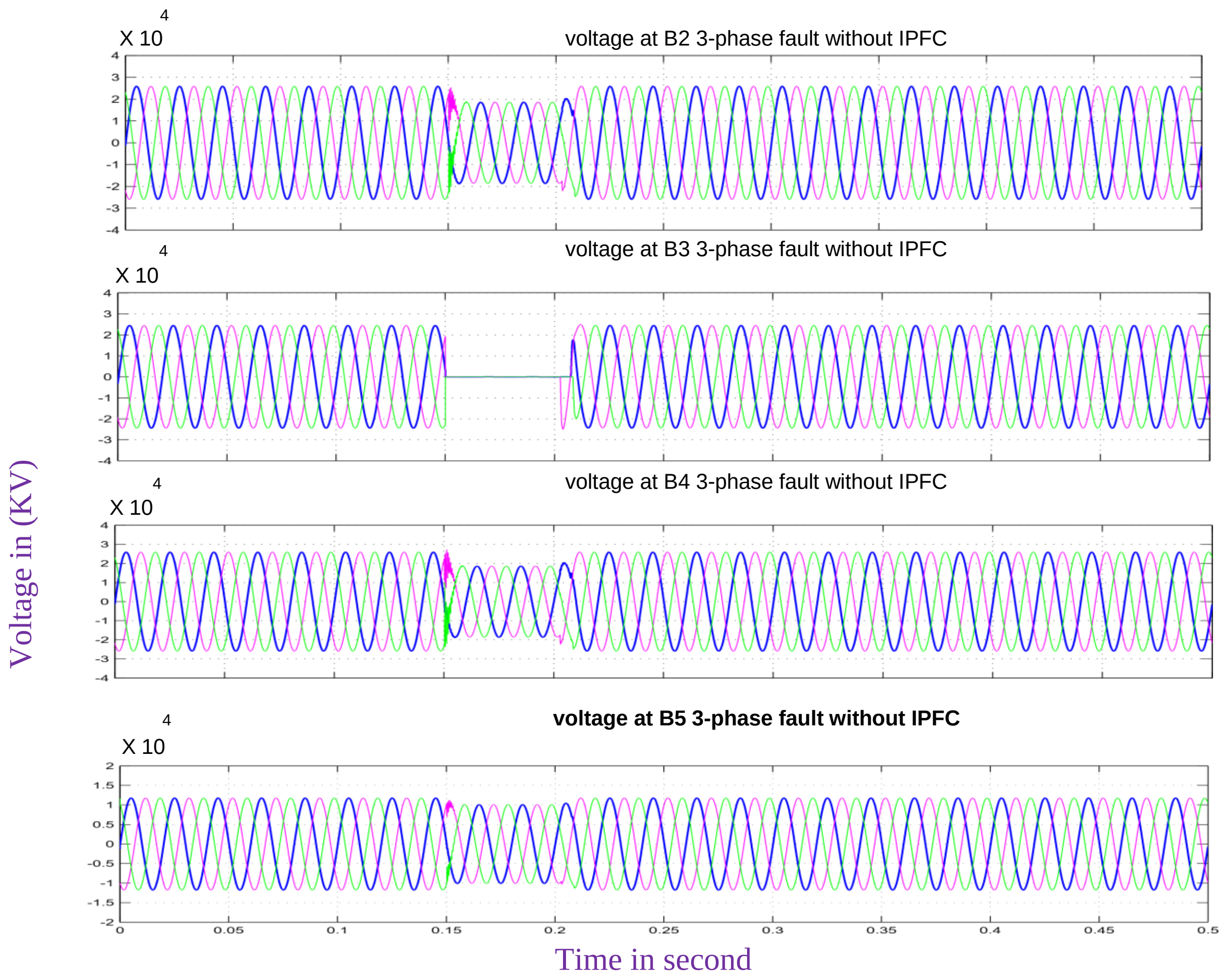


Fig 5. 2 The Voltage of substation three phase fault applied at after B3 from 0.15 to 0.2 sec without IPFC.

**b. The current of the distribution system when the three phase fault is applied**

The current of distribution power system are also changed by increasing it's initial steady state value. From the Fig. 5.3 shown that the line current 100A to 1500A at bus B2 and B3 during the fault tacks place at outgoing line of B3 for 0.15 to 0.2 seconds. Also the line rather than this faulted occurring line network also changed their magnitude shown outgoing line of B4 at fig5.3 below.

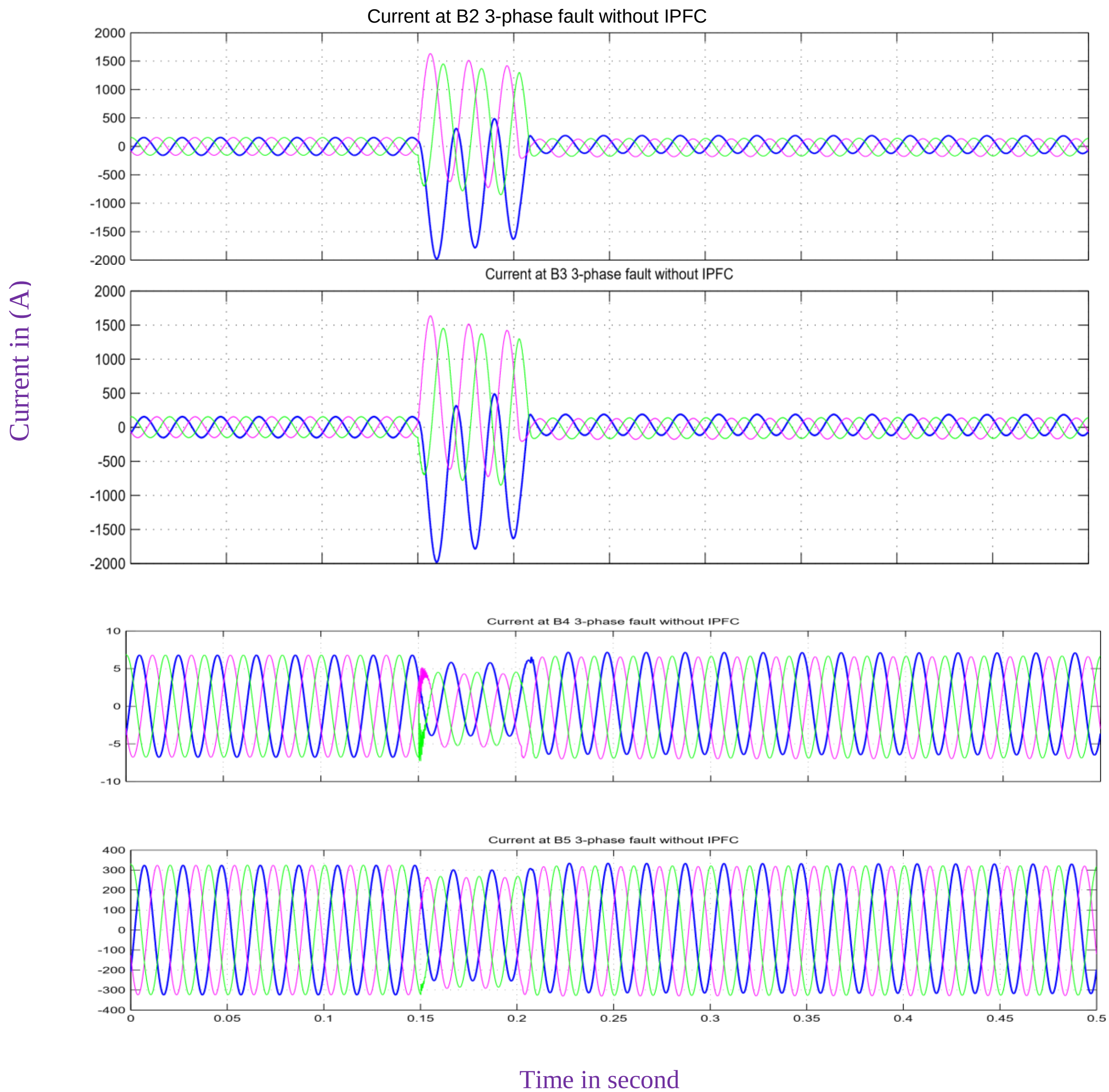


Fig. 5. 3 The simulation result of current the substation at B2, B3 and B4 three phase fault at B3 from 0.15 to 0.2 sec without IPFC.

## 5.2 The power distribution system with three phase fault applied with IPFC

The same time interval with the above case with IPFC, the simulation results run MATLAB Simulink from 0 to 0.5 sec. for the Fig. 4.6 during normal and abnormal condition. The voltage and current characteristics of outgoing lines for the substation system shown as below.

### a. The Voltage of the distribution system when the three phase fault is applied

When the three phase fault is applied at outgoing line of Bus B4, The Voltage simulation result at Bus B2, B4, B6 and B7 as shown Fig. 5.4. During this condition the disturbed power system voltage with IPFC decreased from 33kv approach to zero at faulted line and remain constant with input voltage of B2, B6 and B7 during the fault time interval of 0.15 to 0.2 sec.

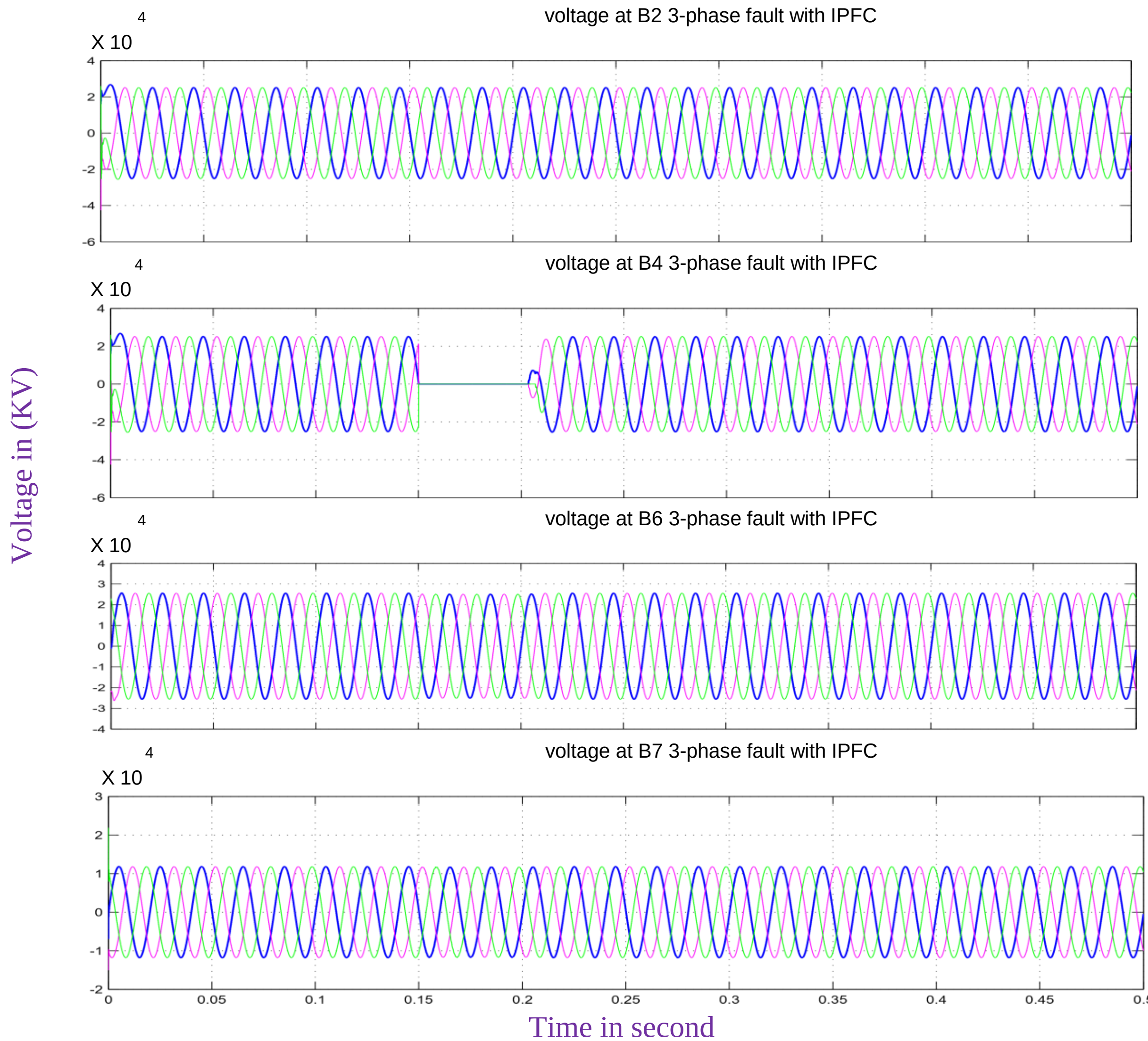


Fig. 5. 4 Voltage simulation with three phase fault at B3 from 0.15 to 0.2 sec with IPFC

**b. The current of the distribution system when the three phase fault is applied**

The current of distribution power system with IPFC are also stable than without using IPFC during three phase fault with the same time interval shown below Fig. 5.5.

From the Fig5.5 shown that the line current 100A to 200A a bus B2 and B4 during the fault tacks place at B4 for 0.15 to 02 seconds. Also the bus rather than this faulted occurring Buses are unchanged their magnitude shown B6 and B7.

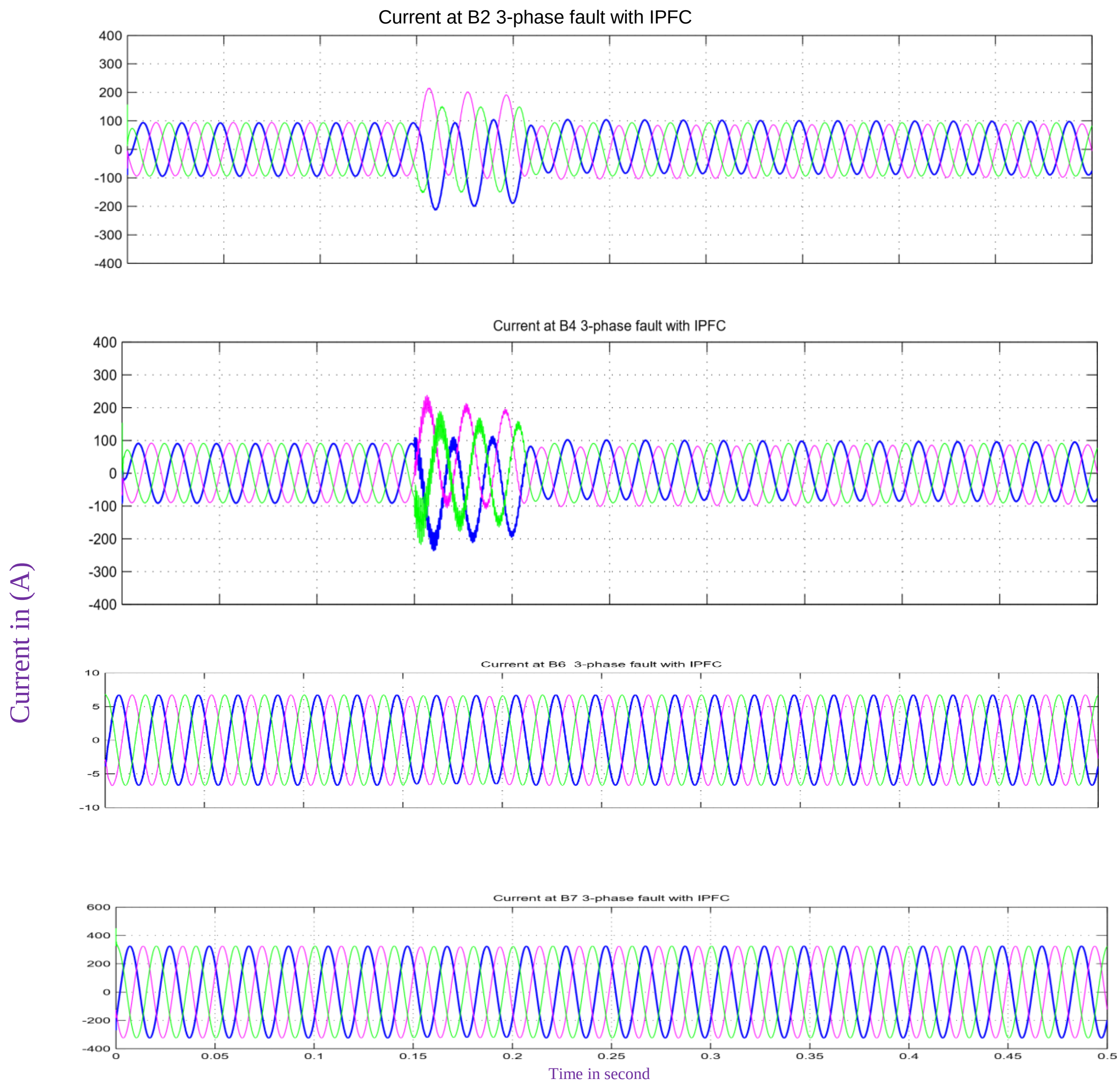


Fig.5. 5 The current simulation result of B2, B4 and B4 with three phase fault at B3 with IPFC

**c. The Injected voltage during fault condition with interline power flow controller**

The voltage injection is applied to the system when the system with the three phase fault at time interval 0.15 to 0.2 seconds as shown fig. 5.6. This injection voltage injected from voltage source convertor of interline power flow controller comparing phase voltage with Vref. There is voltage variation than inject the voltage to the system until the power system disturbance is cleared.

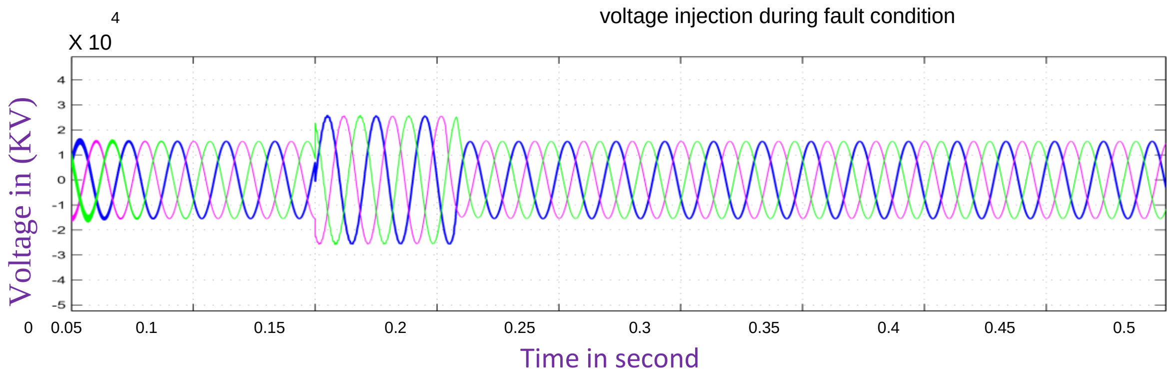


Fig. 5. 6 Voltage injection VSC during three phase fault applied to the system at time interval 0.15 to 0.2 with IPFC

**5.3 The power transferability and loss minimization**

The three phase fault was applied on the any part of Butajira substation power system network especially Butajira and Werabe distribution networks are disturb the normal power handling of the outgoing line and it may leads to power loss of the distribution system. More the power loss at the line due to heating of the transferring network line and the increment of impedance on the line. The magnitude of fault has different impacts on the power loss of the distribution line.

To minimize power loss from this kind of problem could be solved by using IPFC placed at 33KV outgoing line of the distribution substation power system.

The flowing simulation results shows different parts of Butajira substation with and without interline power flow controller during the three phase fault occurred at Worabe outgoing line shown above Fig 4.5 and 4.6. The active and reactive power with and without IPFC with for 0.15 to 0.2 sec as shown below simulation result with necessary figure.

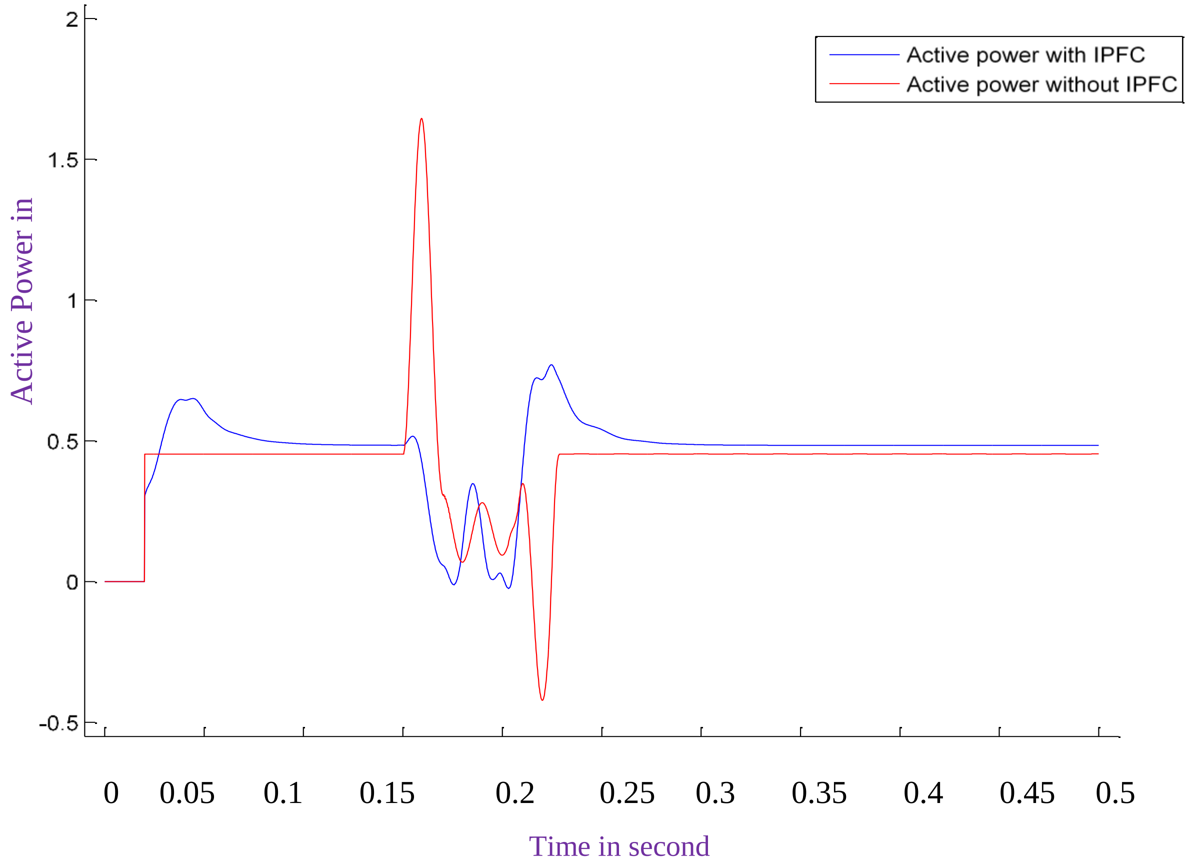


Fig. 5. 7 Simulation result of active power with and without IPFC at B2 of the substation with applied fault.

From the Fig.5.7 shown as the transferability of active power with IPFC is greater than power transferability of without IPFC. The red color assigned as real power without IPFC that power transferred 0.45pu or 5.4MW and blue color assign as active power with IPFC 0.49pu or 5.88MW at normal condition. When the applied fault from 0.15 to 0.2 sec, the transfer power overshoot between -0.4 to 1.75 Pu without IPFC and 0 to 0.75pu with IPFC. This simulation result shows that the active power more stable and more power transferable controllability real power at this position.

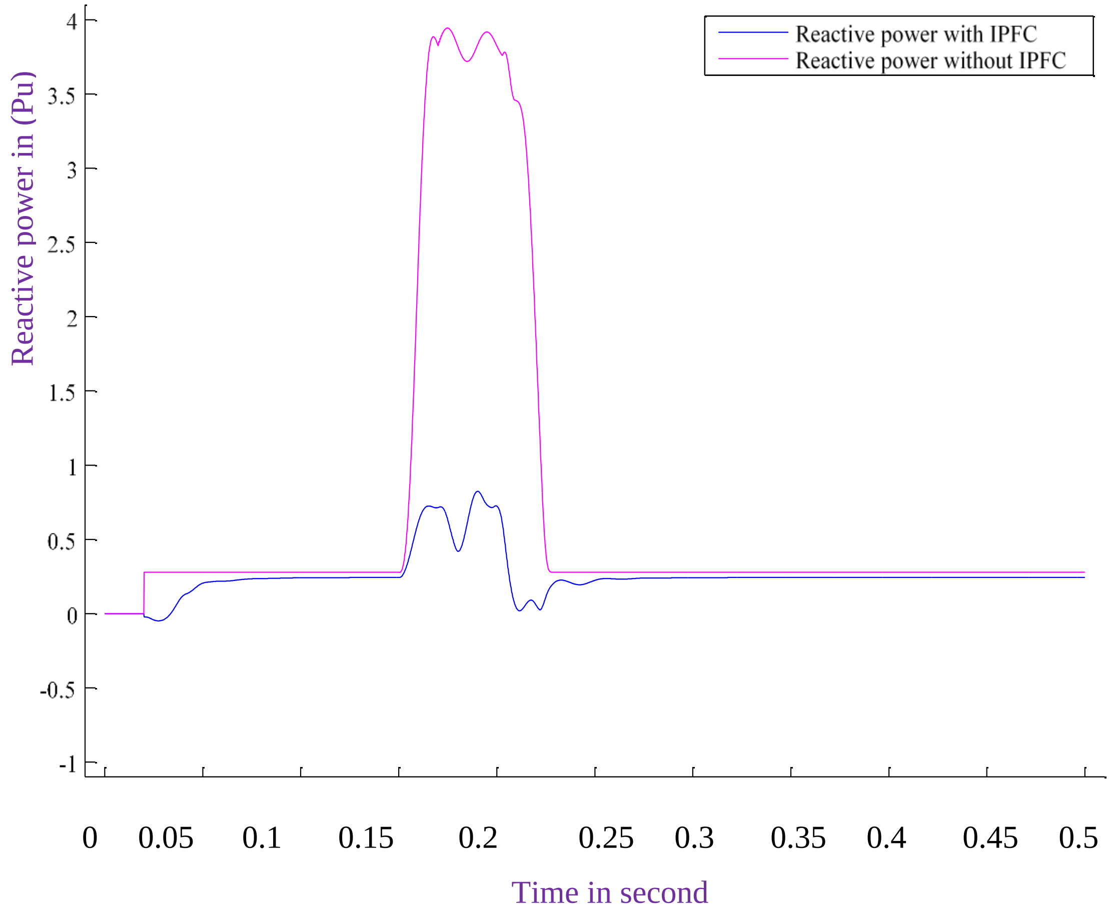


Fig. 5. 8 Simulation result of reactive power with and without IPFC at B2 of the substation with applied fault.

From the simulation result shown fig 5.8 that the red color assigned as reactive power without IPFC and the blue color assign as reactive power with IPFC. When the fault is applied between "0.15 to 0.2" sec, the overshoot reactive power is 0.228 to 4pu or (2.736Mvar to 48Mvar) without IPFC and 0 to 0.67pu or (0 to 8.04Mvar) with IPFC. The reactive power increase during fault condition means power loss of the distribution power system also increase. From these reactive power simulation result the red color line six times garter than the blue color line and it has more power loss.

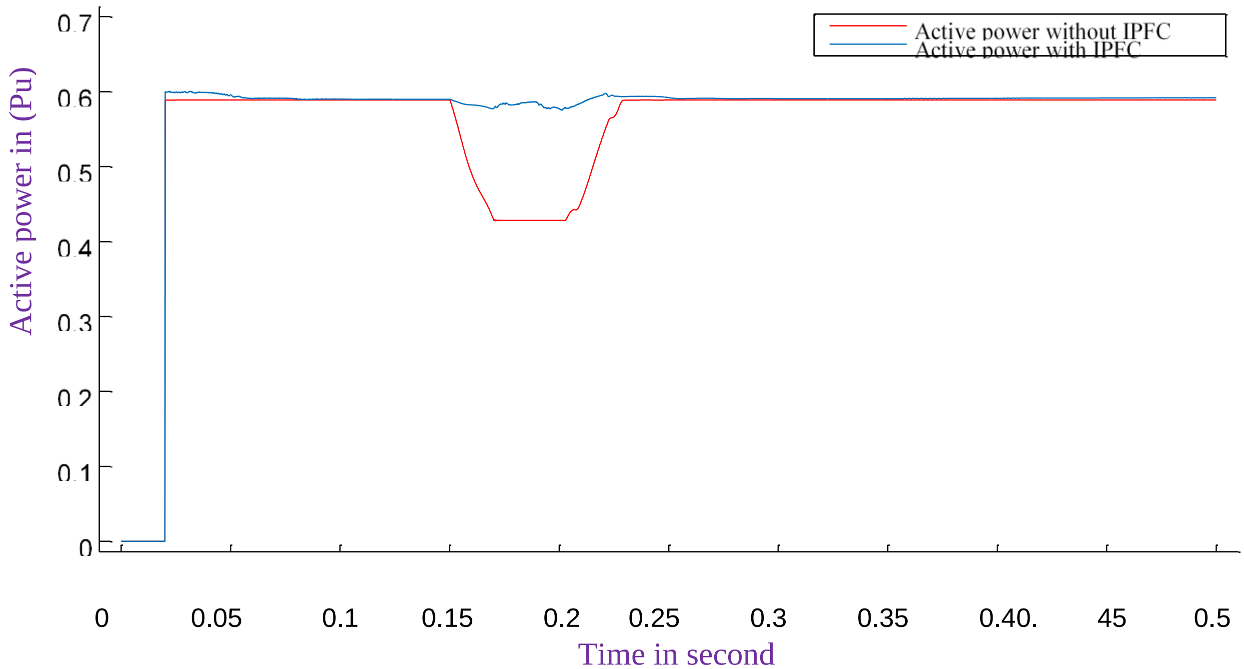


Fig.5. 9 Simulation result of active power with and without IPFC at 15kv outgoing bus bar of the substation with applied fault.

From the simulation result shown fig.5.9 that, the red line active power without IPFC blue line shows active line with IPFC. The three phase fault is applied at worabe outgoing line between 0.15 to 0.2 sec, as a result shows blue line more stable and low power loss with its value approximately 0.6pu and the red line decrease from 0.6pu to 0.418pu during three phase fault, therefore its power loss of red color line is greater than the blue color line during faulted condition.

From the Fig 5.10 below also shows the reactive power with the same line assignment color with Fig 5.9. The reactive power with interline power flow controller is approximately 0.43pu and during fault interval it has more stable than that of reactive power without IPFC. The reactive power without IPFC decrease from 0.43 to 0.33. Due to higher over shooting during fault condition it has more power loss than with IPFC.

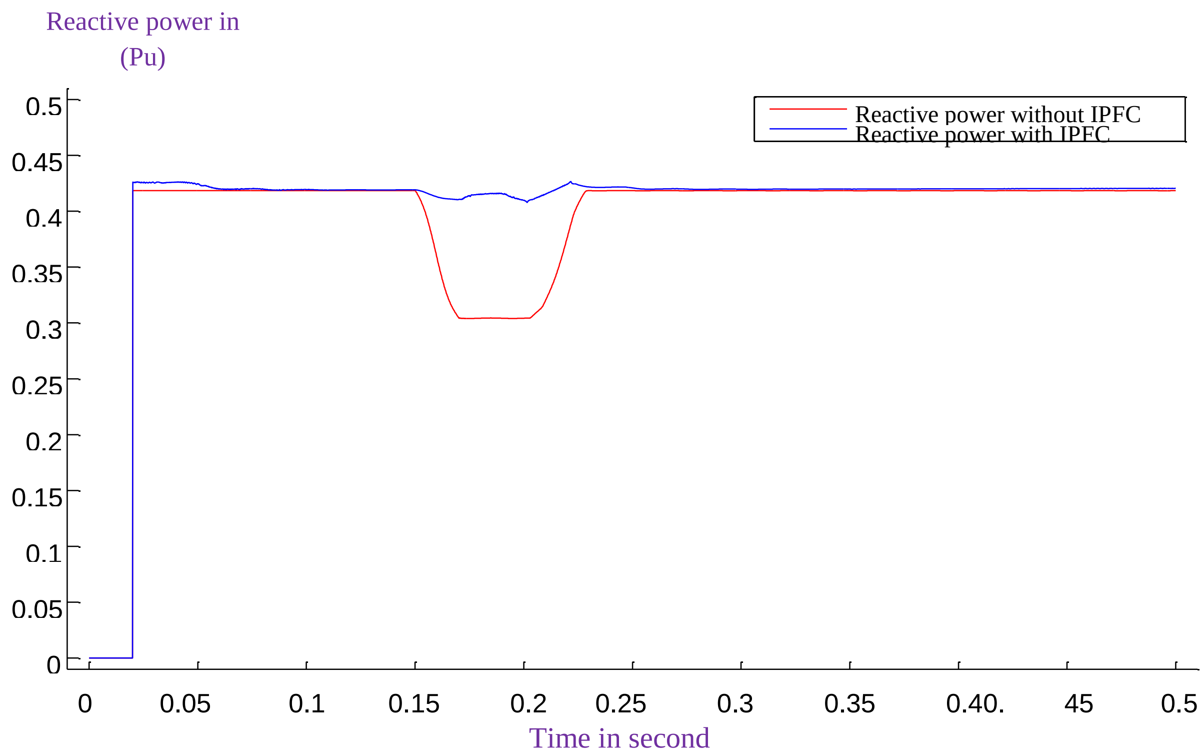


Fig. 5. 10 Simulation result of reactive power with and without IPFC at 15kv outgoing bus bar of the substation with applied fault.

The Fig 5.11 and 5.12 blow shows that active and reactive power with and without IPFC during three phase fault applied at this outgoing line. From this fig in both case red and blue color line assigned to without and with IPFC respectively. The fig 5.11 shows that the active power with IPFC power transferability is 0.48 Pu or 5.76MW which is more than the active power transferability without IPFC which is 0.423pu or 5.07MW after regaining its normal operating condition.

During fault condition overshooting active power without IPFC very higher than active power overshoot with IPFC. Its value between -0.2 to 1.15 and 0 to 0.65pu active power overshoot without and with IPFC respectively the three phase fault applied at interval of 0.15 to 0.2sec the same line.

The fig 5.12 shows that reactive power with and without IPFC, the three phase fault is applied with this line than the reactive power overshoot during this fault time interval was 0 to 1.6pu or 0 to 19.2Mvar and 0 to 0.52pu or 0 to 6.24Mvar . The simulation result of this shows the power transferability and controllability of increase with IPFC and also loss the distribution system decrease with installation modelling IPFC with Butajira distribution substation.

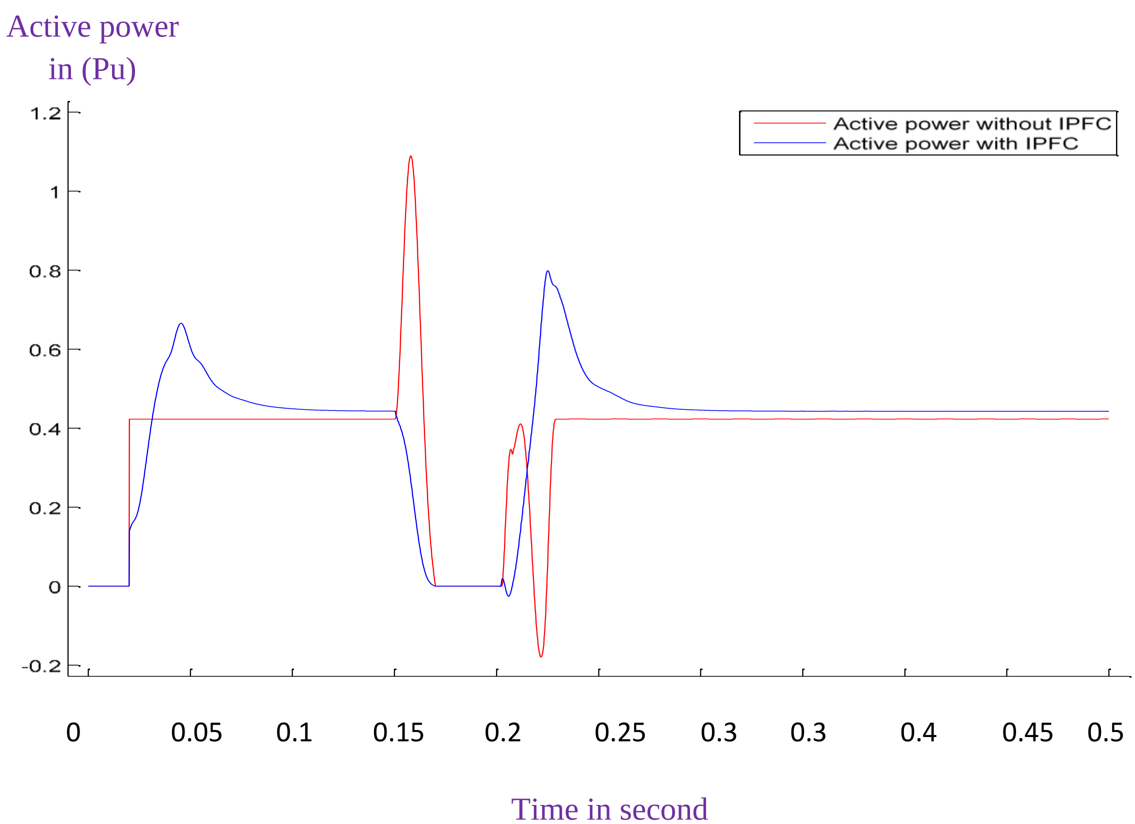


Fig. 5. 11 Active power with and without IPFC with applied three phase fault with same line

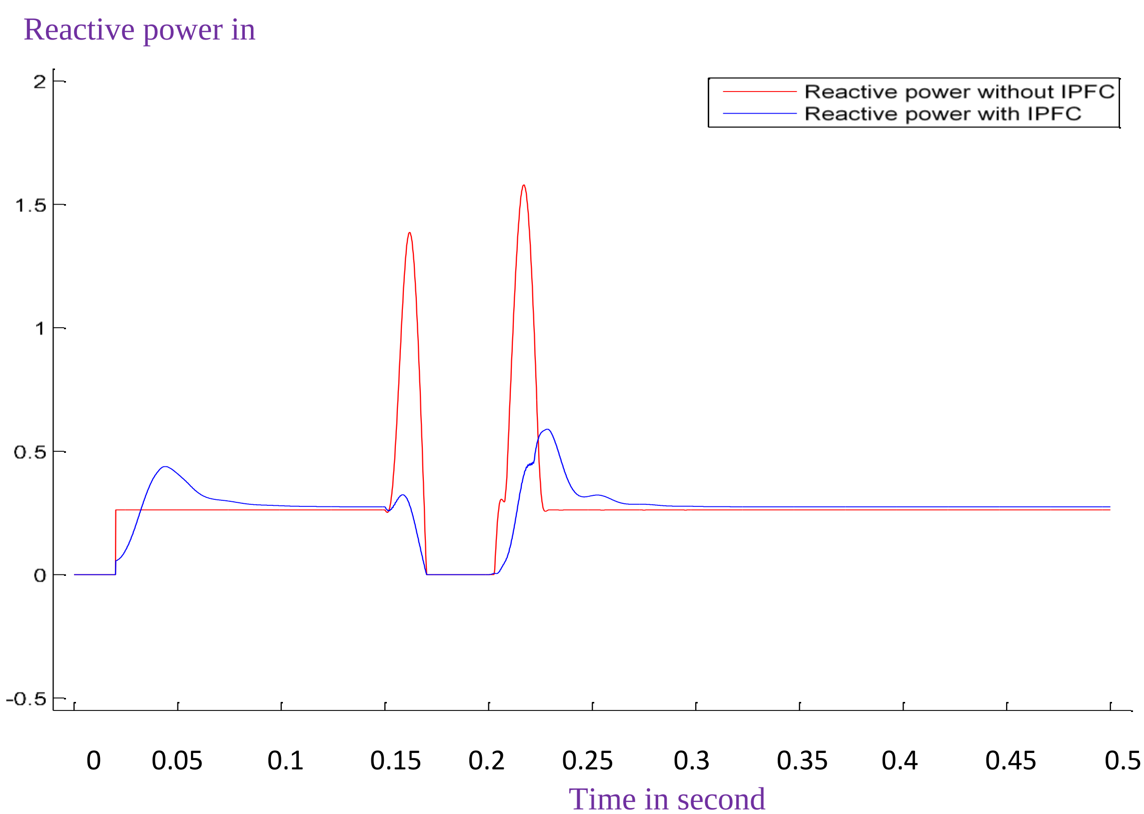


Fig. 5. 12 Reactive power with and without IPFC with applied three phase fault with same line.

# CHAPTER SIX

# CONCLUSION AND RECOMMENDATION

## 6.1 Conclusion

This thesis focused on enhancing voltage stability and loss minimization of Butaiira distribution substation by using FACTS device interline power flow controller with and without applied of three phase fault to the power system. Design and modelling of IPFC with two outgoing 33KV line of substation in MATLAB Simulink with and without three phase line to ground fault.

From the simulation result shows that voltage of distribution system is more stable with interline power flow controller during power system interrupted with three phase fault. During this time, IPFC controlling the power transferability by injecting additional voltage to the system. The controlling parts of IPFC compare input reference voltage with measured phase to phase voltage of the line than there is difference the voltage source convertors are injected voltage to interrupted line. As a result the distribution system fault current is limited and line voltage more stable than without IPFC.

When the three phase fault is applied at worabe 33kv line, the line fault current is from 100A to 1500A and the three phase fault applied with IPFC the line fault current is limited to 200A. The line voltage of the distribution system without IPFC is zero at faulted line and lower than 20KV at another outgoing line of distribution system, but in the case applied fault with IPFC the phase voltage still the same with input phase voltage and the phase voltage at fault line is still zero.

Also IPFC increase power transferability and loss minimization of distribution substation during interruption. From simulation result of 33kv Bus bar shown that real power without IPFC that real power transferred 0.45pu or 5.4MW without IPFC and real power with IPFC 0.49pu or 5.88MW during normal condition. When the three phase to ground fault is applied from 0.15 to 0.2 sec, the real power overshoot between -0.4 to 1.75Pu or (-4.8 to 21MW) without IPFC and 0 to 0.75pu or (0 to 9MW) with IPFC. The reactive power also shown simulation result that the fault is applied between “0.15 to 0.2” sec, the overshoot reactive power is 0.228 to 4pu or (2.736Mvar to 48Mvar) without IPFC and 0 to 0.67pu or (0 to 8.04Mvar) with IPFC these means six time lower than without IPFC. Real and reactive power of the distribution substation with

IPFC almost the same at 15KV line even the three phase to ground fault is occurred at 33KV line.

Therefore, the Butajira distribution system increase its power transferability and enhance voltage stability by controlling input parameter's with IPFC and minimize loss of distribution substation during fault interruption.

### 6.2 Recommendation

Based on the studies and results found in this thesis, it is strongly recommended that Ethiopian Electric Utility to use IPFC for Butajira distribution substation and the substations which have the same problem with this substation to enhance voltage stability, limiting fault current, increase power transferability real and reactive power exchange. When Building new substation is very difficult due to its cost, availability of source and environmental influence, so existing power system performance should be enhanced. It also secure power system and increase the efficiency of power system component by reducing power loss of distribution outgoing line of substation. In this thesis designing IPFC with only considered fault interruption. Therefore the designing process also considered load variation of outgoing line of distribution substation including with controlling component of substation.

The main difficulty of designing IPFC is the complexity of its controller and rating size. Therefore, researchers should do a lot to reduce the complexity of its controller and suitability of its size for distribution system.

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## APPENDIXES

### Appendix-A

Monthly Feeders Load Data of Butajira Substation from Sep.2020 to Agu.2021.

| | | Capacity | Sep | Oct | Nov | Dec | Jan | Feb. | Mar | Apr | May | Jun | Jul | Aug |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **132KV Feeder** | | | | | | | | | | | | | | |
| L1 | Peak | MW | 13.4 | 15.1 | 14 | 13.8 | 13.9 | 13.3 | 12.9 | 14 | 12.6 | 12.9 | 13.8 | 13.4 |
| | | A | 64 | 76 | 70 | 65 | 60 | 62 | 61 | 67 | 56 | 59 | 64 | 60 |
| | Min. | MW | 0.1 | 0.2 | 0.2 | 1.7 | 1.2 | 0.7 | 1 | 0.3 | 0.5 | 1.5 | 0.5 | 1.4 |
| | | A | 6 | 7 | 7 | 9 | 16 | 6 | 8 | 6 | 6 | 9 | 6 | 8 |
| T-132 | Peak | MW | 13.4 | 15.1 | 14 | 13.8 | 13.9 | 13.3 | 12.9 | 14 | 12.6 | 12.9 | 13.8 | 13.4 |
| | | A | 64 | 76 | 70 | 65 | 60 | 62 | 61 | 67 | 56 | 59 | 64 | 60 |
| | Min | MW | 0.1 | 0.2 | 0.2 | 1.7 | 1.2 | 0.7 | 1 | 0.3 | 0.5 | 1.5 | 0.5 | 1.4 |
| | | A | 6 | 7 | 7 | 9 | 16 | 6 | 8 | 6 | 6 | 9 | 6 | 8 |
| **33KV Feeder** | | | | | | | | | | | | | | |
| T-33 | Peak | MW | 5.2 | 5.2 | 5.3 | 5.75 | 5.5 | 5.6 | 5.75 | 5.75 | 5.75 | 5.1 | 5.8 | 5.6 |
| | | A | 107 | 107 | 109 | 118 | 113 | 116 | 118 | 118 | 118 | 104 | 119 | 116 |
| | Min | MW | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 1.2 |
| | | A | 16 | 16 | 16 | 16 | 16 | 16 | 16 | 16 | 16 | 16 | 16 | 23 |
| L2 | Peak | MW | 5.25 | 5.2 | 5.3 | 5.35 | 5.5 | 5.6 | 5.54 | 5.75 | 5.75 | 5.1 | 5.8 | 5.6 |
| | | A | 108 | 107 | 109 | 110 | 113 | 116 | 114 | 118 | 118 | 104 | 119 | 116 |
| | | MW | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.55 | 0.8 | 0.8 | 0.58 | 0.8 | 1.2 |

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Min | A | 16 | 16 | 16 | 16 | 16 | 16 | 11 | 16 | 16 | 12 | 16 | 23 |
| L3 | Peak | MW | 0.24 | 0.24 | 0.24 | 0.24 | 0.24 | 0.24 | 0.24 | 0.24 | 0.24 | 0.24 | 0.24 | 0.24 |
| | | A | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 |
| | Min | MW | - | - | - | - | | - | - | - | - | - | - | - |
| | | A | - | - | - | - | - | - | - | - | - | - | - | - |
| **15KV Feeder** | | | | | | | | | | | | | | |
| T-15 | Peak | MW | 7.3 | 7.5 | 7.4 | 7.4 | 5.5 | 6.4 | 6.4 | 5.7 | 5.3 | 5.5 | 5.3 | 5.1 |
| | | A | 327 | 378 | 335 | 354 | 251 | 287 | 228 | 257 | 238 | 247 | 238 | 233 |
| | Min | MW | 0.35 | 0.35 | 0.5 | 0.35 | 0.82 | 0.35 | 0.5 | 0.27 | 0.6 | 0.35 | 0.2 | 0.35 |
| | | A | 16 | 16 | 23 | 16 | 37 | 16 | 23 | 12 | 29 | 16 | 9 | 16 |
| L4 | Peak | MW | 4.6 | 4.4 | 4.4 | 4.35 | 4.13 | 4.13 | 4.17 | 4.4 | 4 | 4.4 | 4.17 | 4.24 |
| | | A | 207 | 198 | 200 | 197 | 187 | 187 | 189 | 200 | 182 | 200 | 189 | 192 |
| | Min | MW | 0.75 | 0.88 | 0.88 | 0.64 | 0.88 | 0.35 | 0.84 | 0.88 | 0.87 | 0.68 | 0.88 | 0.8 |
| | | A | 34 | 40 | 40 | 29 | 40 | 16 | 38 | 40 | 39 | 31 | 40 | 36 |
| L5 | Peak | MW | 2.78 | 2.6 | 2.58 | 2.5 | 0.57 | 0.53 | 0.64 | 0.6 | 0.55 | 0.57 | 0.64 | 0.62 |
| | | A | 126 | 118 | 117 | 112 | 26 | 24 | 29 | 27 | 25 | 26 | 29 | 28 |
| | Min | MW | 0.15 | 0.29 | 0.27 | 0.09 | 0.09 | 0.09 | 0.09 | 0.09 | 0.09 | 0.09 | 0.09 | 0.09 |
| | | A | 7 | 13 | 12 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| L6 | | MW | 1.06 | 0.93 | 1.02 | 0.99 | 1.236 | 1.08 | 1.02 | 1.12 | 1.04 | 1.23 | 1.28 | 1.08 |
| | | A | 48 | 42 | 46 | 45 | 56 | 49 | 46 | 53 | 47 | 51 | 58 | 49 |

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | MW | 0.09 | 0.09 | 0.123 | 0.09 | 0.09 | 0.09 | 0.09 | 0.09 | 0.09 | 0.09 | 0.09 | 0.09 |
| | | A | 4 | 4 | 6 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 |

**Note**: L1: 132 KV Adami Tulu incoming Feeder

L2: 33 KV werabe

L3: 33KV Wita

L4:15KV Butajira

L5: 15KV kella.

T-132: 132 KV Transformer

T-33: 33 KV Transformer Feeder

T-15: 15KV Transformer Feeder

L6: 15KV industrial Zone

**Appendix B**

Yearly interruption of outgoing line of Butajira substation at the year of Sep. 2020 to Agu.2021

| Yearly interruption of outgoing line of Butajira substation at the year of Sep. 2020 to Agu.2021 | | | | | | |
|---|---|---|---|---|---|---|
| No. | Outgoing line | Yearly fault Duration(Hr.) | Average Line current(A) | Average line loads(MW) | Unsold energy(MWHr) | Source |
| 1 | Worabe | 1509.25 | 52.56 | 2.5505 | 3849.34 | Substation R. report |
| 2 | Witta | 406.97 | 5 | 0.2426 | 98.73 | - |
| 3 | Butagira | 510.34 | 119.66 | 2.6394 | 1346.99 | - |
| 4 | Kella | 861.44 | 53.23 | 1.1741 | 1011.42 | - |
| 5 | Industry zone | 782.834 | 27.803 | 0.6133 | 480.11 | - |

## Appendix C

### Useful identity related to dq0 transformation

$$T_\theta = \begin{bmatrix} \cos(\theta) & \cos(\theta + 2\pi/3) & \cos(\theta - 2\pi/3) \\ -\sin(\theta) & -\sin(\theta + 2\pi/3) & -\sin(\theta - 2\pi/3) \\ 1/2 & 1/2 & 1/2 \end{bmatrix} \qquad (1)$$

$$T^{-}{}_{\theta} = \begin{bmatrix} \cos(\theta) & -\sin(\theta) & 1 \\ \cos(\theta - 2\pi/3) & -\sin(\theta - 2\pi/3) & 1 \\ \cos(\theta + 2\pi/3) & -\sin(\theta + 2\pi/3) & 1 \end{bmatrix} \qquad (2)$$

$X_{abc} = [x_a; x_{b;} x_c]^T$ *and* $X_{dq0} = X_{dq0} = [x_d; x_{q;} x_0]^T$ Then

$$X_{dq0} = T_\theta X_{abc}, \text{ and } X_{abc} = T^{-}{}_{\theta} X_{dq0} \qquad (3)$$

Where subscripts d, q, 0 represent direct, quadrature and zero components

$$\frac{d}{dt} T_\theta^{-} = -T_\theta^{-}\omega \text{ , and } \frac{d}{dt} T_\theta = \omega T_\theta \qquad (4)$$

$$\omega = \begin{bmatrix} 0 & \frac{d}{dt}\theta & 0 \\ -\frac{d}{dt}\theta & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \qquad (5)$$

## Appendix D

## Used load and coupling transformer parameters

| Loads connected to outgoing line of Butajira substation | | | |
|---|---|---|---|
| No. | Connected load to | Active line power (MW) | Reactive power(MVAR) |
| 1 | Worabe | 3.8821 | 2.4051 |
| 2 | Witta | 0.2426 | 0.15031 |
| 3 | Butagira | 3.13222 | 1.94051 |
| 4 | Kella | 1.1741 | 0.72742 |
| 5 | Industry zone | 1.01465 | 0.62862 |

## Coupling transformer and capacitor parameter

| No. | Name of component | Parameter Value |
|---|---|---|
| 1 | Nominal power | 12MW |
| 2 | Primary Nominal voltage | 33kv |
| 3 | Secondary Nominal voltage | 15kv |
| 4 | Phase degree | 7.5deg. |
| 5 | Winding1,2 resistance | 0.0167Ω |
| 6 | Winding 1,2 inductance | 0.5 |
| 7 | Capacitor | 0.0004F |
| 8 | Fundamental frequency | 50Hz |
| 9 | PI controller(ki,kp) | 0.002 and 0.0004 |