



**ADDIS ABABA UNIVERSITY  
ADDIS ABABA INSTITUTE OF TECHNOLOGY (AAIT)**

**School of Electrical and Computer Engineering**

**Master of Science in Power Engineering**

**Comparative Studies of FACTS Devices for Power Loss Reduction and  
Voltage Profile Improvement in Radial Distribution Systems**

**(Case Study: Sebbata-I Substation Outgoing Feeder)**

By: Girma Lemma

Thesis Advisor: Prof. N.P. Singh

**A Thesis Submitted to the School of Graduate of Addis Ababa University in  
Partial Fulfillment of the Requirements for the Degree of Master of Science in  
Power Engineering**

July, 2023

Addis Ababa, Ethiopia



**ADDIS ABABA UNIVERSITY**  
**ADDIS ABABA INSTITUTE OF TECHNOLOGY (AAIT)**

**School of Electrical and Computer Engineering**  
**Master of Science in Power Engineering**

**Comparative Studies of FACTS Devices for Power Loss Reduction and  
Voltage Profile Improvement in Radial Distribution Systems**

**(Case Study: Sebbata-I Substation Outgoing Feeder)**

By: Girma Lemma

Thesis Advisor: Prof. N.P. Singh

**APPROVED BY BOARD OF EXAMINERS**

\_\_\_\_\_  
**Chairman, Department of Graduate Committee**

\_\_\_\_\_  
Signature

\_\_\_\_\_  
**Advisor**

\_\_\_\_\_  
Signature

\_\_\_\_\_  
**Internal Examiner**

\_\_\_\_\_  
Signature

\_\_\_\_\_  
**External Examiner**

\_\_\_\_\_  
Signature

**DECLARATION**

I, the undersigned, declare that this MSc thesis is my original work, has not been presented before for fulfillment of a degree in this or any other university. Further, I have acknowledged all sources and materials used for this thesis work and have cited them in the reference section.

Name: Girma Lemma

Signature: \_\_\_\_\_

Place: Addis Ababa, Ethiopia

Date of Submission: \_\_\_\_\_

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

Prof. N.P.Singh

Advisor's Name

\_\_\_\_\_

Signature

\_\_\_\_\_

Date

## **ACKNOWLEDGEMENT**

I would like to acknowledge and give my warmest thanks to my advisor Professor NP.Singh, for his time, effort, and assistance to succeed in my thesis study. His guidance and advice carried me through all the stages of writing my thesis project.

I would also like to thank Ethiopian Electric Power, specifically Sebbata-I substation and utilities staffs members for their sincere cooperation in assisting and providing me the necessary data required for my thesis project. I am also thankful to Mr. Daniel Alemu and Dawit Woldmariam staffs of the Sebbata-I substation & utility for their kind assistance during data collection.

I would also like to give special thanks to my family as whole for their continuous support and understanding when undertaking my research and writing my project. Your prayer for me was what sustained me this far. And also, I would like to say thanks, to all my colleagues from the Department of Electrical Power Engineering at AAiT for their cooperation and an academic experience they shared with me.

Finally, I would like to thank God, for letting me through all the difficulties. I have experienced your guidance day by day. You are the one who let me finish my degree. I will keep on thrusting you for my future.

## **ABSTRACT**

The power quality of any radial distribution system is determined in terms of voltage profile and power loss level of the system. The FACTS controllers can improve the performance of power transfer capability through controlling of the parameters of the distribution system. This thesis carries out comparative studies and performance analysis of DSTATCOM, SVC and UPQC devices in improving the performance of a radial distribution system. Sabbata-I substation 15 kV outgoing feeder-12 radial distribution network is considered to be a test system to evaluate the effectiveness of these devices. The location for placement of DSTATCOM, SVC and UPQC devices is determined by selecting the buses with higher values of loss sensitivity index which is calculated using MATLAB software. The size of these FACTS devices for each of the candidate buses are decided by using Particle Swarm Optimization (PSO) method. The effectiveness of each of these devices in improving the voltage profile and reducing the power loss under 75%, 100% and 125% of full load condition is evaluated through simulation studies.

From the load flow analysis under normal operating conditions bus numbers 83, 36, 33, 81 and 54 are identified as weak buses for the integration of FACTS controllers. The simulation output reveal with installation of DSTATCOM device, the distribution system voltage profile enhanced by 1.86%, 2.97% and 4.18% under the respective loading conditions as compared to those of the system without installation of these devices. It is further observed that installation of SVC device improves the voltage profile by 1.65%, 1.75% and 1.86% while installation of UPQC device results in voltage profile improvement by 2.86%, 4.15% and 5.54% under the same loading conditions. It is also found that with installation of DSTATCOM device, reduction of the real power loss is 48.06%, 49.49% & 50.92% while installation of SVC device results in active power loss reduction by 34.45%, 33.51% and 31.02% under respective loading conditions. It is further observed that with installation of UPQC device, the real line loss is reduced by 64.85%, 65.72% and 66.61% under the same loading conditions. It is also found that with installation of DSTACOM device, the reactive power loss is reduced by 46.22%, 47.70% and 49.19% respective loading conditions. The simulation results further reveal that installation of SVC device results in reduction of reactive power loss by 35.91%, 34.45% and 31.70% while by using UPQC device the corresponding reactive power loss reduction is 64.13%, 65.02% and 65.93%

under the respective loading conditions. The cost-benefit analysis reveals that installation of DSTATCOM, SVC and UPQC devices result in saving of 4,349,766.76 ETB, 2,945,561.84 ETB and 5,776,106.31 ETB respectively per annum under full load condition on account of power loss reduction. It is also found that the investment cost on account of installation of DSTATCOM, SVC and UPQC devices requires 8,780,813.64 ETB, 15,074,587.21 ETB and 11,728,658.22 ETB respectively under full load condition.

It is concluded that effectiveness of UPQC device is better than those of DSTATCOM and SVC devices in regard to reducing the loss and enhancing the voltage profile of outgoing feeders under reduced, normal as well as overloaded operating conditions. Moreover, UPQC device is cost effective as compared to DSTATCOM and SVC devices. Therefore, use of UPQC device is recommended for power loss reduction and voltage profile improvement of distribution systems rather than using DSTATCOM and SVC devices.

**Keywords:** Radial Distribution System, Power Losses, Voltage Profile, DSTATCOM, SVC and UPQC, PSO, Loss Sensitivity Index, BFS.

**TABLE OF CONTENTS**

DECLARATION ..... iii

ACKNOWLEDGEMENT ..... iv

ABSTRACT ..... v

TABLE OF CONTENTS ..... vii

LIST OF FIGURES ..... xii

LIST OF ABBREVIATIONS .....xiv

CHAPTER 1 INTRODUCTION .....1

1.1 Background .....1

1.2 Problem of Statement .....2

1.3 Objectives .....2

    1.3.1 General Objectives .....2

    1.3.2 Specific Objectives: .....2

1.4 Methodology .....3

1.5 Significance of the Study .....4

1.6 Scope of the Study .....4

1.7 Organization of the Thesis .....4

CHAPTER 2 DISTRIBUTION SYSTEM PERFORMANCE ANALYSIS AND  
IMPROVEMENT .....6

2.1 Introduction .....6

2.2 Electrical Power system Structure .....6

    2.2.1 Radial Distribution System .....8

    2.2.2 Loop Distribution System (Ring Main System) .....9

    2.2.3 Inter-Connected System .....10

2.3 Power Loss in Distribution Systems .....11

2.4 Voltage Drop in Distribution Systems .....	12
2.5 Distribution System Performance Improvement Technique .....	13
2.6 Flexible AC Transmission System (FACTS) Devices .....	15
2.7 Literature Review .....	17
CHAPTER 3 DISTRIBUTION SYSTEM PERFORMANCE ENHANCEMENT USING FACTS DEVICES .....	21
3.1 Introduction .....	21
3.2 Description of the Distribution System.....	21
3.2.1 Single Line Diagram Representation of the Feeder .....	25
3.2.2 Line and Bus Data of the Feeder.....	27
3.3 Distribution System Power Flow Analysis .....	31
3.3.1 Radial Distribution System Load Flow Analysis.....	32
3.4 Particle Swarm Optimization method to Solve the Power Loss and Voltage Problem.....	36
3.5 Performance Enhancement of Distribution System Using FACTS Devices .....	42
3.5.1 Distribution Static Synchronous Compensator (DSTATCOM) .....	42
3.5.2 Static VAR Compensators (SVC).....	47
3.5.3 Unified Power Quality Conditioner (UPQC) .....	51
3.6 Optimal Sizing and Placing of FACTS Device.....	60
3.6.1 Loss Sensitivity Index .....	60
3.6.2 Size and placement optimization process.....	61
CHAPTER 4 SIMULATION STUDIES AND ANALYSIS OF RESULTS.....	63
4.1 Introduction .....	63
4.2 Distribution System Performance Analysis before Installation of FACTS devices.....	63
4.2.1 Active and Reactive Power Losses Simulation Studies and Result Analysis .....	64

4.2.2 Voltage Profile before Installation of FACTS Devices .....	68
4.2.3 Loss Sensitivity Index Result before installation of FACTS Devices.....	71
4.3 Performance Enhancement Using FACTS Devices .....	75
4.3.1 Power Loss Reduction Performance of FACTS Devices.....	75
4.3.2 Voltage Profile Improvement .....	91
4.3.3 Loss Sensitivity Index Improvement After installation of FACTS devices.....	100
4.4 Cost Benefit Analysis for Installation of FACTS Devices .....	106
4.4.1 Cost Analysis for Distribution Static VAR Compensator (DSTACOM) Installation	107
4.4.2 Cost Analysis for Static VAR (SVC) Compensator Installation .....	110
4.4.3 Cost Analysis for Unified Power Quality Conditioner (UPQC) Installation .....	112
4.5 Summary of the Simulation Result.....	114
CHAPTER 5 CONCLUSION, RECOMMENDATION AND FUTURE WORK.....	117
5.1 Conclusion.....	117
5.2 Recommendation .....	119
5.3 Suggestion for Future Work.....	120
REFERENCES .....	121
APPENDICES .....	129
Appendix A: Power Interruption Data .....	129
Appendix B: Substation Transformer Data .....	130
Appendix C: Capacity of the Outgoing feeders of Sabbata-1 Substation .....	130
Appendix D: Length and Capacity of Each Feeder .....	131
Appendix E: Yearly Peak Load and Minimum Load of the Feeders .....	131
Appendix F: The impedance of Distribution Line .....	132
Appendix H: Costs of different FACTS Controller .....	132
Appendix I: Monthly Peak and Minimum Load Demand on the Feeder.....	133

**LIST OF TABLE**

Table 3-1:- Incoming Source to Sebbata-I substation.....23

Table 3-2:- Sebbata-I substation outgoing feeders .....23

Table 3-3:- Line and bus data of Sabbata-12 feeder .....27

Table 4-1:- Active and Reactive Power losses at 75%, 100% and 125% of full load .....64

Table 4-2:- Base case Voltage Profile at 75%, 100% and 125% loading conditions .....68

Table 4-3:- Loss Sensitivity Index at 75% of full load, 100% and 125% loading conditions .....71

Table 4-4:- Candidate buses LSI value at 75% of full load, 100% and 125% loading conditions73

Table 4-5:- Summary of Simulation Result before Installation of FACTS Devices .....74

Table 4-6:-Sizes of FACTS devices for each candidate buses at 75% of full load .....75

Table 4-7:-Power losses after installation of FACTS Devices at 75% of full load .....76

Table 4-8:-Installed FACTS Devices values at the candidate buses at 100% loading .....81

Table 4-9:- Power losses after installation of FACTS Devices at full load (100% loading) .....81

Table 4-10:- Installed FACTS Devices values at the candidate buses at 125% loading .....86

Table 4-11:- Voltage Profile Improvement with installation FACTS devices at 75% of full load  
.....92

Table 4-12:- Summary of minimum Voltage with and without FACTS at 75% of full load .....93

Table 4-13:-Voltage Profile Improvement with FACTS Devices at 100% loading .....95

Table 4-14:-Summary of minimum Voltage with and without FACTS at 100% loading .....96

Table 4-15:-Voltage Profile Improvement with FACTS Devices at 125% loading .....98

Table 4-16:- Minimum Voltage with and without FACTS at 125% overloading .....99

Table 4-17:- Loss Sensitivity Index with installation FACTS at 75% of full load ..... 100

Table 4-18:-Loss Sensitivity Index with FACTS at full load..... 102

Table 4-19:- Loss Sensitivity Index with FACTS at 125% overloading ..... 104

Table 4-20:- Cost analysis before and after installation of DSTATCOM ..... 107

Table 4-21:-Investment cost analysis for DSTATCOM device installation ..... 108

Table 4-22:-Cost analysis before and after installation of SVC device ..... 110

Table 4-23:-Investment cost analysis for SVC installation ..... 111

Table 4-24:-Cost analysis before and after installation of UPQC device ..... 112

Table 4-25:-Investment cost analysis for UPQC installation ..... 113  
Table 4-26:- Comparison of FACTS performance at 75% of full load ..... 114  
Table 4-27:-Comparison of FACTS Performance at 100% overloading ..... 115  
Table 4-28:-Comparison of FACTS Performance at 125% overloading ..... 116

## LIST OF FIGURES

Figure 1-1:-Block diagram of the methodology followed.....	3
Figure 2-1: Single line diagram of a typical distribution system.....	7
Figure 2-2:- Radial distribution systems .....	8
Figure 2-3:- Ring main systems.....	9
Figure 2-4:- Inter connected system.....	10
Figure 2-5:-Classification of FACTS Devices [25] .....	17
Figure 3-1:- Geographical view of Sebbata-I Substation.....	22
Figure 3-2:- Overview of single line diagram of Sebbata-I Substation .....	25
Figure 3-3:- Sabbata-I substation feeder-12 single line diagram.....	26
Figure 3-4:- Forward backward sweep algorithm flow chart before installation of FACTS .....	35
Figure 3-5:-Searching point in solution space [55].....	37
Figure 3-6:- Particle movement components [55] .....	38
Figure 3-7:-PSO Algorithm Flow Charts .....	41
Figure 3-8:- Single line diagram of two consecutive nodes of a distribution system.....	42
Figure 3-9:-Phasor diagram of voltage and current of the system shown in Fig. 2.8.....	43
Figure 3-10:- Single line diagram of two buses with DSTATCOM Consideration .....	43
Figure 3-11:-Phasor diagram of fig. 3-10.....	44
Figure 3-12:- Forward backward sweep algorithm flow chart with installation of DSTATCOM.....	46
Figure 3-13:- (a) SVC firing angle Model (b) SVC total susceptance model [48].....	47
Figure 3-14:- Forward backward sweep algorithm flow chart with installation of SVC.....	50
Figure 3-15:- Basic UPQC based system configuration [49] .....	51
Figure 3-16:-UPQC (S) type Phasor representation [49].....	52
Figure 3-17:-Determination of $V_{Srand}$ and $\phi_{Sr}$ [49] .....	53
Figure 3-18:- PAC: current phasor representation [49] .....	54
Figure 3-19:-Determination of $I_{sh'}$ and $\phi_{sh} - s'$ [49] .....	55
Figure 3-20:- Forward backward sweep algorithm flow chart with installation of UPQC.....	59
Figure 3-21:-Two-bus systems for LSI analysis.....	60
Figure 4-1:- Active power losses at 75%, 100% and 125% loading conditions.....	67

Figure 4-2: Reactive power loss at 75%, 100% and 125% loading conditions .....67

Figure 4-3:-Base Case Voltage profile at 75% of full load, 100% and 25% loading conditions ..70

Figure 4-4:- Base case LSI at 75% of full load, 100% and 25% loading conditions.....73

Figure 4-5:- Active power losses with and without FACTS Devices at 75% of full load .....79

Figure 4-6:- Reactive power losses with and without FACTS Devices at 75% of full load.....79

Figure 4-7:-Total active and reactive Power losses with and without FACTS devices at 75% of full load.....80

Figure 4-8:- Real line losses before and after installation of FACTS Devices at full load .....84

Figure 4-9:- Reactive losses before and after installation of FACTS Devices at full load.....85

Figure 4-10:-Total Active and reactive Power losses with and without FACTS devices .....85

Figure 4-11:- Active power losses with and without FACTS Devices at 125% overloading .....89

Figure 4-12:- Reactive loss before and after installation of FACTS Devices at 125% overloading .....90

Figure 4-13:- Total Active and reactive Power losses with and without FACTS devices at 125% loading .....90

Figure 4-14:-Voltage profile comparison with and without FACTS at 75% of full load .....94

Figure 4-15:-Voltage profile comparison with and without FACTS at 100% loading.....97

Figure 4-16:-Voltage profile comparison with and without FACTS at 125% loading.....99

Figure 4-17:- LSI With and without FACTS devices at 75% of full load ..... 102

Figure 4-18: LSI with and without FACTS devices at 100% loading ..... 104

Figure 4-19:- LSI with and without FACTS devices at 125% loading..... 106

**LIST OF ABBREVIATIONS**

AAC	Aluminum Conductor Cable
APF	Active Power Filter
BCBV	Branch Current Branch Voltage
BFS	Backward Forward Sweep
BIBC	Bus Current Injections and Branch Currents
DC	Direct Current
DE	Differential Evolution
DG	Distributed Generation
DLF	Distribution Load Flow Matrix
DSTATCOM	Distribution Static Compensator
EEP	Ethiopian Electric Power
EEU	Ethiopian Electric Utility
ETB	Ethiopian Birr
FACTS	Flexible AC Transmission System
IEEE	Institute of Electrical and Electronics Engineering
IGBT	Insulated-Gate Bipolar Transistor
KCL	Kirchhoff's Current Law
kWhr	Kilo Watt Hour
kVAr	Kilovolt-Ampere Reactive
LSI	Loss Sensitivity Index
MVA	Mega Volt Ampere
MVar	Mega Volt Ampere of Reactive

MW	Mega Watt
NTL	Non-Technical losses
PSO	Particle Swarm Optimization
SSSC	Static Synchronous Compensator
STATCOM	Static Synchronous Compensator
SVC	Static Var Compensator
TCDB	Thyristor Controlled Dynamic Brake
TCR	Thyristor controlled reactor
TCSC	Thyristor Controlled Series Capacitor
TCSR	Thyristor Controlled Series Reactor
TSC	Thyristor switched capacitor
UPFC	Unified Power Flow Controller
UPQC	Unified Power Quality Conditioner
VD	Voltage Deviation
VSC	Voltage Source Convertor
VSI <sub>s</sub>	Voltage Source Inverters
P	Active Power
Q	Reactive Power
S	Apparent Power
V <sub>r</sub>	Receiving end Voltage
V <sub>s</sub>	Sending end Voltage
pu	Per unit
EHV	Extra-High Voltage
EH	High Voltage
MV	Medium Voltage

## **CHAPTER 1 INTRODUCTION**

### **1.1 Background**

Electrical power system basically consists of generation, transmission and distribution system and Electric power produced at generation utilities is conveyed through transmission lines to different many distribution circuits that the utility operates. Significant portion of the electric power which is produced at the generating station is lost in the transmission and distribution process. These losses occur in numerous small components in the distribution system, such as transformers and distribution lines. While each of these components may have relatively small losses, the large number of components involved makes it important to examine the losses in distribution system [2].

The power loss of the distribution network can be decreased either by transforming the distribution network structure or by using the compensation devices methods. The first method is performed through changing of the network connection, stepping up of the voltage level, decreasing the distribution network length, increasing the cable cross section or by changing of high energy consuming transformers. However, these all activities require high initial investment cost and difficult to implement.

Whereas, using of power compensation devices through allocation of reactive power controllers at appropriate location for compensating the reactive load demand and hence, the power loss of the distribution system can be reduced and also the voltage level can be increased. Recently, along with emerging of renewable energy sources technologies in a distributed manner, there is a growing need for flexible control of the power distribution system and this can be achieved by using appropriate FACTS controllers [7].

## **1.2 Problem of Statement**

Now-a-days, there is a highly increasing demand of electrical power due to rapid population growth as well as industries in our country. Due to this fact, most distribution systems are overloaded beyond their carrying capacity and as a result, electrical power loss occurs in the entire distribution networks and also the network system suffer from voltage drop problems.

Whereas, increasing of the power loss and dropping of voltage of the distribution system beyond the acceptable limit range will lead for large current to be draw from the system which dangerously affects both power utilities and connected customers as the system voltage lower below a tolerable voltage level limit. In this regard, it is highly important to look for effective and efficient method of enhancing the distribution system performance.

This thesis aims to carry out comparative studies of FACTS devices with regard of enhancing the performance of power distribution system. Sebbata-I substation 15 kV outgoing feeder-12 has been taken as a test system to examine the efficiency of different FACTS devices on improving the performance of distribution systems.

## **1.3 Objectives**

### **1.3.1 General Objectives**

This thesis project is aimed to accomplish the general objective which is stated as comparative studies of Distribution Static Synchronous Compensator (DSTATCOM), Static VAR Compensator (SVC) and Unified Power Quality Conditioner (UPQC) devices for power loss reduction and voltage profile improvement of the radial distribution systems. To evaluate the effectiveness of these devices, Sebbata-I substation outgoing feeder is considered as a test system.

### **1.3.2 Specific Objectives:**

This thesis project addresses the following specific objectives;

- To gather the required data, select a test system, and to investigate the test system performance by using Backward-Forward Sweep load flow analysis

- To decide the size and location of FACTS devices using the powerful and efficient optimization method called Particle Swarm Optimization (PSO) and Loss Sensitivity Index techniques so as to enhance the performance of power system of a test system
- To analyze the simulation results and to evaluate the performance of different FACTS devices in respect of power loss reduction and voltage profile improvement.
- To evaluate the cost-effectiveness of the DSTATCOM, SVC and UPQC devices
- To draw conclusion and make recommendation regarding use of DSTATCOM, SVC and UPQC for the power loss reduction and voltage profile improvement of distribution systems

## 1.4 Methodology

In order to accomplish this thesis project objective the following methodology and techniques have been followed and implemented;

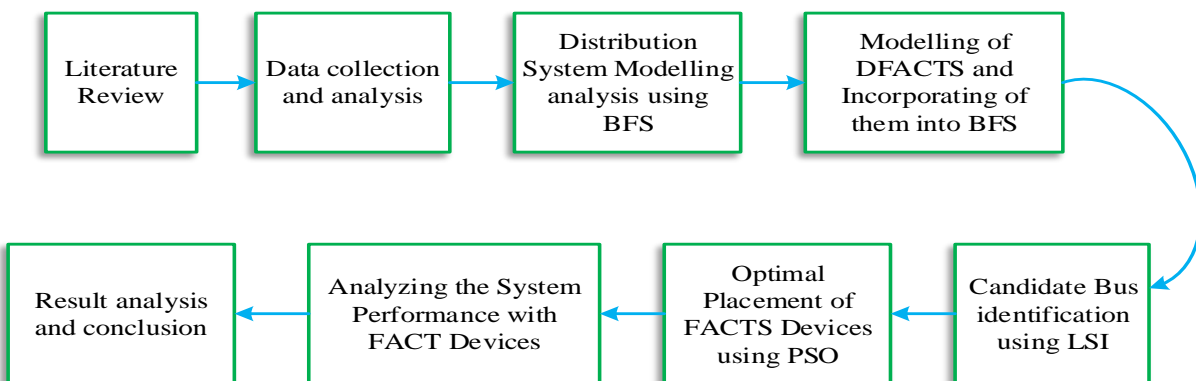


Figure 1-1:-Block diagram of the methodology followed

- **Literature Review:-** Reviewing different journals, article and papers of subject related the methods of enhancing the distribution system performance including FACTs devices compensating techniques
- **Data collection and analysis:-** All data required for proper execution of this thesis project is gathered and analyzed
- Distribution System has been modeled and analyzed using BFS algorithm in MATLAB software
- DSTATCOM, SVC and UPQC devices have been modeled and incorporated into the BFS power flow analysis

- The Loss Sensitivity Index (LSI) of the system has been evaluated and arranged in descending order and those buses with maximum value of LSI are identified as weak buses for placement of the FACTS devices
- Using PSO algorithm, the appropriate sizes of the FACTS devices has been calculated for each candidate.
- With installation of DSTATCOM, SVC and UPQC devices into the system, the power distribution system performance has been evaluated and analyzed
- From the simulation result analysis, relevant conclusion and recommendation has been presented

### **1.5 Significance of the Study**

This thesis project has been performed by integrating FACT devices on real radially configured distribution system and it has a high contribution for examining the power system performance enhancing efficiency of different FACTS controllers. Moreover, the output of this project will help to analyze the cost benefit and payback period of different FACTS controllers before deciding on the FACTS devices type to be installed on a radially configured distribution network in order to reduce the system power loss and to enhance the voltage profile by any utility.

### **1.6 Scope of the Study**

The main objective of this thesis is to investigate the performance of DSTATCOM, SVC and UPQC FACTS devices for enhancing the performance of radially configured distribution power systems. The scope of the thesis is limited to evaluate the effectiveness of various FACTS devices in power loss reduction and voltage profile improvement of distribution systems. Sebbata-I distribution substation is taken as test system for this purpose and not intended to reduce the power loss and improve the voltage profile of the system.

### **1.7 Organization of the Thesis**

This thesis project has been organized in five chapters and the content addressed in all chapters summarized as follow;

**Chapter One:** under this chapter, explanation about the background of the thesis project, Statement of the problem, objectives, methodology, scope, significance and organization of the project has been addressed.

**Chapter Two:** This chapter addresses the theoretical background on electrical distribution system structure, system losses and voltage dropping, distribution system performance improvement techniques, Flexible AC Transmission System (FACTS) controllers and literature review of the study, mainly on implementation of different FACTS devices in distribution system for power loss reduction and voltage profile improvement.

**Chapter Three:** Describes the distribution system, distribution system power flow analysis, utilized optimization method, distribution system performance using FACTS device

**Chapter Four:** Simulation Studies and Analysis of Results without and with installing of DSTATCOM, SVC and UPQC devices and cost calculation for implementation of FACTS devices.

**Chapter Five:** under this chapter based on the output of this thesis project final conclusion, recommendation and Future Work have been presented

## **CHAPTER 2**

### **DISTRIBUTION SYSTEM PERFORMANCE ANALYSIS AND IMPROVEMENT**

#### **2.1 Introduction**

The electrical power distribution system is commonly affected with power loss and voltage drop problems which occurs due to overloading and also due to the unbalanced loads connected to distribution networks. Under this chapter, distribution system performance analysis and improvement technique of minimizing the power loss and improving voltage profile are discussed in detail. Accordingly, Section 2.2 focuses on description of electrical power system structure while Section 2.3 describes the causes and types of power losses which exist in distribution system. Section 2.4 covers the common causes and factors affecting the voltage drop in distribution systems. A brief discussion on various techniques used for improvement of distribution system performance is presented in Sections 2.5. The Flexible AC Transmission System (FACTS) have been discussed in section 2.6. At the end, literature review on implementation of FACTS devices for minimizing the power loss and enhancing the voltage profile of the distribution system are presented in Section 2.7.

#### **2.2 Electrical Power system Structure**

In any electrical power structures all electric components are incorporated in order to transfer the required electrical power energy to the consumers. In general, the electrical power structures can be divided into three broad categories. The first part is the power generation system where the electrical power is generated at different generation voltage level. Then, this generated voltage is increased to the required voltage level with the help of step-up transformers and transmitted over a long distance to the substations. The second part of the electrical power structure is the transmission system which is used to convey the power to the substation or load centers through cable or overhead transmission lines. The transported power through this line can be of extra-high voltage level, or high voltage level. The third part is the power distribution network, where the voltage is stepped down at the substation to the medium voltage (MV) level and delivered through the distribution lines to the local distribution at which the voltage is reduced to the consumer level and the power lines of the local utility or distribution company carry electricity to

home or commercial establishments [9]. The distribution system is consisting of the following three main components;

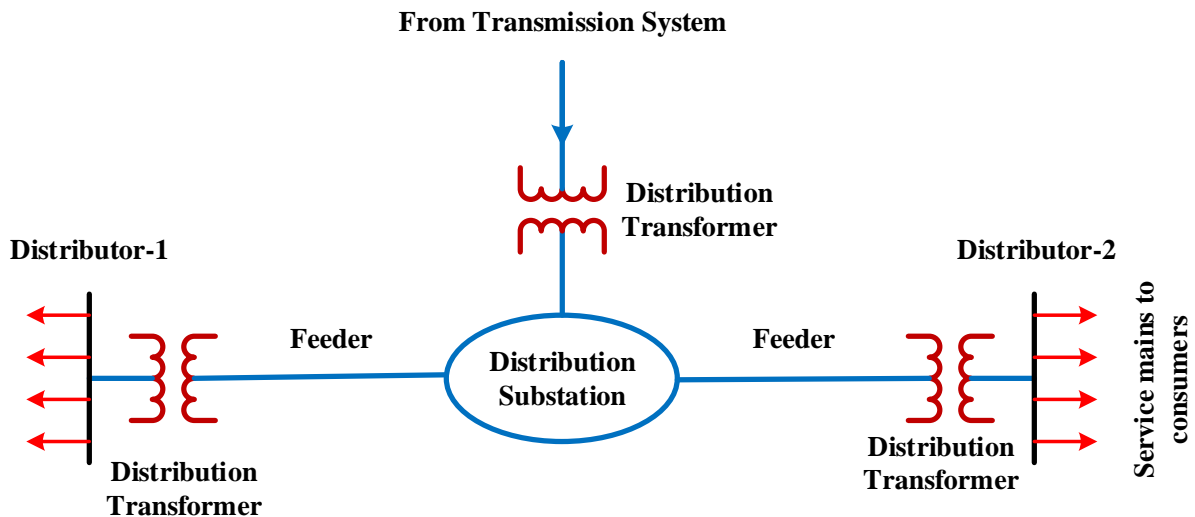


Figure 2-1: Single line diagram of a typical distribution system

**Feeder:** - In electrical distribution system, feeder is the electrical cable through which electrical power is transmitted to the consumers. Constant current is flowing through the feeder line as no tapping is connected to the feeder. And also, in feeder designing process, the current carrying capacity of the feeder has to be considered properly.

**Distributors:** - is one of the distribution network component through which electrical power is supplied to the end consumers. It is allowed to take tapping from distributor and as a result the current flowing through the distributor will be varied. Therefore, in the process of designing a distributor primary concern shall be given for dropping of voltage.

**Service Mains:** - is one of the distribution network components and it connects the distributor to the end consumers.

Based on scheme of connection, the distribution network structure can be categorized in to Radial, Loop and inter-connected system and detail of these structures has been discussed as follow;

### 2.2.1 Radial Distribution System

Most distribution networks are radial in configuration and this is due to the facts that such structures can be constructed at lower investment cost than the other type of network configurations. This type network configuration mainly implemented at less densely populated areas such as rural places. The power is supplied to the system from a single source and during occurrence of any fault in the upper side of the network, flowing of the electrical power is disconnected downside of the line.

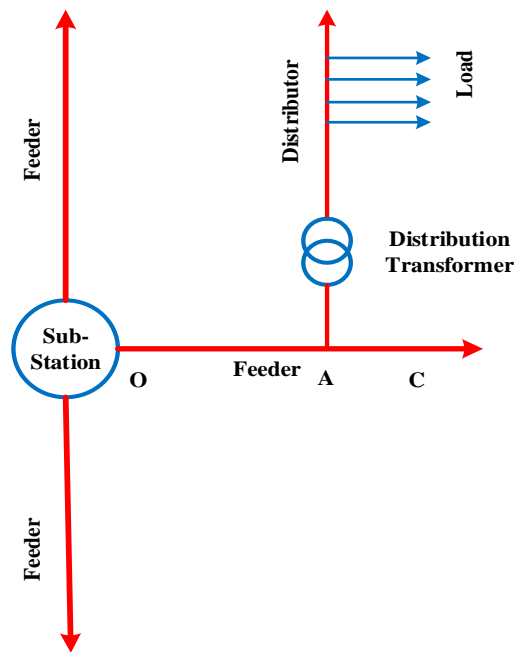


Figure 2-2:- Radial distribution systems

The radial distribution system has the following advantages;

- The structure is simple and ease for construction
- And also, its cost is lower than other type of configuration

Radial distribution system has the following disadvantages:

- Distributor connected to closest of the source will be highly loaded.
- All users are connected to the single line and when any fault occurs, consumers connected next to the fault point will be disconnected.

- Possibility of voltage variation for those customers connected at the far end

### 2.2.2 Loop Distribution System (Ring Main System)

A ring main system differ from the radial system that the starting and ending points of the line are tied together and as a result, the electrical power flow in multiple directions and the end consumers obtained power from many directions. Therefore, if fault occurred at any point of the line, electrical power will not be totally disconnected from the consumers as there are alternative directions for the electrical power to be supplied to the consumers.

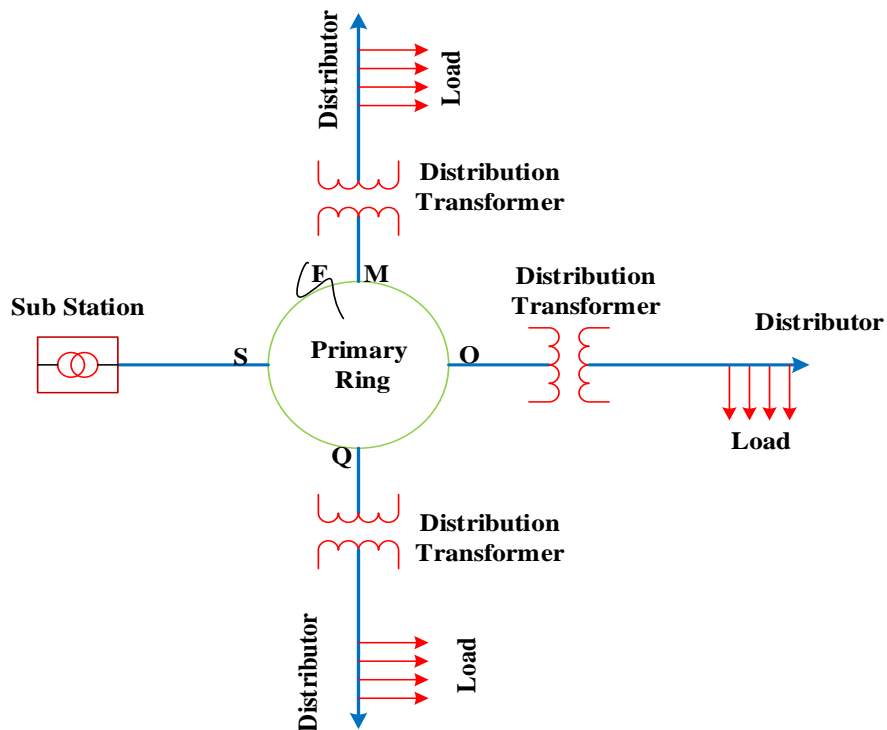


Figure 2-3:- Ring main systems

Advantages of this configuration are;

- Possibility of voltage variation at consumer terminals is less than radial system
- Supplying of the feeders from two substation increases the reliability of the system.
- During occurrence of fault at any point of the feeder section, the consumers are not disconnected from power as power can continue to flow from the other direction.

Disadvantage of the system is:

- Ring system initial investment cost is relatively high when compared to radially configured network structure.

### 2.2.3 Inter-Connected System

Unlike radial and ring system, inter-connected system is supplied electrical power from two or more substations. As a result, the end consumers have the alternative to obtain electrical power from both substation and this makes the system to be more reliable than radial and ring system.

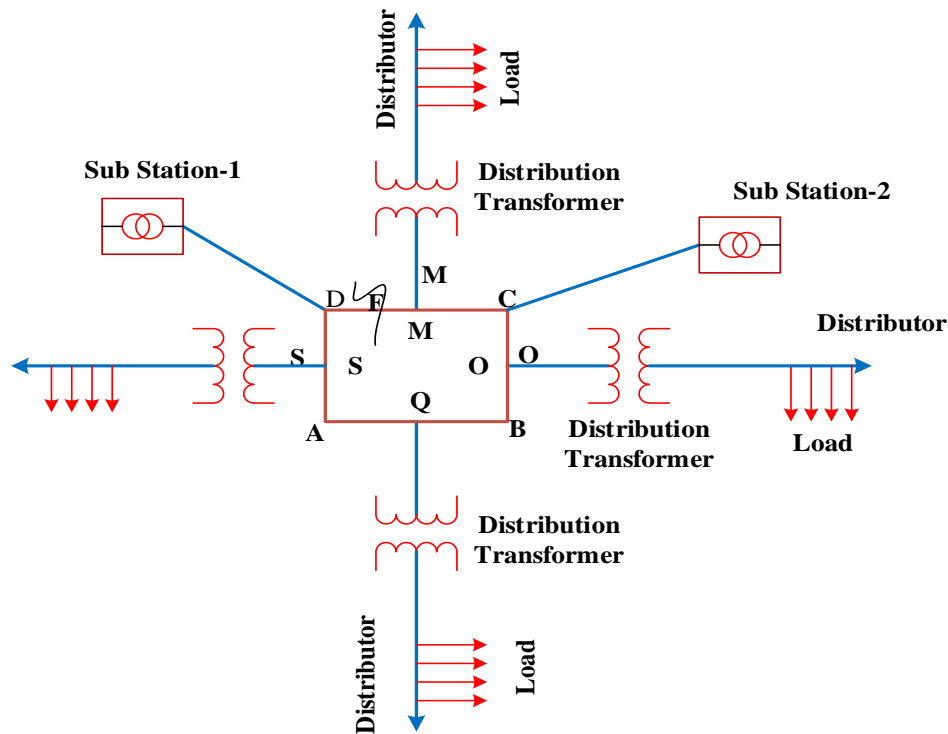


Figure 2-4:- Inter connected system

Advantages of this type of network configuration are the following;

- This type of configuration has much better service reliability than other schemes
- During occurrence of fault as well as peak load hours, the system is fed from the other sources so that the efficiency is much greater than the other others scheme of configuration

Disadvantages of inter connected scheme of configuration are;

- The initial investment cost of this system is more expensive than other configurations
- The designing, planning and operation of such configuration is complex

### **2.3 Power Loss in Distribution Systems**

Due to different factors, power distribution networks are exposed for both active and reactive power losses. It is mainly the result of the system impedance where the resistance part causes the active power loss, while reactive power loss is produced due to the reactive elements. However, the performances of the power delivered to the consumers mainly depend on the active power loss level of the system. Therefore, ensuring the reactive power flow at the required level can maintain the system voltage level at required level.

In general, the power losses in the distribution systems are categorized as technical losses and non- technical losses.

**Technical Losses:** Electrical distribution system components like electrical conductors, step-down transformers, joints, power measuring devices and instruments which are incorporated in the system create significant amount of power loss due to the nature of the components and this loss is called technical loss. As the electrical energy is transmitted in the distribution network, some amount of the supplied power part will be changed in to heat and noise, so that it is also called physical loss. The consumers are accounted-for to pay money for lost energy cost, though they are not consumed, it is assumed to be consumed by the customers while it was lost in the distribution network in the process of transferring it to the consumers. The amount of energy lost as technical loss is directly related to the design structure of the electrical grid, level of the voltage transmitted and also the distance covered by the power distribution lines. And also it is dependent on the electrical distribution network components such as transformers connected to the system which is directly related to the investment costs and operational expenditure. Therefore, planning and designing efficient distribution system is a determinant factor on the technical loss level occurred in the system. Depending up on the load condition and equipment utilized, the technical loss further categorized into variable loss, fixed losses and network service losses.

**Non-Technical Losses:-** Beside the technical loss, all the electrical power transmitted in the distribution system is not fully consumed by the end users and certain amount of transmitted power part will be lost in between the utility and the end consumers where is not accounted for, and this loss are called non-technical loss. This type of energy loss is sometime called commercial losses and it is not charged directly by the utilities or power suppliers. Power losses primarily relate to unidentified, misallocated, and inaccurate energy flows are categorized under non-technical losses and they represent the amount of energy that is delivered but not accounted for. In non-technical losses, the end energy consumer is unknown and also the amount of energy being consumed is uncertain. External factors such as load connected by consumers but not discovered by the utilities, will contribute for non- technical losses. In such condition, the undetected energy has been consumed by unknown load and it is usually be the issue of the customer management process. In general, non-technical losses can be categorized as Network equipment issues, Network information issues, Energy data processing issues.

## **2.4 Voltage Drop in Distribution Systems**

The level of the power quality of the distribution network depends on the voltage level of the system; consequently dropping of system voltage has an implication that the system power quality has been lowered and as a result, the proper functioning of the electrical appliances connected to this system will be affected. Therefore, the level of the power quality the system has shall be given significant attention. The distribution system voltage can be affected and lowered due to the following factors;

- **Poor jointing and termination:** - In general, the poor termination/loose connection in an electrical system causes a rise in resistance which further leads to overheating at the joints and a voltage drop at that location.
- **Size of Conductors:** - The resistance value of the conductor is inversely proportional to cross sectional area of the conductor which on the other hand increases the voltage drop in the system. Accordingly, conductors having larger cross sectional area will have less voltage drop whereas, conductors having small cross sectional area will have large voltage drop
- **Type of Material from which the conductor is made:** - The electrical power conductivity of a conductor is mainly determined by the material from which the conductor is made. For

instance, Copper conducts electricity better than aluminum and will cause less voltage drop than aluminum for a given length and conductor size

- **Temperature of the Conductor:** - As a general rule, most conductive materials will increase their resistance with an increase of temperature. Increasing of the resistance will result the increase in voltage drop in the distribution system.
- **Distribution feeder length:** - Shorter distribution feeders will have less voltage drop than longer distribution feeders for the same conductor size, as the impedance of the conductor is directly proportional with the length
- **Current being carried by the conductor (Ampere Load):-** Voltage drop increases on a distribution network conductor with an increase in the current flowing through the conductor.
- **Harmonics:** Due to presence of nonlinear loads connected to the system creates harmonics by distorting the voltage waveform, and voltage drop occurs on the entire system
- **Power factor:** - Low power factor causes higher current flow through the circuit which increases the voltage drop in the conductor, in turn reducing power efficiency. Significant voltage drop can result in improper or erratic operation which ultimately causes damage to the equipment
- **The substation transformer's rated capacity:** - The reactance and the resistance cause a voltage drop in the transformer winding which depends on the load current supplied and the effective impedance of the secondary windings. And this explains that an increase in the secondary winding current leads to an increase in the voltage drop in the transformer winding

## **2.5 Distribution System Performance Improvement Technique**

There are different techniques which have been implemented at different time for reducing the power loss and improving the voltage profile of a distribution system [20]. The most popular methods are discussed as follows;

- **Network Reconfiguration:** - is the process of changing the topological structure of feeders by changing open/closed status of sectionalizing and tie switches. It can be applied as tool of planning, and real time control of distribution system. As most distribution networks have radial structure, changing such structures frequently by exchanging the open/closed switching states so as to shift load from one to another may crucially upgrade the operating

condition of the system in general. This techniques gives the possibility of getting minimized active power losses through shifting the load from heavily-loaded feeders to lightly loaded feeders and from higher-impedance routes to lower- impedance routes, though the system impedance of the feeder is considered from the starting to the end point of the load. And hence, beside the effectiveness of this technique with regard of shifting the load on the line being switched, it can also be useful for in enhancing the voltage profile and minimizing the system power loss in general [1].

- **Distributed Generation Allocation:** - is the concept of the generating the required electrical power by near or closes to the load by using different technologies and as a result the real power loss of the system can be minimized. Currently, the demand of this technique is highly increasing and in near future, most electrical demand expected to be covered by this method. However, such units shall be allocated properly to obtain the intended result; otherwise it can negatively affect the distribution power flow system in general [2].
- **Reactive Power Compensation:** - this is done by properly allocating of the capacitor devices to inject or absorb fixed reactive power into or from the system and as a result, the distribution system power loss can be minimized. This is due to the fact that the presence of the reactive power flowing in the system has a significant contribution for the power loss. Therefore, by applying this technique to the distribution system having inductive load, the system loss can be maintained to be minimum.
- **Network Reconductoring:** - Due to increasing of power demand due to increasing of population growth, the initially designed power structures are not efficient to supply the power to the consumers. Therefore, this technique is done by replacing the previous feeder conductor with proper conductor dimensions in order to supply the required power to the consumers and this technique may be useful of countries having a high population growth rate.
- **Locating and Sizing Distribution Transformers:** - in normal distribution network structure the distribution transformers are randomly placed in respect of the consumers connected. As a result the consumers connected at far distance gets decreased voltage level while there is proper voltage level is exist at the other transformer. Hence, placing the transformers at

central location will reduce the occurrence of loss in the distribution network. Therefore, by placing the distribution transformers to close to the load center and changing the transformers of larger capacity with small ones so that it supplies only to small number of consumers, so that optimum voltage level is maintained.

- **Using of High-Efficiency Transformers:** -The use of high efficient of transformers will also reduce losses, i.e. using amorphous core transformers instead of cold rolled grain oriented steel transformers. As it have high magnetic vulnerability, with less coactivity and maximum electrical resistance. As in transformers, minimum losses due to the high resistance by eddy currents[73]
- **High-Voltage Power Distribution System:** - is performed by changing the previous low voltage level distribution networks to high voltage level distribution networks. This includes changing of the large rating of transformers with different small rating of transformers and the high voltage lines will be extended till the load so that the current flowing through such voltage level is low and as a result the power loss is gets minimized. Therefore, required power quality of a distribution system can be achieved by effectively and efficiently minimizing of technical losses of the system.
- **Using Flexible AC Transmission System (FACTS) controllers:** - along with the advancement of the power electronics technology, the demand of the FACTS controllers is growing rapidly as they are getting more attention by the transmission and distribution networks designers. These controllers significantly increase the power transfer in the distribution network and enhance the quality of the power flow through the distribution network will increases. And also these controllers increase the system reliability, offer a greater flexibility and control in operation of the system

In this thesis work, the performance of different FACTS devices have been analyzed in respect of reducing the power loss and improving voltage profile of radially configured distribution network considering Sebbata-I substation as test system.

## **2.6 Flexible AC Transmission System (FACTS) Devices**

FACTS (Flexible Alternating Current Transmission System) concept was first given by Hingorani in [24]. These electronic-based devices are capable to control both active and reactive power flow of the system [21]. And also, they can redistribute power in congested lines under

heavily loaded conditions, thus improve the system stability. FACTS controllers are constructed to from power electronics and can enhance the system stability, ensure proper controlling and power flowing of the system through controlling of main distribution network parameters. Based on their construction structure, the FACTS devices are categorized as follows;

**Series Controllers:** these are variable source convertors which are either in the capacitor or reactor based power electronics devices. The voltage injected by these types of devices is in phase with system voltage. While the current and voltage is injected in quadrature, the devices will be at supplying or absorbing state of reactive power to or from the system. When the voltage is injected at any other angle, except in phase and in quadrature, the real power can also be supplied to the system. Static Synchronous Series Compensator (SSSC), Interline Power Flow Controller (IPFC), Thyristor Controlled Series Capacitor (TCSC), Thyristor Switched Series Capacitor (TSSC), Thyristor Controlled Series Reactor (TCSR), Thyristor Switched Series Reactor (TSSR) are classified under series controller [78]

**Shunt Controllers:** similar to the series controllers, these are also variable source convertors which are either a capacitor or reactor based power electronics devices. These controllers can inject a current to the system in quadrature to the system voltage so that a variable reactive power can be supplied or absorbed to or from the system based on the requirement of the system. Other than this angle, i.e. in quadrature, the active power supply can be considered. The Static Synchronous Compensator (STATCOM), Static Synchronous Generator (SSG), Static Var Compensator (SVC), Thyristor Controlled Reactor (TCR), Thyristor Switched Reactor (TSR), Thyristor Switched Capacitor (TSC), Static Var Generator or Absorber (SVG) are the most commonly used shunt controllers[78].

**Combined series-series Controllers:** - It is a combination of series controllers. Both the series connected controllers operate in coordinated manner and this make these devices more powerful in multi transmission system. And also these controllers can be used for balancing both active and reactive power the system [78].

**Combined series-shunt Controllers:** - It is a combination of series and shunt controller which operated and controlled in coordinated manner. The series connected controller injects voltage at any angle different from  $90^0$  degree in order to supply both active and reactive power for compensating the load. Whereas, the shunt connected controller inject current in quadrature to

the system voltage so that the reactive power is supplied to compensate the load. In this manner both series and shunt connected controllers will share and take part in compensating the load reactive power demand. As a result, these types of controllers are more efficient and effective for load reactive compensation

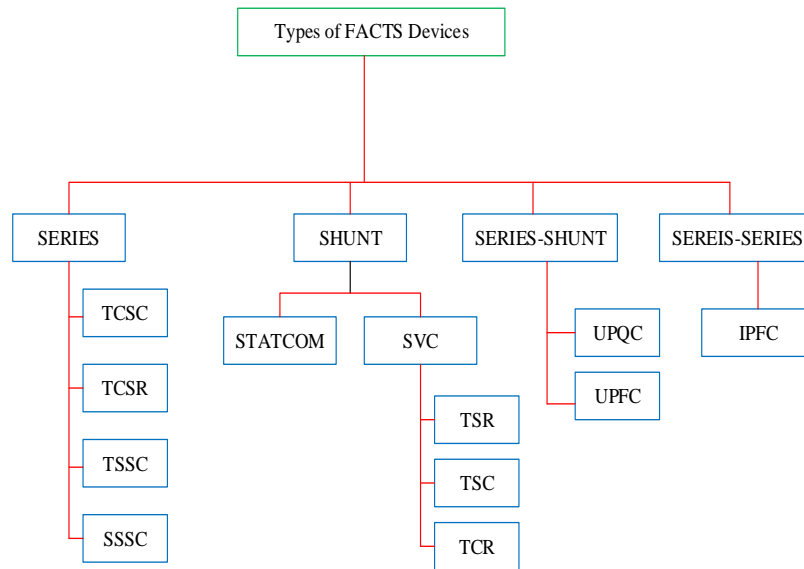


Figure 2-5:-Classification of FACTS Devices [25]

## 2.7 Literature Review

Different techniques have been implemented by many researchers so as to reduce the power loss and improve the voltage drop problems of the distribution system. Accordingly, devices such as network reconfiguration, distributed generation, synchronous condenser, and capacitor banks as well as FACTS devices have been utilized by researchers. Therefore, this thesis work is aimed to study comparative performance analysis of DSTATCOM, SVC and UPQC devices for power loss reduction and voltage profile improvement of radial distribution system and Sebbeta-I substation 15KV outgoing feeder-12 is taken as test system. The literature on the installation of DSTATCOM, SVC and UPQC devices in distribution networks is discussed as follows;

**A. Gupta and A. Kumar [28]** conducted a research using the variation techniques to find an optimal size and location of DSTATCOM for radial distribution system to reduce the amount of loss, and to improve the voltage profile. The research was conducted using the MATLAB software associated with the IEEE of 33-bus system. The radial distribution network was

compared using the voltage stability index and the power loss index with the result of two other researches. The results showed a significant reduction in losses and an improvement in the voltages profile and the size of DSTATCOM obtained by the proposed method is lower than reported in these two researches

**Amin, Amal, Salah Kamel, and Juan Yu [29]** have proposes an analytical technique to determine the optimal allocation of Distributed generation (DG) and Distribution static compensator (DSTATCOM) in radial distribution systems. Minimizing the power loss and improving the voltage profile are taken as the main objective functions. Power stability index (PSI) is used to determine the optimal locations of DG and DSTATCOM that identifies the candidate buses which are more suitable for connecting these devices. Sensitivity analysis is used to determine the optimal size of DGs, while the size of DSATCOM is increase gradually by step size until reach to lowest losses. The developed algorithm is validated using standard IEEE 34 bus system and 69 bus system and the results are compared with other well-known techniques

**Gowtham, G., and A. Lakshmi Devi [30]** used Fuzzy and particle swarm optimization algorithm of two-stage methodology for optimal placement and sizing of DSTATCOM with the objective of reducing the power loss and improving the voltage profile in radial distribution system. The effectiveness of the proposed system is tested using standard IEEE 33 bus system and 69 bus systems. Power loss and voltages are calculated for the four optimal locations based on priority 125%, 150%, 175% overloading cases are also considered and the result analysis shows that the two stage methodology effectively improves the voltages and reduces the power loss of the system

**Kaliaperumal Rukmani, Devabalaji, et al. [32]** has proposed a new approach based on a bio-inspired Cuckoo Search Algorithm (CSA) that can significantly envisage with several issues for optimal allocation of distribution static compensator (DSTATCOM) in Radial Distribution System (RDS). In the proposed method, optimal locations of the DSTATCOM are calculated by using the Loss Sensitivity Factor (LSF). The optimal size of the DSTATCOM is simulated by using the newly developed CSA. In the proposed method, load flow calculations are performed by using a fast and efficient backward/forward sweep algorithm. Here, the mathematically formed objective function of the proposed method is to reduce the total system power losses. Standard 33-bus and 69-bus systems have been used to show the effectiveness of the proposed

CSA-based optimization method in the RDS with different load models. The simulated results confirm that the optimal allocation of DSTATCOM plays a significant role in power loss minimization and enhanced voltage profile.

**Ahmed, Walaa, et al. [33]** has proposed a solution procedure for probabilistic load flow problem considering the optimal allocation of Static Var Compensator (SVC) in radial distribution systems. Pareto Envelope-based Selection Algorithm II (PESA-II) with fuzzy logic decision maker is developed to determine the optimal location and size of SVC based on the minimum total power losses and Voltage Deviation (VD). Combined cumulants and gram-chalier expansion are used for solving the probabilistic load flow problem. The proposed algorithm is tested on 33- bus and 69-bus distribution systems. The developed algorithm gives an acceptable solution with low number of iterations and less computation cost compared with the Monte Carlo method

**Ahmed, W., Selim, A., Kamel, S., Yu, J., & Jurado, F. [34]** has proposed a solution procedure for probabilistic load flow problem considering the optimal allocation of Static Var Compensator (SVC) in radial distribution systems. Pareto Envelope-based Selection Algorithm II (PESA-II) with fuzzy logic decision maker is developed to determine the optimal location and size of SVC based on the minimum total power losses and Voltage Deviation (VD). Combined cumulate and gram-chalier expansion are used for solving the probabilistic load flow problem. The proposed algorithm is tested on 33- bus and 69-bus distribution systems. The developed algorithm gives an acceptable solution with low number of iterations and less computation cost compared with the Monte Carlo method

**Ramanaiah, M. Laxmidevi, and M. Damodar Reddy [35]** have evaluated the performance of Unified Power Quality Conditioner (UPQC) in radial distribution systems. In the proposed approach, the series compensator injects the series voltage in normal operating conditions. The series and shunt compensators take part in providing compensation to the distribution network. In order to include the effect of series and shunt compensator, a forward-backward sweep load flow algorithm comprising of UPQC is used. The optimization is carried out with Particle Swarm Optimization (PSO) method with the aim of minimization of power loss in the distribution

network power. The distribution systems used to study the effectiveness of the proposed approach are 33-bus system and 69-bus system

**Ramanaiah, M. Laxmidivi, and M. Damodar Reddy [36]** this paper acquaints us with the problem of Unified Power Quality Conditioner (UPQC) placement in radial distribution systems. The objective of UPQC placement is to reduce the real power losses and improve the voltage profile. The problem is formulated as a nonlinear single objective problem. The voltage compensation is done by injecting active and reactive power with the aid of series compensator of UPQC. The shunt compensator provides the required load reactive power along with the series compensator. The optimal placement of UPQC is unraveled using the latest optimization method known as Ant Lion Optimization (ALO) method. The proposed method is tested using 33 bus system and 69 bus system standard distribution systems.

According to the literature review above, it is possible to allocate FACTs devices in the distribution network using different optimization algorithm, to reduce system losses and improve the voltage profile of the radial distribution network.

The techniques proposed by different researchers have been centered on compensating devices using various optimization methods to solve the distribution network's power quality issue. However, most researchers didn't consider both real and reactive power, voltage stability, and voltage profile, and cost analysis at the same time. In addition to that, all authors have tested their methods on the IEEE distribution system i.e. their results are not applied to the real application of the distribution system.

## **CHAPTER 3**

### **DISTRIBUTION SYSTEM PERFORMANCE ENHANCEMENT USING FACTS DEVICES**

#### **3.1 Introduction**

In recent time, distribution system performance has been affected badly because of increasing of load demand due to rapid population growth and expansion of industries. As a result, distribution feeders are overloaded beyond their carrying capacity and as a result, higher voltage variation and power loss problem are created in the system. Advancement of power electronic devices has made it imperative to search for more effective alternatives that guarantee appropriate operating level of power losses and voltage profile of the distribution networks. DSTATCOM, SVC and UPQC devices can be considered as the most suitable enhancement devices for distribution systems that reduce power losses and improving the voltage profile of the system. The objective of this thesis project is to investigate the performance of DSTATCOM, SVC and UPQC devices for power loss reduction and voltage profile improvement taking Sebbata-I substation 15kV outgoing feeders as a test system.

Therefore, this chapter mainly focuses on distribution system performance enhancement using FACTS devices. Accordingly, section 3.2 describes about Sebbata-I substation outgoing feeders, and methodologies followed for collecting the necessary data required to meet the objective of this thesis; section 3.3 describes about power flow method used to evaluate the operating performance of the system, section 3.4 describes about the Particle Swarm Optimization method, section 3.5 explains about the performance enhancement of FACTS devices used in this thesis and optimal sizing and placing of FACTS devices has been discussed in detail in section 3.6 of this chapter

#### **3.2 Description of the Distribution System**

Sebbata-I substation is located at Western side of Addis Ababa, at area called Kara Kore, which is located at the geographical coordinates of 08°58'41.0" North and 038°40'51.0" East. Sebbata -I substation is high voltage level substation having 230 kV incoming lines and 132 kV, 45 kV and 15kV outgoing lines which supplies one-third of Addis Ababa City.



Figure 3-1:- Geographical view of Sebbata-I Substation

Sebbata-I substation is connected to Sebbata-II, Gilgelgibe-I & II, Kalitit-1 and Wolkit stations via 230kV lines, and with Gefersa, Mekanissa, and Addis west, Black Line, stations via 132kV lines. All incoming lines are tapped to the same double bus bars in Sebbata-I substation to which three autotransformers having a capacity of 125MVA, 230/132KV are connected. The outgoing line which feeds Gedja substation has been connected through three winding transformers having a capacity of 25/25/10 MVA, 132/45/15 kV. The fifteen outgoing feeders of 15 kV are categorized into three parts which are named as SAB-I-A, SAB-I-B, and SAB-I-C. Outgoing Feeders 2,6,8,10,11&13 are supplied by SAB-I-A and 1,4,5 & 7 and 3,9,12,14, 15 are supplied by SAB-I-B and SAB-I-C respectively through transformer-1, 2, and 3 with a capacity of 50 MVA, 132/15 kV. All outgoing feeders from Sebbata-I substations are radially configured.

The important primary and secondary data regarding the outgoing feeders have been collected from various sections of Ethiopian Electric Power (EEP) and Ethiopian Electric Utility (EEU) by direct involvement and visiting Sebbata-I substation's switching sections, control room, loading of transformer and feeder, and also by interviewing the operator of the substation.

Accordingly, the past three year data i.e. 2022, 2021, & 2020 which include the cause of the power interruption, duration of the power interruption, frequency of power interruption, and

length of the feeder, impedance (resistance and reactance) of each segment line, the active and reactive power on load point, peak, average, and minimum load of the feeder, each capacity of power and distribution transformer have been presented. Among the fifteen 15 kV outgoing feeders of Sebbata-I substation, feeder-12 have a high peak load demand, covering long distance and supply power to industrial, commercial and residential customers and it is one of the vulnerable feeder for power interruption and this feeder is selected as a test system.

Table 3-1:- Incoming Source to Sebbata-I substation

Substation	Incoming Lines from	Voltage level
Sebbata-I Substation	Gilgel Gibe-I	230 kV
	Sabbata-II (line 1 & 2)	230 kV
	Geffersa line	230 kV

Table 3-2:- Sebbata-I substation outgoing feeders

Outgoing lines/ feeders	Voltage level	Covered area
KAL-1 line	132 kV	This high voltage line supplies power to the kality-I substation
ADW-1&2 line:	132 kV	This high voltage line supplies power to Addis west substation
GAF line	132 kV	This high voltage line supplies power to Gefersa substation
Black lion	132kV	This high voltage line supplies power to Black lion substation
Gedja line	45 kV	This high voltage line supplies power to Gedja substation
Feeder-1	15 kV	This feeder supplies power to the area of Ayer tena, koshe sefer up to Jemo-2 condominium, fana sefer plastic factory, fana sefer inside liul plastic factory
Feeder-2	15 kV	it goes through underground cable from substation and supply to area Welete, around Noc, Sebete dima, Yes Water Factory, Hora food complex, Meta Brewery Factory, Berchiko Fabrica, Arba minch cherkacherk, Sebete biherawi alcohol up to sabbata
Feeder-3	15 kV	This feeder supplies power to Zenebework, woreda-5 tena tabia,

		Kolfe industrial college, Holland Embassy and Torhiloch Hospital up to Keranyo.
Feeder-4	15 kV	This feeder goes with underground cable and supplies power to half of Bethel area and Berchuko Fabrica, gulele condominium
Feeder-5	15 kV	This feeder supplies power to the area called Kenteri, Butajra mazorya, Noc and Waliya Metal Factory
Feeder-6	15 kV	This feeder supplies power to Jemo 2 condominium water pump, Furi, including Ayka Addis Factory
Feeder-7	15 kV	This feeder supplies power to Alemgena 08 kebele, Furi Lebu railway station, Furi radio station, Hannan flour factory, Chayihun chipud factory, Bms plastic factory, Cosmetics and plastic factory, IKEA textile, Conplas industrial, Ethio paradise, Ethiopian drug factory
Feeder-8	15 kV	This feeder supplies power to residential around, Karakore, Jemo condominium 3
Feeder-9	15 kV	This feeder supplies power to Welete, Dambi real estate, Jima bar NOC, and Gelan area
Feeder-10	15 kV	This feeder supplies power to the Girar condominium, Kara agmas water, and the area around Ayertena.
Feeder-11	15 kV	This feeder supplies power to the area called Furi, Ayer Tena condominium, Jemo-1 mestawet fabrica, Alemgena germent fabrica, Mark Food Processing Complex and Alemgena condominium.
Feeder-12	15 kV	This feeder supplies power to condominium in front of the substation, Korke, welete nemi, Walate condominium, Rapi, karra-kore, Zenebework Hospital, Welete mismar fabrica, Welete young plastic factory, Welete zenebe frew real estate and Rapi wuha limat and Iniy Building construction

Feeder-13	15 kV	This feeder supplies power to Labu Ethio-Djbout railway corporation, Alemayehu textile, Habesha Gypsum fabrica, Jemo-2 condominium including Sebeta industrial zones and Welete area
Feeder-14	15 kV	This feeder supplies power to area around kara condominium, madanialem church, and fana water pump
Feeder-15	15 kV	This feeder supplies power to kara kore fana sefer, Jemo Michael, koshe sefer,ayer tena chahina camp and fana sefar plastic factory

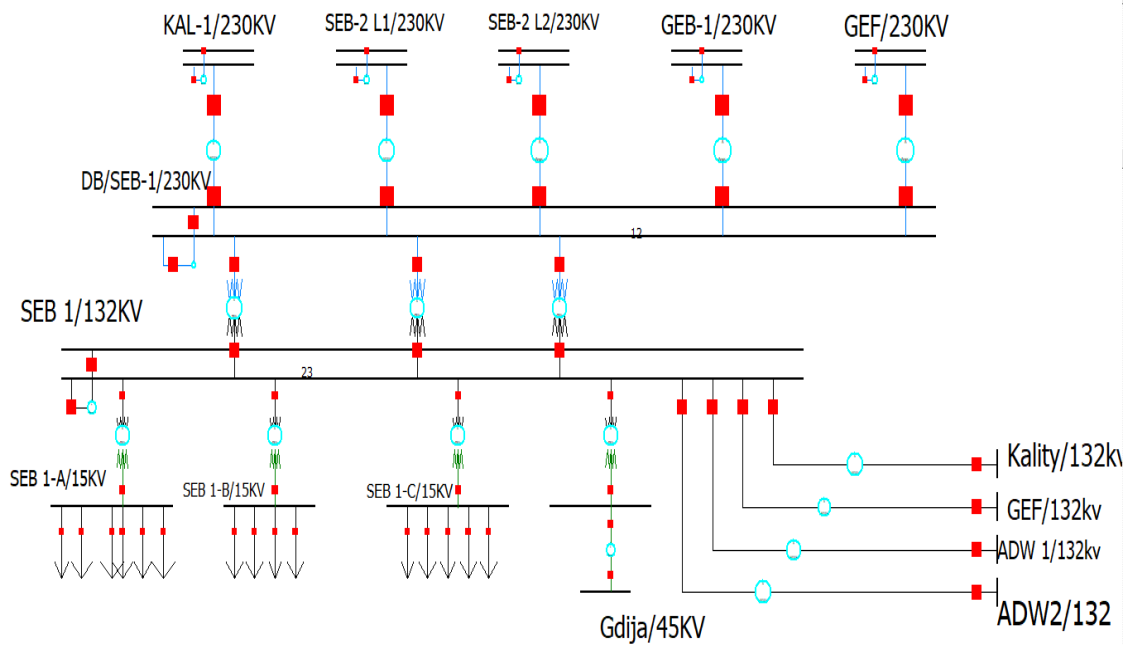


Figure 3-2:- Overview of single line diagram of Sebbata-I Substation

### 3.2.1 Single Line Diagram Representation of the Feeder

Among 15 kV outgoing feeders of Sebbata-I substation, feeder-12 has been selected as a test system because of its vulnerability to power quality problems due to overloading and also this feeder has a high peak demand and cover a large area and travel long distance starting from the substation to the end consumer. This feeder is radially configured and supplying power to industrial, commercial and residential customers.

The feeder has CT Ration 800/1 (Refer Appendix-C) which implies that the feeder’s maximum power supplying capacity is up to 18.7MW. However, mostly the CT ration is adjusted to be

operated up to 80% of its maximum capacity which means the feeder can operate and supply up to 15MW load. Whereas, currently, this feeder has been loaded peak active and reactive powers of 9.588 MW and 7.145 MVar respectively. And also, the feeder has eighty-nine (89) buses, Eighty Eight branches (88), sixty-nine (69) distribution transformers and is constructed from different types of aluminum conductors including AAC-35, AAC-50, and AAC-95 with a total length of 27.83 km. The single diagram of the selected feeder which is drawn by visio13 software as shown in figure 3.3 below;

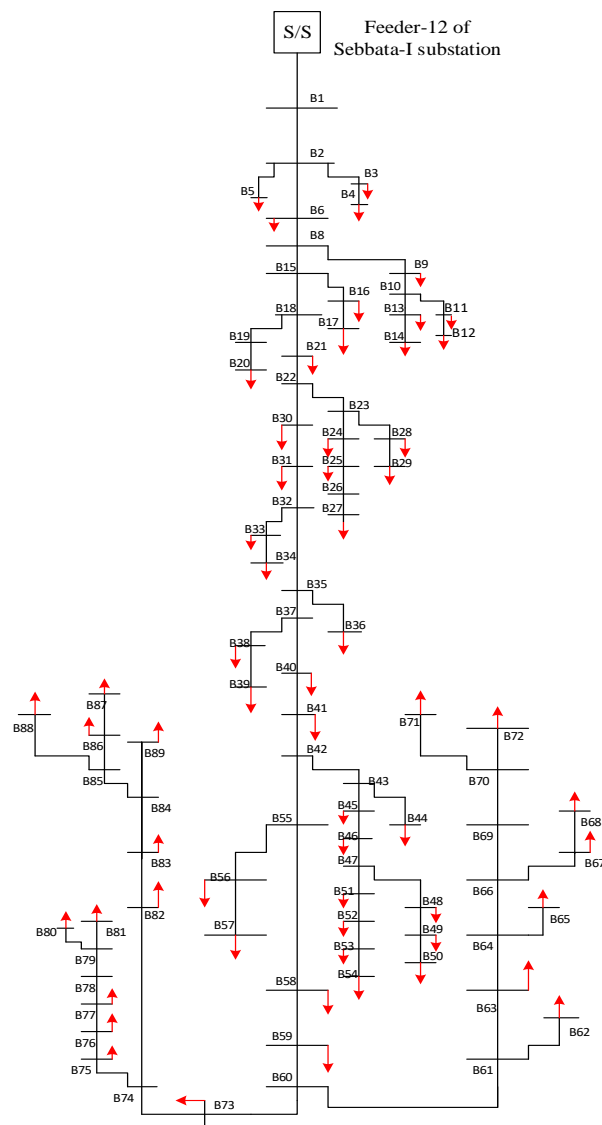


Figure 3-3:- Sabbata-I substation feeder-12 single line diagram

### 3.2.2 Line and Bus Data of the Feeder

In order to analyze the distribution system performance, parameters such as branch line resistance, reactance, segment distance, and active and reactive power data are required for initialization. However, to obtain the exact figure of these parameters is very challenging and difficult task. Therefore, the following impedance (resistance and reactance) values are collected and organized from previous done papers and assessment carried out on the outgoing feeder lines at Sebbata-I substation by the substation staff members and also by external researchers at different times. The resistance and reactance values are calculated manually depending on the distance, and the nature of the conductor that is used during the installation of the selected feeder. Taking the approximate branch length in meters and also the resistance and reactance ( $\Omega/\text{km}$ ) from Appendix-F, each branch line resistance (R) and line reactance (X) of the distribution network are calculated in the following manner

$$R (\Omega) = R_0 * \text{branch length in km}$$

$$X (\Omega) = X_0 * \text{branch length in km}$$

Where  $R_0$  is the resistance value of the distribution cable in  $\Omega/\text{Km}$  and where  $X_0$  is the reactance value of the distribution cable in  $\Omega/\text{Km}$

All buses, sending end, receiving end, type of conductor, length of each segment line, resistance, and reactance, are tabulated in table 3.3 as shown below.

Table 3-3:- Line and bus data of Sabbata-12 feeder

<b>Bus</b>	<b>Sending End</b>	<b>Receiving End</b>	<b>Type of Conductor</b>	<b>Length of Conductor (KM)</b>	<b>Resistance (<math>\Omega</math>)</b>	<b>Reactance (<math>\Omega</math>)</b>
1	1	2	AAC-95	0.13064	0.0404	0.04173
2	2	3	AAC-50	0.3422	0.198	0.11676
3	3	4	AAC-50	0.175	0.1013	0.05971
4	2	5	AAC-35	0.05387	0.0498	0.01898
5	2	6	AAC-95	0.02182	0.00673	0.00695

Table 3-3: line data and bus data (Cont...)

<b>Bus</b>	<b>Sending End</b>	<b>Receiving End</b>	<b>Type of Conductor</b>	<b>Length of Conductor (KM)</b>	<b>Resistance (<math>\Omega</math>)</b>	<b>Reactance (<math>\Omega</math>)</b>
6	6	7	AAC-50	0.051	0.02951	0.0174
7	6	8	AAC-95	0.5763	0.1778	0.18355
8	8	9	AAC-50	0.2972	0.172	0.1014
9	9	10	AAC-50	0.17432	0.101	0.0595
10	10	11	AAC-50	0.244	0.1412	0.0833
11	11	12	AAC-50	0.5248	0.30365	0.17906
12	10	13	AAC-35	0.13147	0.122	0.04633
13	13	14	AAC-35	0.1917	0.17722	0.06756
14	8	15	AAC-95	0.0663	0.02045	0.02112
15	15	16	AAC-50	0.3864	0.22357	0.13182
16	16	17	AAC-50	0.727	0.421	0.2481
17	15	18	AAC-95	0.22687	0.06997	0.07226
18	18	19	AAC-50	0.3861	0.2234	0.1317
19	19	20	AAC-50	0.7249	0.42	0.24734
20	18	21	AAC-95	0.1801	0.1042	0.06145
21	21	22	AAC-50	0.1011	0.0585	0.0345
22	22	23	AAC-50	0.0486	0.02812	0.01658
23	23	24	AAC-50	0.02768	0.01602	0.00944
24	24	25	AAC-50	0.0974	0.0564	0.03323
25	25	26	AAC-50	0.157	0.091	0.05356
26	26	27	AAC-50	0.1502	0.08691	0.05124
27	24	28	AAC-50	0.07832	0.04532	0.02673
28	28	29	AAC-50	0.169	0.0978	0.05767
29	22	30	AAC-95	0.0631	0.01946	0.0201

Table 3-3: line data and bus data (Cont...)

<b>Bus</b>	<b>Sending End</b>	<b>Receiving End</b>	<b>Type of Conductor</b>	<b>Length of Conductor (km)</b>	<b>Resistance (<math>\Omega</math>)</b>	<b>Reactance (<math>\Omega</math>)</b>
30	30	31	AAC-95	0.26678	0.0823	0.085
31	31	32	AAC-95	0.0334	0.0103	0.01064
32	32	33	AAC-50	0.2776	0.16062	0.09472
33	33	34	AAC-50	0.31	0.1794	0.10577
34	32	35	AAC-95	0.0567	0.0175	0.0181
35	35	36	AAC-35	0.11	0.102	0.03876
36	35	37	AAC-95	0.3042	0.09382	0.09689
37	37	38	AAC-95	0.2937	0.09058	0.09355
38	38	39	AAC-50	0.168	0.09721	0.05733
39	37	40	AAC-50	0.22	0.1273	0.07506
40	40	41	AAC-50	0.08362	0.0484	0.02853
41	41	42	AAC-50	0.0345	0.02	0.0118
42	42	43	AAC-35	0.19	0.17566	0.067
43	43	44	AAC-35	0.14884	0.13761	0.05245
44	43	45	AAC-35	0.9279	0.85785	0.327
45	45	46	AAC-35	0.2474	0.2287	0.0872
46	46	47	AAC-35	0.22434	0.21	0.0791
47	47	48	AAC-50	0.3494	0.2022	0.11922
48	48	49	AAC-50	0.149	0.0862	0.0508
49	49	50	AAC-50	0.61	0.353	0.208
50	47	51	AAC-35	0.7493	0.693	0.264
51	51	52	AAC-50	0.09842	0.05695	0.03358
52	52	53	AAC-50	0.1074	0.0622	0.0367
53	53	54	AAC-50	0.142	0.0822	0.0485

Table 3-3: line data and bus data (Cont...)

<b>Bus</b>	<b>Sending End</b>	<b>Receiving End</b>	<b>Type of Conductor</b>	<b>Length of Conductor (km)</b>	<b>Resistance (<math>\Omega</math>)</b>	<b>Reactance (<math>\Omega</math>)</b>
54	42	55	AAC-95	0.2138	0.0141	0.0681
55	55	56	AAC-50	0.536	0.31	0.183
56	56	57	AAC-50	0.81747	0.473	0.27893
57	55	58	AAC-95	0.01765	0.00544	0.00622
58	58	59	AAC-95	0.0949	0.0293	0.03022
59	59	60	AAC-95	0.08992	0.02773	0.02864
60	60	61	AAC-95	0.11456	0.03533	0.0365
61	61	62	AAC-50	0.41	0.2373	0.1399
62	61	63	AAC-50	0.9681	0.561	0.3303
63	63	64	AAC-50	0.3302	0.191	0.11266
64	64	65	AAC-50	0.11822	0.0684	0.04033
65	64	66	AAC-50	1.9658	1.13742	0.671
66	66	71	AAC-50	1.25187	0.72433	0.4272
67	71	72	AAC-50	0.5782	0.334	0.19723
68	66	67	AAC-50	0.3835	0.222	0.13085
69	67	68	AAC-50	0.7931	0.4589	0.271
70	68	69	AAC-50	0.3342	0.1934	0.114
71	68	70	AAC-50	0.454	0.2627	0.155
72	60	73	AAC-50	0.2575	0.14899	0.08786
73	73	74	AAC-50	0.1256	0.0727	0.04286
74	74	75	AAC-50	0.05628	0.03257	0.01921
75	75	76	AAC-50	0.2046	0.1184	0.06981
76	76	77	AAC-35	0.1774	0.164	0.06252
77	77	78	AAC-35	0.556	0.514	0.196

Table 3-3: line data and bus data (Cont...)

<b>Bus</b>	<b>Sending End</b>	<b>Receiving End</b>	<b>Type of Conductor</b>	<b>Length of Conductor (km)</b>	<b>Resistance (<math>\Omega</math>)</b>	<b>Reactance (<math>\Omega</math>)</b>
78	78	79	AAC-35	0.0567	0.05242	0.02
79	79	80	AAC-50	0.1943	0.11243	0.0663
80	79	81	AAC-50	0.08024	0.04643	0.0274
81	74	82	AAC-50	0.2898	0.1677	0.0989
82	82	83	AAC-50	0.1567	0.091	0.0535
83	83	84	AAC-50	0.1117	0.06463	0.03811
84	84	85	AAC-50	0.9693	0.561	0.33071
85	85	86	AAC-50	0.19734	0.1142	0.06733
86	86	87	AAC-95	0.2625	0.081	0.08361
87	85	88	AAC-50	0.3393	0.19632	0.11577
88	84	89	AAC-50	0.1891	0.1094	0.06452

### 3.3 Distribution System Power Flow Analysis

In power engineering, the power-flow study or load flow study is a numerical analysis of the flow of electric power in an interconnected system. It usually utilize simplified notation such as a one-line diagram and per-unit system, and focuses on various aspect of AC power parameters, such as voltage, voltage angle, real power and reactive power. Power-flow studies are important for planning future expansion of power systems as well as in determining the best operation of existing systems. Transmission system and distribution system has similar way of analysis. Voltage at starting node and the power of load at each bus is known before starting the analysis assuming constant power load. In some cases power that is supplied to root node is also known. By doing load flow analysis of radial Distribution Network [51], system parameters can be determined.

The electrical power distribution system is characterized by heavy loading conditions at some buses, a high R/X ratio, unbalanced load, having very large number of nodes and branches,

dynamically changing of connected loads and mostly radial topology. Because of these factors, the newton raphson and other load flow methods which are used in transmission lines designing process are not suitable for distribution systems due to the problem of their convergence as well as their computational efficiency. And hence, Backward-Forward System (BFS) method is the most accurate method for power flow analysis of Radial Distribution System (RDS) because its convergence ability is high and also calculations burden is very less [51, 52, and 53].

### **3.3.1 Radial Distribution System Load Flow Analysis**

The backward-forward sweep method has two computational stages from two sets of recursive equations. The first set of equations for calculation of the power flow through the branches starting from the last branch and proceeding in the backward direction towards the root node and this is called Backward Sweep operation. The other set of equations are for calculating the voltage magnitude and angle of each node starting from the root node and proceeding in the forward direction towards the last node and named as Forward Sweep Operation [67]

**Forward Sweep Operation:** - It is a process of determining the value of voltage drop in each branch by updating of the value of the current flowing through it. It starts from the first node, the voltage on each nodes are updated toward forward sweep direction until it reaches the end node. Accordingly, the voltage value of each node is determined starting from the initial node up to the end node of the distribution system. Voltage of the source is assumed to have a unity value. The power of each branch is held constant both in forward and backward calculation process [67].

**Backward Sweep Operation:** - is the process of calculating the value of the branch current by updating the corresponding value of branch voltage. The process starts from end node and propagates towards the branches connected to the initial node or source. Accordingly, each node voltage which is calculated in the forward direction is kept constant and the corresponding branch current will be calculated in the backward direction. Therefore, the backward sweep operation starts from the last node of the system and moves in backward direction up to the initial node or sources so as to calculate the current flowing through each node [67].

**Backward-Forward Sweep Load Flow Algorithm**

Assuming flat initial voltage level for all nodes starting from the root node up to the end node, the process of recursive load flow solution is explained as follows [67];

**Step-1: Calculating the node current**

The current flowing through each node of the distribution network at iteration k can be calculated as;

$$I_i^{(k)} = \left( \frac{S_i}{V_i^{(k-1)}} \right)^* \quad i=1, 2 \dots n \quad (3.1)$$

Where  $V_i^{(k-1)}$  is the voltage at node 'i' calculated during the (k-1)<sup>th</sup> iteration and  $S_i$  is the apparent power flowing through the node 'i'.

**Step-2: Backward Sweep:**

At iteration k, starting from the end branches moving progressively towards the branches connected to the source node, the current flowing through branch L ( $I_L$ ) is computed by directly by applying the KCL which can be expressed with the following equations:

$$I_L^{(k)} = -I_{L2}^{(k)} + \sum_{L = b, b-1 \dots 1} (\text{Currents in branches emanating from node L2}) \quad (3.2)$$

Where  $I_{L2}^{(k)}$  is the current flowing into or out of node  $L_2$ .

**Step-3: Forward sweep:** here the voltages at each node are updated starting from the root node moves progressively towards the end nodes. Accordingly, for each branch, L, the voltage at node  $L_2$  is calculated using the updated voltage at previous node  $L_1$  and the branch current is calculated in the preceding backward sweep:

$$V_{L2}^{(k)} = V_{L1}^{(k)} - \sum_{L=1, 2 \dots b} I_L^{(k)} Z_L^{(k)} \quad (3.3)$$

Where  $Z_L$  is the series impedance of branch L. This is the direct application of the KVL.

Steps 1, 2 and 3 are repeated until convergence is achieved

**Convergence Criterion:** - as convergence criterion, the maximum active and reactive power mismatches between the sending and receiving nodes of each branch are considered. As described in the solution algorithm, the nodal current injections, at iteration  $k$ , are calculated using the scheduled nodal power injections and node voltages from the previous iteration (equation (3.1)). The node voltages at the same iteration are then calculated using these nodal current injections (equations (3.2) and (3.3)). Hence, the power injection for node  $i$  at  $k^{\text{th}}$  iteration,

$$S_i^{(k)} = V_i^{(k)} \left( I_i^{(k)} \right)^* - Y_i \left| V_i^{(k)} \right|^2 \quad (3.4)$$

Then, at each bus the power mismatches is computed as follows;

$$\begin{aligned} \Delta P_i^{(k)} &= \text{Re} \left[ S_i^{(k)} - S_i \right] \\ \Delta Q_i^{(k)} &= \text{Im} \left[ S_i^{(k)} - S_i \right] \\ & \quad i= 1, 2 \dots n \end{aligned} \quad (3.5)$$

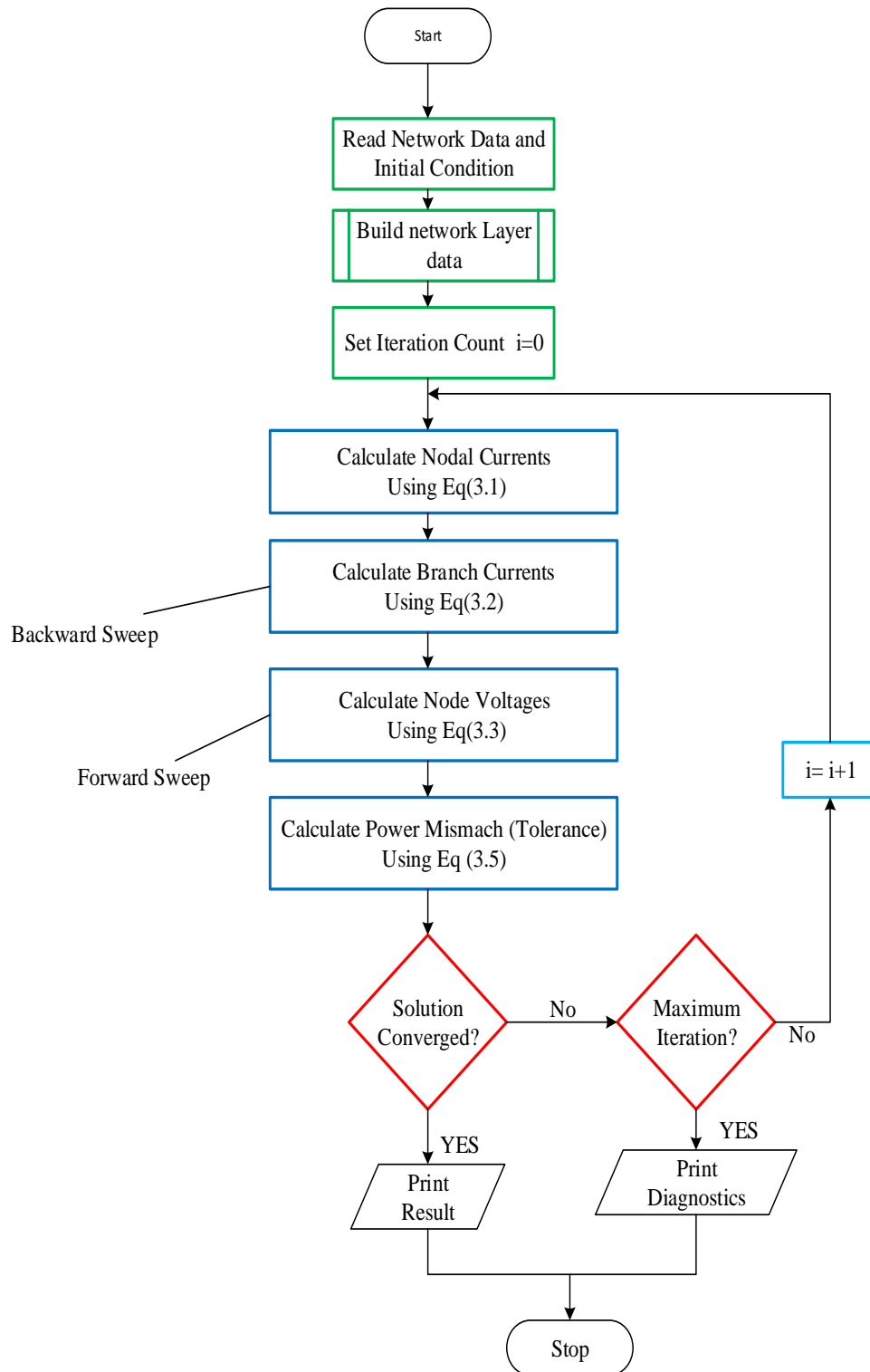


Figure 3-4:- Forward backward sweep algorithm flow chart before installation of FACTS

### **3.4 Particle Swarm Optimization method to Solve the Power Loss and Voltage Problem**

The Particle Swarm Optimizer (PSO) method is a meta-heuristic-based optimization technique presented by James Kennedy and Russell Eberhart in 1995 (Pereira). It is inspired by the cooperative behavior and the exchange of information practiced by various animal species. In PSO, each particle corresponds to a candidate solution that adjusts its velocity and position according to its own experiences and experiences of nearby particles to find the optimal solution [56, 57]. A PSO system follows social behavior of the swarms and based on social behavior the swarms improve their knowledge on each iteration and they get adapted to that new value. Based on the updated results PSO works as a simulator for different applications.

The techniques require small size of memory and its time of computation is short. The searching method is based on the swarms like fish schooling and bird flocking. Initially, the technique was established for non-linear optimization problems with continuous variable. But, the optimization can be applied for discrete variables as well. This features makes to be appropriate and efficient to the load flow analysis and voltage control problems. Studies reveal that, the phenomenon of birds flocking, birds are not searching food individually rather they find by flocking. This indicates that the birds communicate information in flocking. Similarly, in human nature the behavior of the individual is affected by the experience the individual has in the group he/she participates with. Therefore, the particle swarm optimization algorithm is developed based on these assumptions. This optimization algorithm will have n-dimensional space for the solution in the process of dealing with any problems.

Throughout the solution space, each swarm particles movement is examined by some fitness rules. Later on the swarms accelerate in the direction of particles which have the better fitness values. Mostly, two dimensional spaces are designed in simulation of birds flocking in PSO. Accordingly, all agents are given their XY coordinates and the velocity of X-axis is denoted as  $V_x$  and the velocity of Y-axis as  $V_y$ . The position and velocity information of each agent are updated and modified repeatedly. Based on the above assumption, the PSO procedure will be developed as follow;

Considering bird flocking as a procedure of optimizing a given function, every agent will have the knowledge of its best value  $P_{best}$  and its XY position. In addition, all agents have the information that out of the  $P_{best}$  in the group to be taken as  $G_{best}$ . In order to modify its position the current velocity and distance of each agent are used from  $P_{best}$  and  $G_{best}$  and it is denoted in terms of velocity. This is done as follows;

$$V_i = V_i + \text{rand}(P_{best_i} - X_i) + \text{rand}(G_{best} - X_i) \quad (3.6)$$
$$X^{k+1} = X^k + V^{k+1}$$

Where,  $V_i$  : particle velocity, rand: number randomly distributed uniformly between 0 and 1,  $X_i$  is particle position,  $P_{best_i}$  is particle personal best and  $G_{best}$  is global best of the group. And also  $X^{k+1}$  and  $V^{k+1}$  are updated position and velocity respectively.

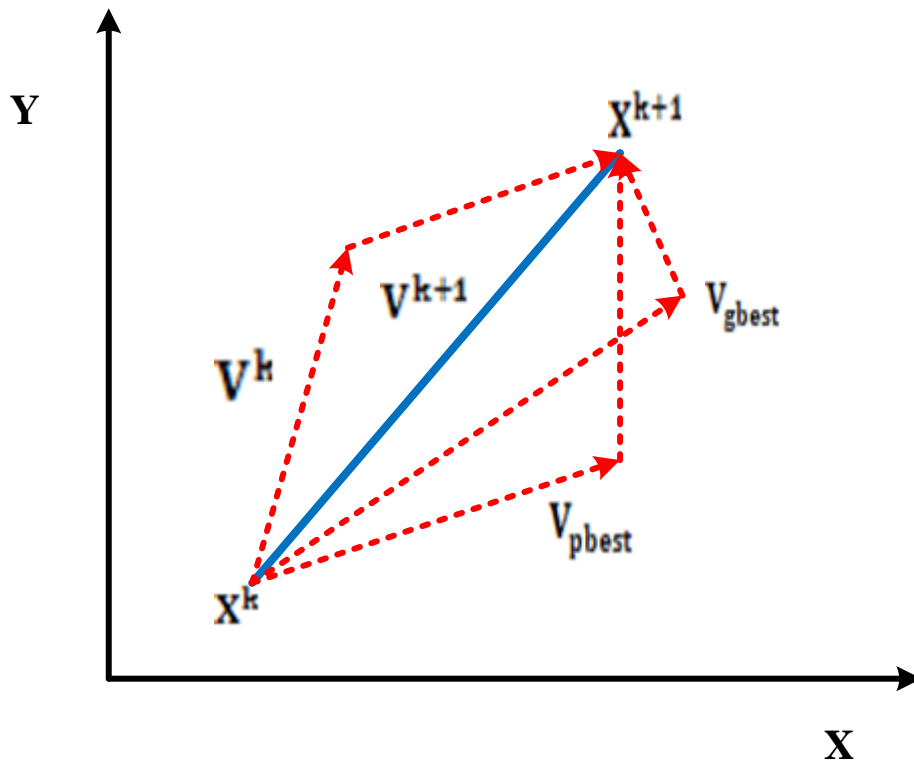


Figure 3-5:-Searching point in solution space [55]

Memory, inertia and co-operation are the main determinant factors which affect the movement of the particle. The particle movement causes new position and this is updated iteratively. By

beginning from the current position, the particle movement is affected by its best position found by itself in its life or best position obtained by other particle in their life.

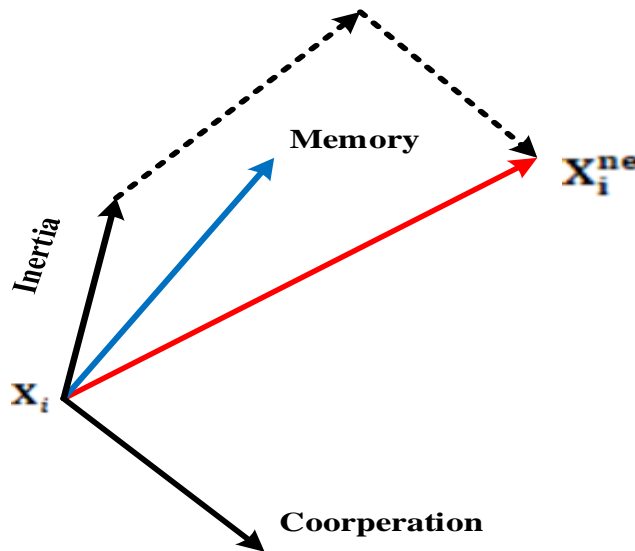


Figure 3-6:- Particle movement components [55]

- **PSO Algorithm Parameters**

In PSO optimization process, there are a lot of governing parameters and the speed of convergence performance and quality of the solution obtained is highly affected by these parameters. These parameters are discussed as follows;

**Population Size:** this determines the entire numbers of the particles in the search space. Increasing the number of the particles enables to address most part of the search space per iteration, but it also increases the computational complexity per iteration. It can also be possible that a larger number of particles may lead to a lesser number of iterations to obtain an optimal solution. However, it is also found that the optimal population size is usually problem dependent

**Random Numbers:** Attraction of the particles in the direction of pbest and gbest positions is monitored by adding random numbers in the update criteria [75]. These are random assumptions which determine the magnitude of random forces in the direction of the two best positions. They add a random component to the PSO algorithm and help prevent the algorithm from getting stuck at a non-optimal local minimum or maximum solution

**Acceleration Coefficients:** The acceleration coefficients,  $c_1$  and  $c_2$ , together with the random vectors  $r_1$  and  $r_2$ , control the stochastic influence of the cognitive and social components on the overall velocity of a particle. The constants  $c_1$  and  $c_2$  are also referred to as trust parameters, where  $c_1$  expresses how much confidence a particle has in itself, while  $c_2$  expresses how much confidence a particle has in its neighbors. Balancing the values of  $c_1$  and  $c_2$  are highly significant as incorrect values of  $c_1$  and  $c_2$  can lead to divergent and repeating behavior of the entire particle.

**Inertia Weight:** the swarm global and local exploration and the exploitation capacity are controlled by this parameter and also influence the previous velocity on the particle's current movement. The proper value of this parameter enables to obtain the optimal solution at a fewer iteration. To make at equilibrium the global and local search and to confirm the convergence to optimal solution in a small number of iterations, an adjustment in the value of this parameter is extremely important. Therefore, higher values of this parameter facilitate the global exploration while a lesser values promote the local exploitation. Hence, the value of the inertia this parameter is usually decreased linearly from the maximum value of 0.9 to the minimum value of 0.4

**Number of iterations:** similarly to swarm size parameter, the number of iterations is dependent on problem in order to get best results in the particle swarm optimization (PSO) algorithm. On contrary, having small number of iterations may lead for early stoppage of the search process. And hence, having a higher number of iterations can add to the computational complexity in obtaining a quality solution, if the termination criterion depends on a number of iterations.

### **Procedure for Implementation of Particle Swarm Optimization**

PSO required varies pre-processing steps before the actual identification and the main steps that are followed to achieve identification are discussed as follows [7];

- **Step 1:** under this step all PSO parameters such as maximum number of particle, dimension of the search space, correction factors, inertia, random variables and the current fitness function are initialized. And also, the swarm velocities and its positions are initialized at this step. Current position is defined and the local best position is calculated.

- **Step 2:** on this step the current personal fitness value of the particles are calculated and the result will be compared with previous values. And if the current value of Pbest is better than previous value, the current Pbest is recognized as best if not the previous value is kept as Pbest value.
- **Step 3:** on this step the best position's fitness value (Pbest ) will be assigned to the global best (gbest).
- **Step-4:-** while max iter > iter
- **Step 5:** Update swarm velocity
- **Step 6:** Update the position of each particle

### **Advantage and Disadvantages of PSO Technique**

The PSO algorithm used in various optimization problems has certain advantages and disadvantages given below [75];

#### **Advantages of PSO algorithm**

- Transformation calculation or preference operation does not incorporated in PSO algorithm
- Through changing the speed of the particle, frequently search can be computed.
- By sharing the experience from the group, the particles move only to the direction where the food is possibly found.
- By learning from group's experiences, particles fly only to good areas (where there is a possibility of finding food).
- PSO algorithm is based on artificial intelligence and thus, can be applied into both scientific research and engineering applications.
- Simple calculations are involved in PSO algorithm and with development of newer evaluation techniques they are be done easily.

#### **Disadvantages of PSO**

- Due to increasing of search space dimension, the PSO suffers from a substantial rise in search complexity.
- The method is weak to partial optimism, which leads to a much less accurate regulation of its speed and the direction.

- Due to the lack of dimensionality, this technique cannot be used for problems of non-coordinate system, such as the solution to the energy field and the moving rules of the particles in the energy field

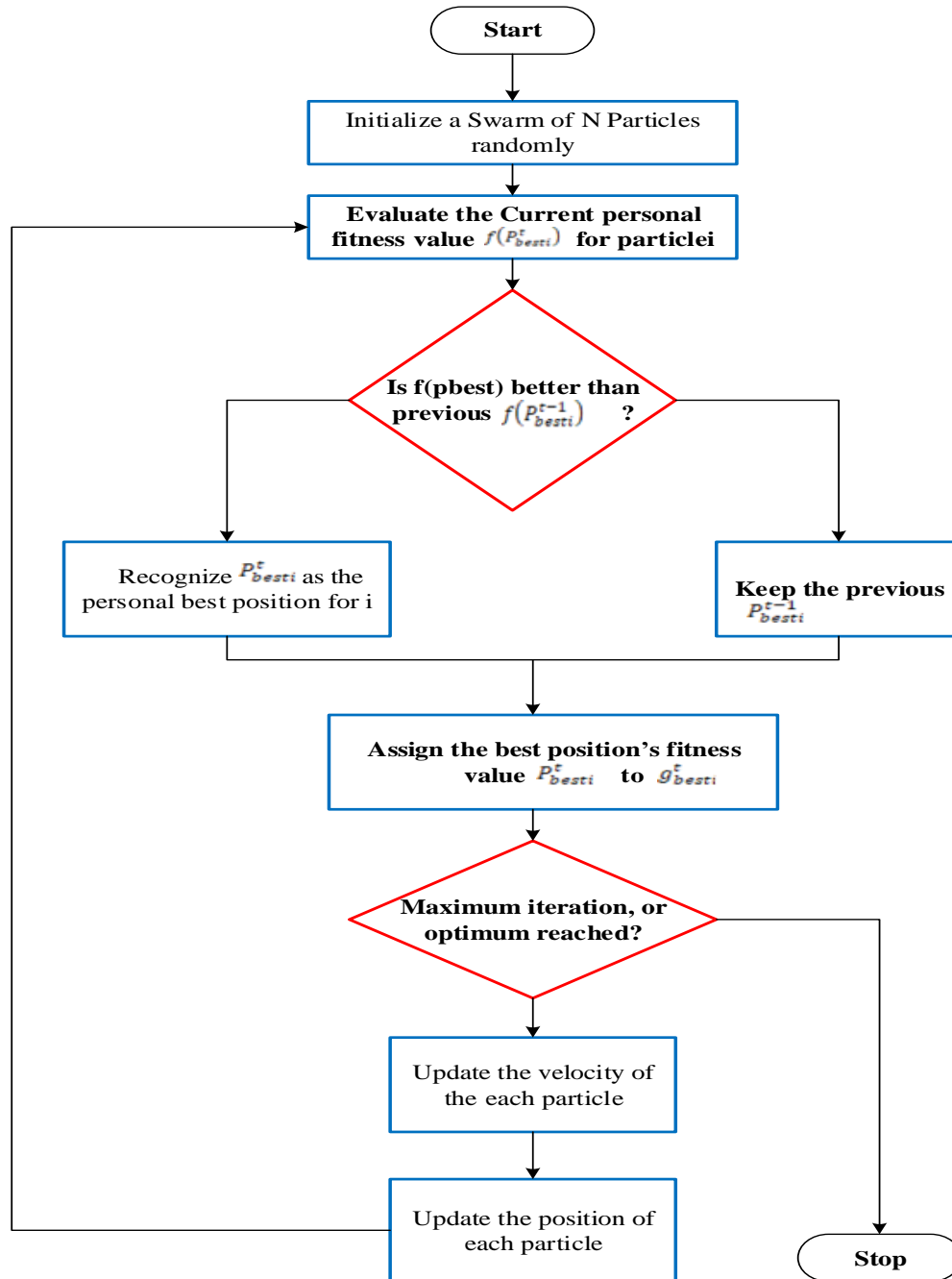


Figure 3-7:-PSO Algorithm Flow Charts

### 3.5 Performance Enhancement of Distribution System Using FACTS Devices

The performance of radial distribution system can be enhanced using different Flexible AC Transmission System (FACTS) devices and this has been investigated by different researcher at different time. In this thesis project comparative studies of DSTATCOM, SVC and UPQC devices for power loss minimization and voltage profile improvement performance of radial distribution system has been analyzed taking Sebbata-I substation 15 kV outgoing feeder-12 as test system. Accordingly, the basic working principles and mathematical modeling of DSTATCOM, SVC and UPQC devices has been discussed in the following sections.

#### 3.5.1 Distribution Static Synchronous Compensator (DSTATCOM)

DSTATCOM controller is a shunt connected devices and mainly integrated to the distribution network with an objective of supplying shunt power compensation. It has a fast response time to inject the current in quadrature to the system so that the performance of the distribution network will be enhanced. With the help of principle of self-commutation techniques, it operation is controlled with transformers and power electronics switching devices incorporated together.

##### 3.5.1.1 Mathematical Modeling of DSTATCOM

With installation of DSTATCOM at a particular nod of the distribution network system, the required reactive power can be injected or absorbed to or from the system based on the voltage level of the system. Let us consider the line connected between two consecutive nodes of node  $i$  and  $i+1$  for installation of this controller for radially configured system as shown in the figure below [38][39];

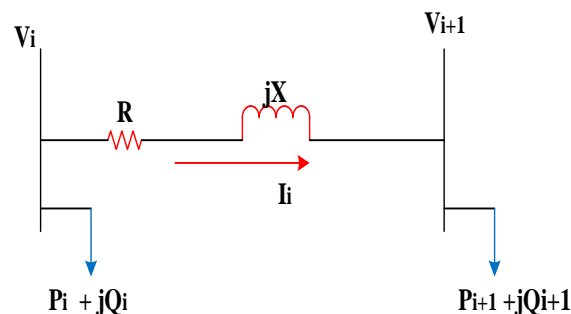


Figure 3-8:- Single line diagram of two consecutive nodes of a distribution system

The above single line diagram phasor diagram is expressed as:

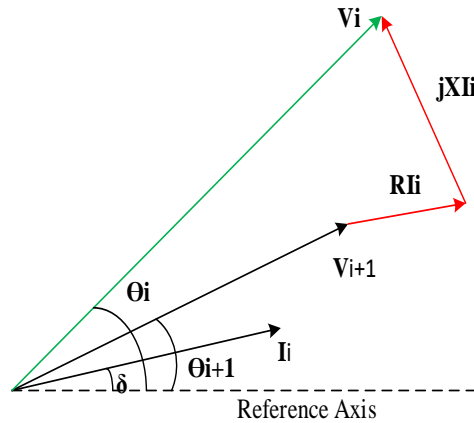


Figure 3-9:-Phasor diagram of voltage and current of the system shown in Fig. 2.8

By applying the KVL (Kirchhoff’s voltage law) equation, the voltage at the receiving end can be calculated as;

$$V_{i+1} < \theta_{i+1} = V_i < \theta_i - (R + jX)I_i < \delta \tag{3.7}$$

In Eq. (3.7),  $R + j X$  is the line impedance between two nodes,  $V_i$  is the voltage at the  $i^{\text{th}}$  node,  $\theta_i$  is the phase angle of  $V_i$ ,  $I_i$  is the line current between the two nodes  $i$  and  $i+1$ , and  $\delta$  is the phase angle of  $I_i$ .  $P_i$  and  $Q_i$  are the active and reactive power loads at node  $i$ .

Now, assume that DSTATCOM controller is installed at a nod  $i+1$  and its modeling can be developed as shown in the figure below:

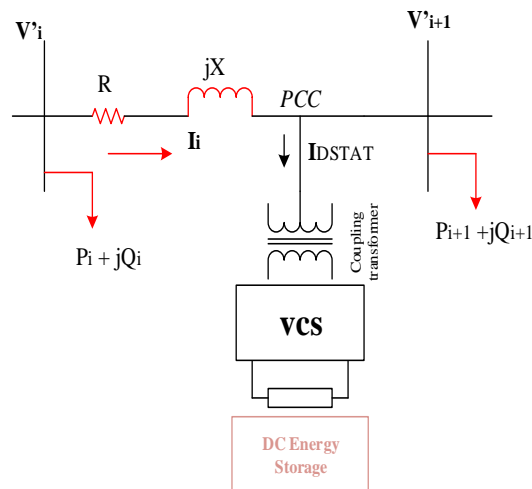


Figure 3-10:- Single line diagram of two buses with DSTATCOM Consideration

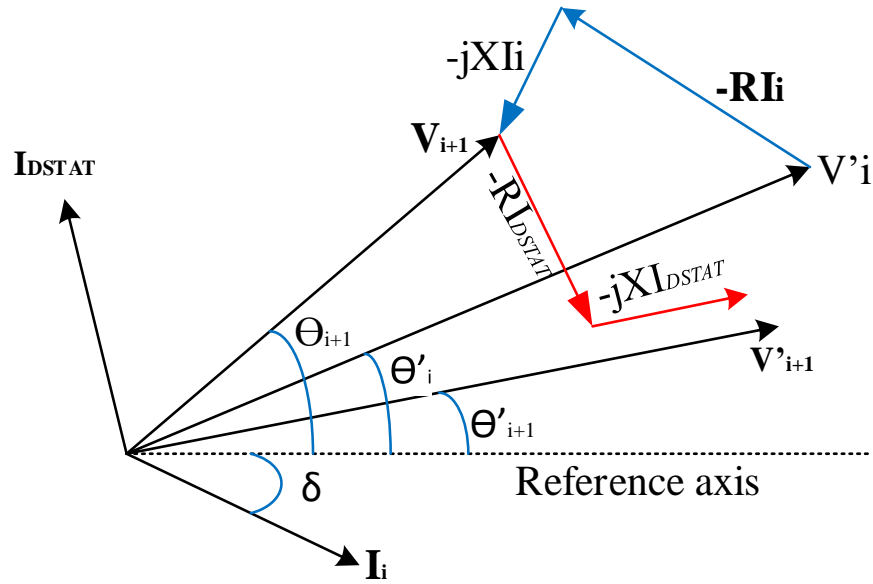


Figure 3-11:-Phasor diagram of fig. 3-10

The KVL of single line diagram after the placement of DSTATCOM is shown in Eq. (3.8)

$$V'_i < \theta'_i = V'_{i+1} < \theta'_{i+1} + (R + jX) \left( I_i < \delta + I_{DSTAT} < \left( \frac{\pi}{2} + \theta'_{i+1} \right) \right) \quad (3.8)$$

The respective phase diagram representation of equation (3.8) has been shown in figure 3-11 and with installation of DSTATCOM controller at node i+1 the previous voltage  $V_{i+1}$  changed to  $V'_{i+1}$  due to the current injected by this controller at quadrature phase angle. Therefore, equation (3.8) represents the main idea of the modeling of DSTATCOM device and by splitting the real and imaginary terms, it can be expressed as follows;

Real Part:

$$\begin{aligned} I_{DSTAT} \cos (\theta'_{i+1} + 90^0) & \quad (3.9) \\ & = \left( \frac{V_i R \cos \theta'_i}{R^2 + X^2} + \frac{V'_i X \sin \theta'_i}{R^2 + X^2} - \frac{V'_{i+1} R \cos \theta'_{i+1}}{R^2 + X^2} \right. \\ & \quad \left. - \frac{V'_{i+1} X \sin \theta'_{i+1}}{R^2 + X^2} - I_i \cos \delta \right) \end{aligned}$$

Imaginary part:

$$\begin{aligned}
 & j(I_{DSTAT} \sin(\theta'_{i+1} + 90^\circ)) \quad (3.10) \\
 & = \left( \frac{V'_i R \sin \theta'_i}{R^2 + X^2} - \frac{V'_i X \cos \theta'_i}{R^2 + X^2} - \frac{V'_{i+1} R \sin \theta'_{i+1}}{R^2 + X^2} \right. \\
 & \quad \left. + \frac{V'_{i+1} X \cos \theta'_{i+1}}{R^2 + X^2} - I_i \sin \delta \right)
 \end{aligned}$$

Let,

$$\begin{aligned}
 A &= \frac{V'_i R}{R^2 + X^2}, B = \frac{V'_i X}{R^2 + X^2}, C = \frac{V'_{i+1} R}{R^2 + X^2}, D = \frac{V'_{i+1} X}{R^2 + X^2}, \quad (3.11) \\
 E &= I_{DSTAT}, \quad \alpha = \theta'_{i+1} + 90^\circ, \beta = I_i
 \end{aligned}$$

Hence, by substituting the above assumptions to Eq. (3.9) and Eq. (3.10) and the magnitude of the current injected by the DSTATCOM devices can be calculated as follows;

$$I_{DSTAT} = \frac{[K_1 \sin((\theta'_i - \delta) - \varphi)] + K_2}{\sin(\theta'_{i+1} + \delta)} \quad (3.12)$$

Where

$$K_1 = \sqrt{A^2 + B^2} = \frac{V'_i}{\sqrt{R^2 + X^2}} \quad (3.13)$$

$$K_2 = A \sin(\theta'_{i+1} + \delta) + B \cos(\theta'_{i+1} - \delta)$$

$\varphi$  is a unique angle satisfying the following conditions:

- i.  $-\pi < \varphi < \pi$ ,
- ii.  $\tan \varphi = \frac{B}{A} = \frac{X}{R} = \frac{D}{C}$ , Since  $B \neq 0, A \neq 0, D \neq 0, C \neq 0$

And finally, the reactive power which can be injected by the DSTATCOM device for compensating the system at the point of installation can be calculated as follow;

$$Q_{DSTAT} = \text{Img} (V'_{i+1} \cdot I_{DSTAT}^*) \quad (3.14)$$

The symbol ‘\*’ in Eq. (3.14) designates the complex conjugate. The  $I_{DSTAT}$  is decided by the variables  $K_1, K_2, (\theta'_i), (\theta'_{i+1}), \varphi$ , and  $\delta$  and its value is dependent on the location of the DSTATCOM. The power loss to be reduced is affected by the phase angle  $(\theta'_{i+1})$ , it has been considered as an optimal variable. Except the optimal variable, all variable value is calculated forward-backward power flow analysis [38].

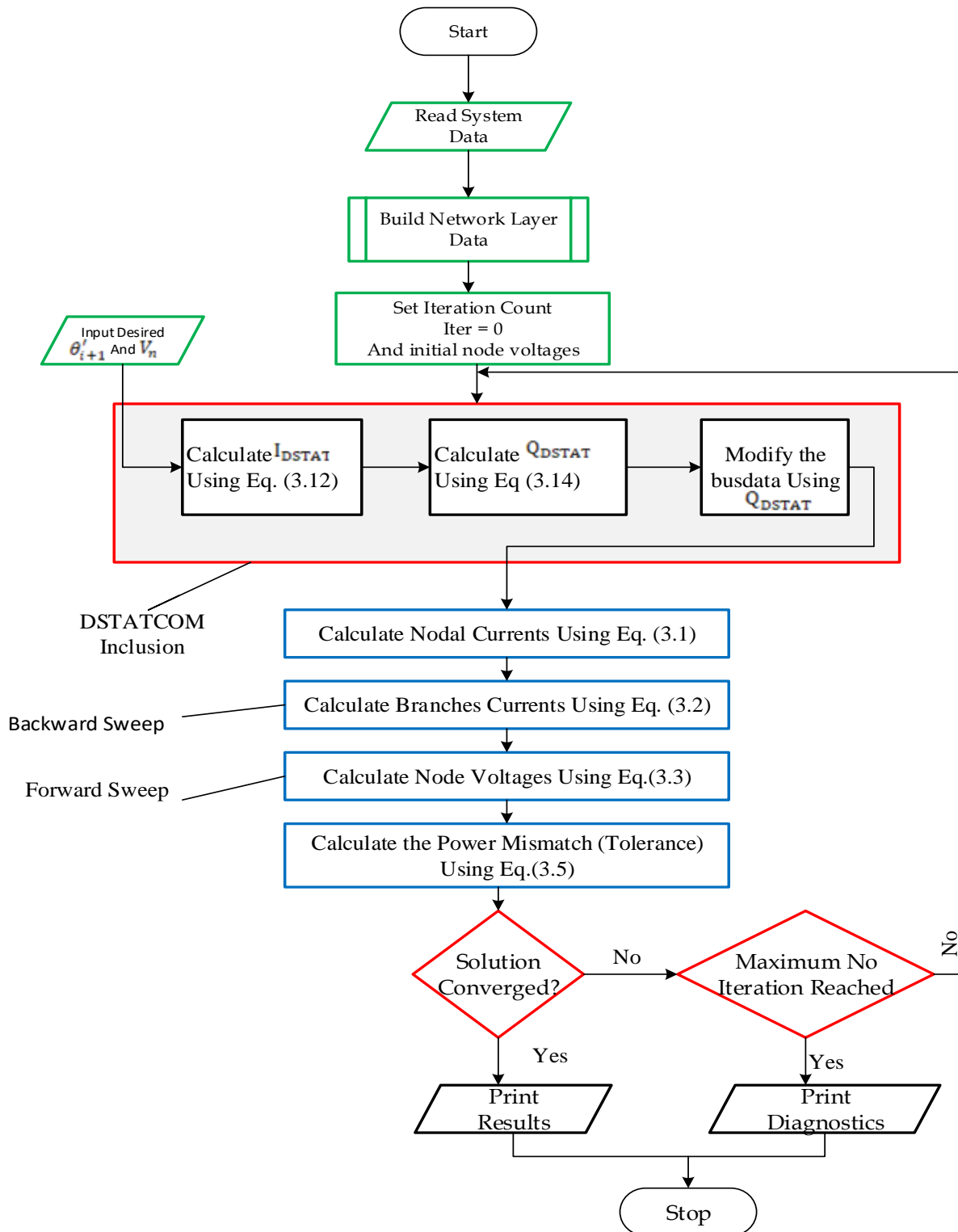


Figure 3-12:- Forward backward sweep algorithm flow chart with installation of DSTATCOM

### 3.5.2 Static VAR Compensators (SVC)

Static VAR Compensator (SVC) is a shunt connected FACTS controller whose main functionality is to regulate the voltage at a given bus by controlling its equivalent reactance. The basic components of SVC are shunt capacitors and reactors. The amounts of these components are varied with thyristor switching [55]. The popular types of SVC are thyristor controlled reactor (TCR), thyristor switched capacitor (TSC), and TSC with TCR. A TCR is employed in combination with a TSC when reactive power generation or absorption is required. This is usually the optimum solution for sub-transmission and distribution networks to improve voltage profile [56]

#### 3.5.2.1 Mathematical Model of Static VAR Compensators (SVC)

Generally they are two configurations of the SVC for application [46]

- i. **SVC total susceptance model**:- A changing susceptance ( $B_{svc}$ ) represents the fundamental frequency equivalent susceptance of all shunt modules making up the SVC as shown in Fig. 3-13 (b).
- ii. **SVC firing angle model**:- The equivalent reactance  $X_{svc}$ , which is function of a changing firing angle  $\alpha$ , is made up of the parallel combination of a thyristor controlled reactor (TCR) equivalent admittance and a fixed capacitive reactance as shown in Fig. 3-13 (a). This model provides information on the SVC firing angle required to achieve a given level of compensation.

The SVC's general circuit structure is demonstrated in Figure 3-13 (a) (b) [46].

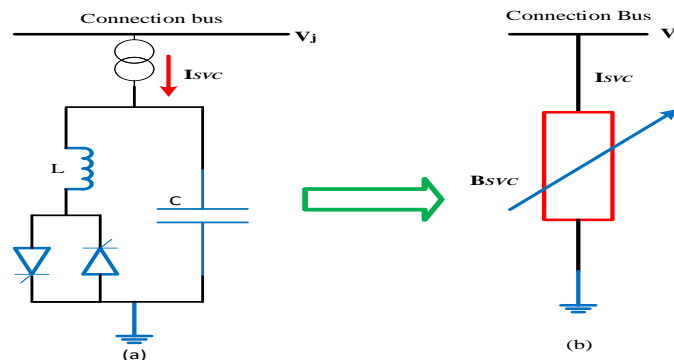


Figure 3-13:- (a) SVC firing angle Model (b) SVC total susceptance model [48]

SVC firing angle model is implemented in this thesis project. Thus, the model can be developed with respect to a sinusoidal voltage, differential and algebraic equations can be written as follows [45], [46]

The fundamental frequency TCR equivalent reactance  $X_{TCR}$

$$X_{TCR} = \frac{\pi X_L}{\sigma - \sin \sigma} \quad (3.15)$$

Where

$$\sigma = 2(\pi - \alpha), \quad X_L = \omega L$$

And in terms of firing angle

$$X_{TCR} = \frac{\pi X_L}{2(\pi - \alpha) + \sin(2\alpha)} \quad (3.16)$$

Where  $\sigma$  and  $\alpha$  are conduction and firing angles respectively

At  $\alpha = 90^\circ$ , TCR conducts fully and the equivalent reactance  $X_{TCR}$  becomes  $X_L$ , while at  $\alpha = 180^\circ$ , TCR is blocked and its equivalent reactance becomes infinite.

The SVC effective reactance  $X_{SVC}$  is determined by the parallel combination of  $X_C$  and  $X_{TCR}$

$$X_{SVC} = \frac{\pi X_C X_L}{X_C [2(\pi - \alpha) + \sin 2\alpha] - \pi X_L} = X_{eq} \quad (3.17)$$

Where  $X_C = 1/\omega C$  and  $X_C, X_L$  are the capacitance and reactance of SVC, respectively

The susceptance of SVC can be given [57]

$$B_{eq} = \frac{1}{X_{eq}} = B_{DSVC} \quad (3.18)$$

The reactive power and current controlled by the SVC device represented by the following equations;

$$Q_{DSVC} = -B_{DSVC} \times V_j^2 \quad (3.19)$$

$$Q_{DSVC} = -V_j^2 \left\{ \frac{X_C [2(\pi - \alpha) + \sin 2\alpha] - \pi X_L}{\pi X_C X_L} \right\} \quad (3.20)$$

$$I_{DSVC} = -j B_{DSVC} \cdot V_j \quad (3.21)$$

Where  $V_j$  is the value of voltage in node j

When the load of the system is capacitive, the SVC utilizes thyristor-controlled coils to consume  $Q_{SVC}$ , otherwise, when the load of the system is inductive which is predominantly, the

SVC utilizes the parallel-coupled capacitors and delivers  $Q_{SVC}$ . The acceptable limits of SVCs are also included in the formulated problem as a reactive power (inductive or capacitive) function [48]:

$$-Q_{SVC}^{max} \leq Q_{SVC} \leq +Q_{SVC}^{max} \quad (3.22)$$

Where,  $-Q_{SVC}^{max}$  max and  $+Q_{SVC}^{max}$  are the injected reactive power limits (inductive and capacitive operation modes) of the SVCs, respectively

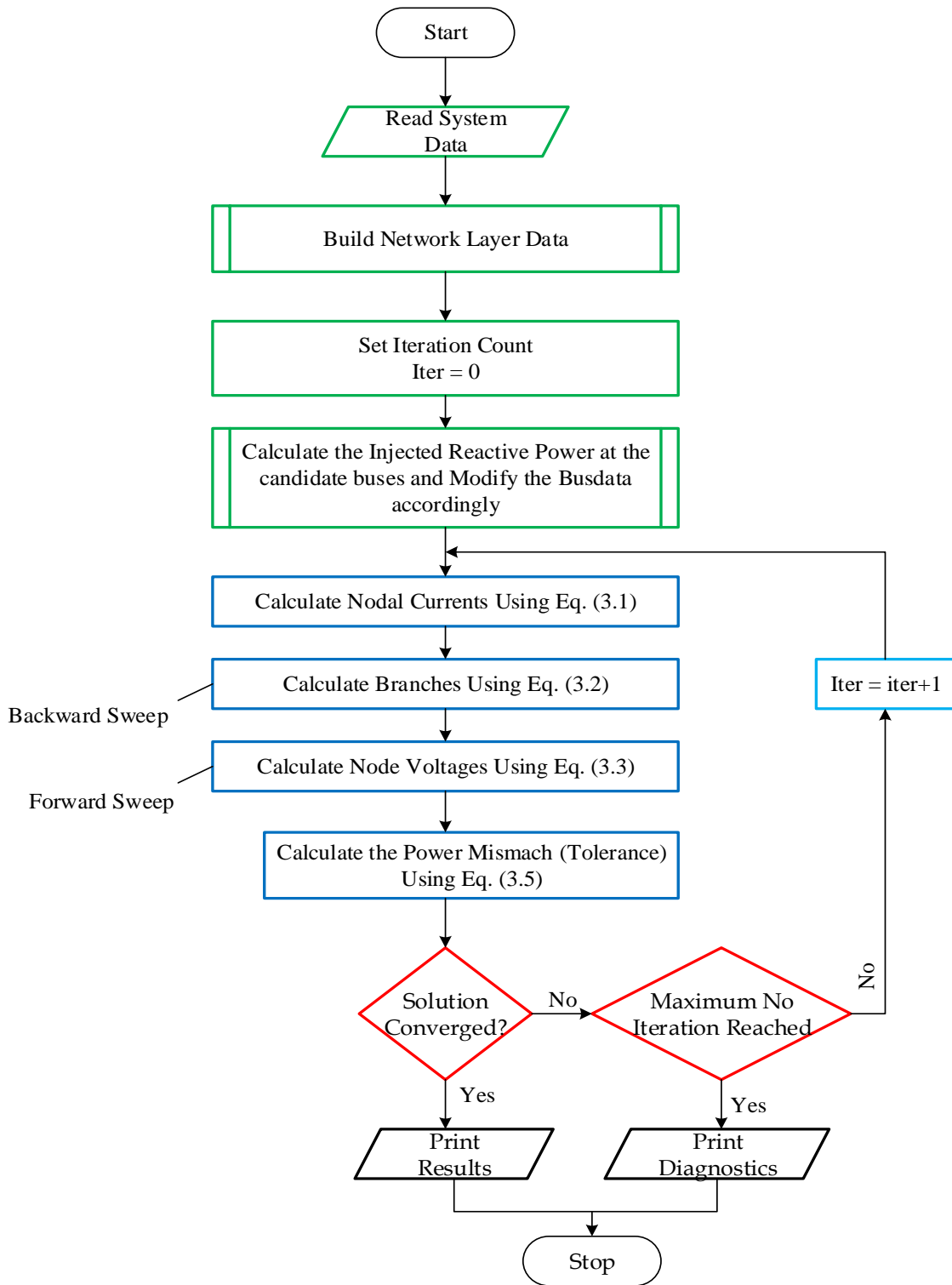


Figure 3-14:- Forward backward sweep algorithm flow chart with installation of SVC

### 3.5.3 Unified Power Quality Conditioner (UPQC)

This type device has both series and shunt connected FACTS controllers. The load-reactive power compensation in most of the UPQC based power quality compensation application is done by the shunt connected device, whereas, the series connected controller is generally utilized to compensate voltage related problems [49]. Therefore, the utilization factor of the shunt connected devices is higher than the series connected device because in distribution system the voltage related problems are occurred for short duration while the load-reactive power demand of a system is directly load dependent and constant for a particular type of load.

By creating an angle difference between the sending end (Source voltage) and receiving end voltage (Load voltage) keeping their magnitude equal, it enables the series connected controller to share the burden of the shunt connected controller, and thus its rating will be reduced.

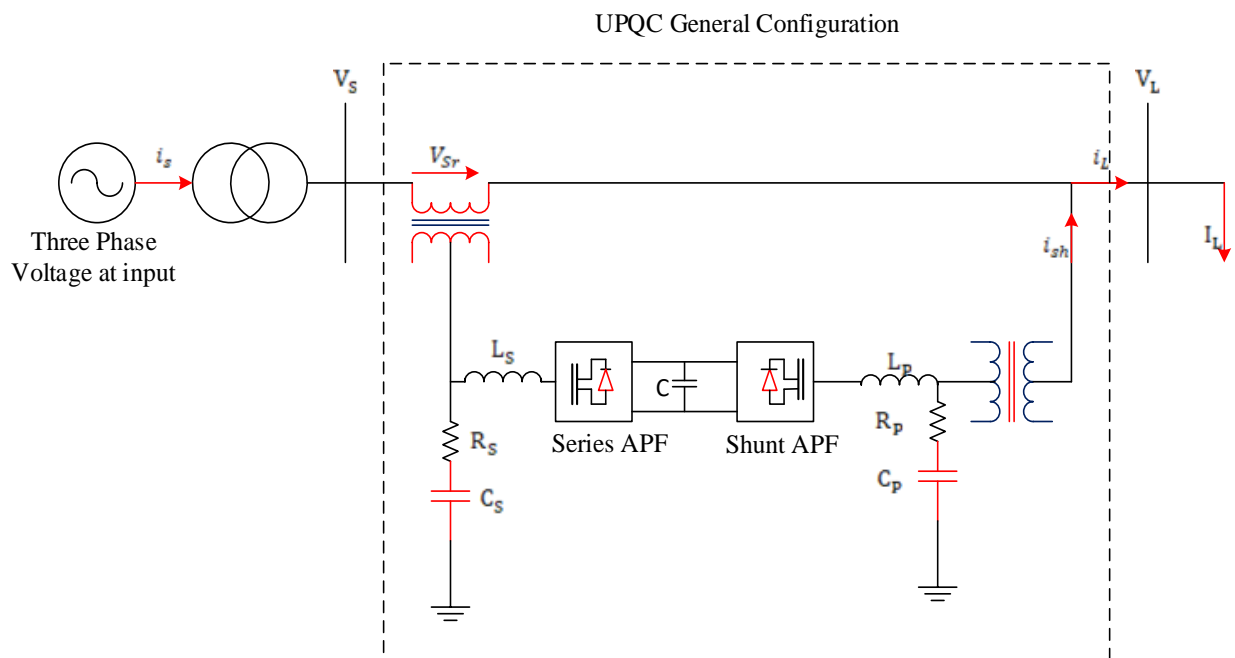


Figure 3-15:- Basic UPQC based system configuration [49]

So, due injection of the series voltage at angle different of  $90^0$  (not in quadrature), the source current will cause a phase angle difference with load current without changing resultant load voltage magnitude and as a result, required amount of active as well as reactive power would flow through series controller.

Assuming that the system is balanced and harmonic free at normal working condition, the sending and receiving end voltage magnitude is equal, the phasor diagram is depicted as follows;

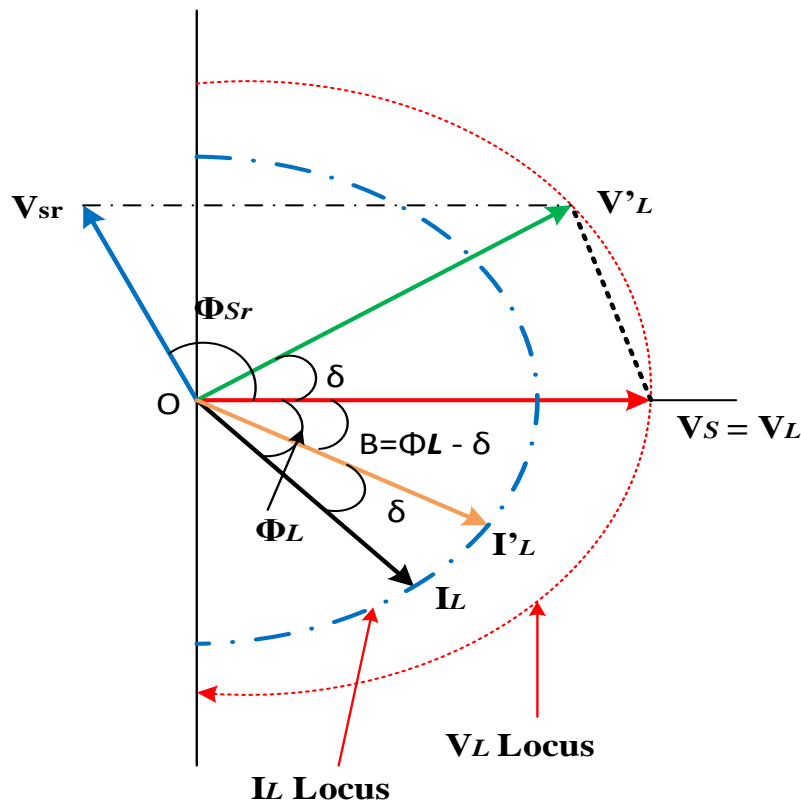


Figure 3-16:-UPQC (S) type Phasor representation [49]

Hence, the series controller shall inject the voltage  $V_{sr}$  such that the magnitude of the  $V'_L$  will be at the desired load voltage giving  $\delta$  power angle difference. This causes the load current phasor advancement from  $I_L$  to  $I'_L$  maintaining the same load phase angle  $\phi_L$  relationship with load voltage i.e  $\phi_L$  boost to  $\beta$ , this enable the series controller to generate required amount of reactive power. Accordingly, both the series and shunt connected controllers will take part on load-reactive power compensation.

In order to estimate the series controller to supply the needed voltage, considering 'k' as rms value of the load voltage desired and representing with k, the series injected voltage magnitude and phase angle can be estimated as follow;

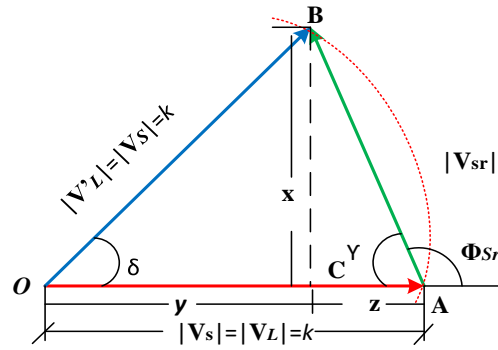


Figure 3-17:-Determination of  $V_{Sr}$  and  $\phi_{Sr}$  [49]

$$\sin\delta = \frac{x}{k} \quad (3.23)$$

$$x = k \cdot \sin\delta \quad (3.24)$$

$$y = k \cdot \cos\delta \quad (3.25)$$

From isosceles triangle OAB in the figure 3-17 above, z can be calculated as follow;

$$OA = k = y + z \quad (3.26)$$

$$z = k - k \cdot \cos\delta \quad (3.27)$$

$$z = k \cdot (1 - \cos\delta) \quad (3.28)$$

Similarly from the triangle ABC of figure 3-17 above, the magnitude of  $V_{Sr}$  can be calculated as follows;

$$|V_{Sr}| = \sqrt{x^2 + z^2} \quad (3.29)$$

$$|V_{Sr}| = \sqrt{\left((k \cdot \sin\delta)^2 + (k \cdot (1 - \cos\delta))^2\right)} \quad (3.30)$$

$$|V_{Sr}| = k \cdot \sqrt{\sin^2\delta + (1 - \cos\delta)^2} \quad (3.31)$$

$$|V_{Sr}| = k \cdot \sqrt{\sin^2\delta + 1 - 2\cos\delta + \cos^2\delta} \quad (3.32)$$

$$|V_{Sr}| = k \cdot \sqrt{2 - 2\cos\delta} \quad (3.33)$$

$$|V_{Sr}| = k \cdot \sqrt{2} \cdot \sqrt{1 - \cos\delta} \quad (3.34)$$

Now, the angle  $\angle CAB$  is calculated as:

$$\angle CAB = \gamma = \tan^{-1}\left(\frac{x}{z}\right) \quad (3.35)$$

$$\gamma = \tan^{-1} \left( \frac{k \cdot \sin \delta}{K(1 - \cos \delta)} \right) \quad (3.36)$$

$$\gamma = \tan^{-1} \left( \frac{\sin \delta}{1 - \cos \delta} \right) \quad (3.37)$$

$$\angle \phi_{Sr} = 180 - \angle \gamma \quad (3.38)$$

Therefore, the series controller shall inject a voltage having a magnitude of  $|V_{Sr}|$  at a phase angle of  $\angle \phi_{Sr}$  in order to attain the desired load voltage. Both magnitude and angle are dependent on the angle  $\delta$ .

Likewise, in order to determine the compensating current injected by the shunt controller under this condition, the current phasor representation due to introducing of angle  $\delta$  will be considered and its magnitude and phase angle can be estimated as follows;

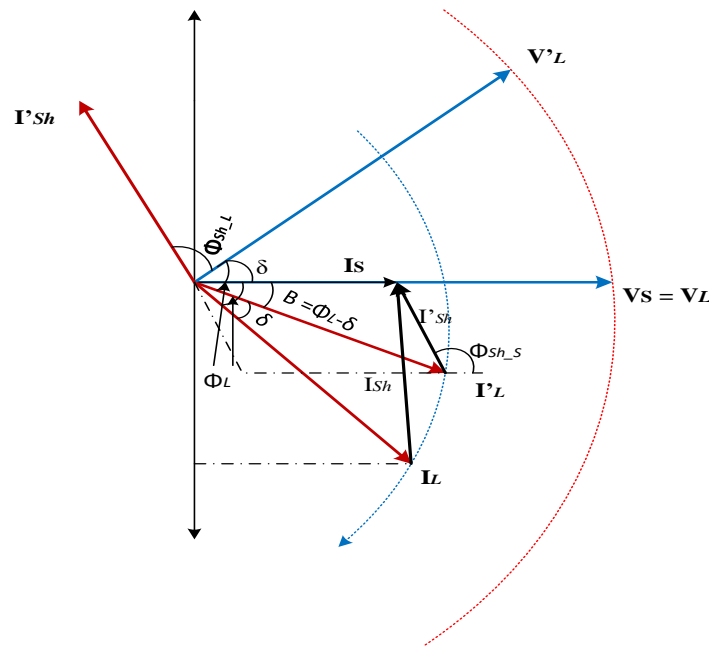


Figure 3-18:- PAC: current phasor representation [49]

Considering only the load current advancement from  $I_L$  to  $I'_L$  and detailed parameter estimation of the shunt compensating current ( $I'_{sh}$ ) and its phase angle ( $\phi'_{shL}$ ) can be calculated as follows;

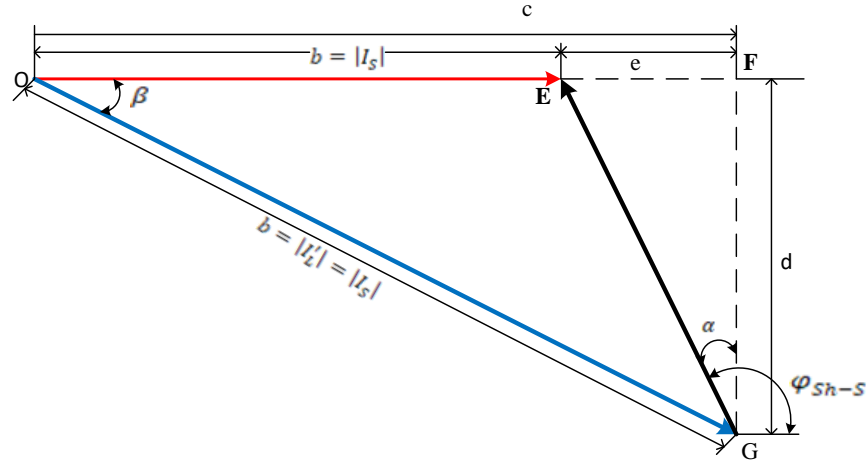


Figure 3-19:-Determination of  $I'_{sh}$  and  $\phi'_{sh-s}$  [49]

$$\beta = \phi_L - \delta \quad (3.39)$$

By considering the triangle OGF in the figure above, the magnitude and phase angle of the current injected by the shunt controller can be estimated as follow;

$$\cos\beta = \frac{OF}{OG} \quad (3.40)$$

$$OF = c = |I'_L|. \cos\beta \quad (3.41)$$

$$GF = d = |I'_L|. \sin\beta \quad (3.42)$$

$$EF = e = |I'_L|. \cos\beta - |I_s| \quad (3.43)$$

$$EF = e = |I'_L| \cos\beta - |I_L|. \cos\phi_L \quad (3.44)$$

$$EF = e = |I'_L| [\cos\beta - \cos\phi_L] \quad (3.45)$$

$$|I'_{sh}| = EG = \sqrt{e^2 + d^2} \quad (3.46)$$

$$|I'_{sh}| = \sqrt{\{|I'_L|. [\cos\beta - \cos\phi_L]\}^2 + \{|I'_L|. \sin\beta\}^2} \quad (3.47)$$

$$|I'_{sh}| = |I'_L|. \sqrt{1 + \cos^2\phi_L - 2. \cos\beta. \cos\phi_L} \quad (3.48)$$

$$\tan \alpha = \frac{e}{d} \quad (3.49)$$

$$\alpha = \tan^{-1} \left( \frac{|I'_L|. [\cos\beta - \cos\phi_L]}{|I'_L|. \sin\beta} \right) \quad (3.50)$$

$$\alpha = \tan^{-1} \left( \frac{\cos\beta - \cos\phi_L}{\sin\beta} \right) \quad (3.51)$$

$$\angle \phi'_{Sh-S} = \angle \alpha + 90^\circ \quad (3.52)$$

$$\angle \phi'_{Sh-L} = \angle \alpha + 90^\circ - \delta \quad (3.53)$$

Therefore, the current magnitude and phase angle which shall be injected by the shunt controller to compensate the load can be estimated using equations (3.48) and (3.53) where these parameters again dependent on the angle  $\delta$

Thus, the net reduction in  $I_{Sh}$  magnitude is:

$$I_{Sh} \text{ Magnitude} = |I_{Sh}| - |I'_{Sh}| \quad (3.54)$$

The upper and lower boundaries of the angle  $\delta$  of the can be determined as follows;

$$V_{Series\_APF} = V_{sr\_max} \cdot I_S^* \quad (3.55)$$

By substituting the  $V_{sr\_max}$  from equation (3.34),  $\delta_{max}$  can be estimated as follows;

$$|V_{sr\_max}| = k \cdot \sqrt{2} \cdot \sqrt{1 - \cos \delta_{max}} \quad (3.56)$$

$$K_{Sr} \cdot k = k \cdot \sqrt{2} \cdot \sqrt{1 - \cos \delta_{max}} \quad (3.57)$$

$$K_{Sr} = \sqrt{2} \cdot \sqrt{1 - \cos \delta_{max}} \quad (3.58)$$

$$\delta_{max} = \cos^{-1} \left( 1 - \frac{K_{Sr}^2}{2} \right) \quad (3.59)$$

Therefore, the maximum  $\delta_{max}$  is the maximum bounder for the series controller of the UPQC device so as to perform its proper function of compensating the load reactive demand.

Now, the series controller of the UPQC devices real and reactive power can be determined as follows

Series controller real and reactive power flow:

$$P_{Sr} = V_{Sr} \cdot I_S \cdot \cos \phi_{Sr} \quad (3.60)$$

$$P_{Sr} = I_S \cdot k \cdot \sqrt{2} \sqrt{1 - \cos \delta} \cdot \cos \phi_{Sr} \quad (3.61)$$

$$P_{Sr} = \sqrt{2} I_S \cdot k \cdot \sqrt{1 - \cos \delta} \cdot \cos(180^\circ - \gamma) \quad (3.62)$$

$$P_{Sr} = -\sqrt{2} \cdot I_S \cdot k \cdot \sqrt{1 - \cos \delta} \cdot \cos \gamma \quad (3.63)$$

$$P_{Sr} = -\sqrt{2} \cdot I_S \cdot k \cdot \sqrt{1 - \cos \delta} \cdot \frac{\sqrt{1 - \cos \delta}}{\sqrt{2}} \quad (3.64)$$

$$P_{Sr} = -I_S \cdot k \cdot (1 - \cos\delta) \quad (3.65)$$

In the equation above, the negative sign implies that the series controller of UPQC consumes some amount of real power.

And also, the reactive power flows through the series controller is:

$$Q_{Sr} = \sqrt{2} \cdot I_S \cdot k \cdot \sqrt{1 - \cos\delta} \cdot \sin(180^\circ - \gamma) \quad (3.66)$$

$$Q_{Sr} = \sqrt{2} \cdot I_S \cdot k \cdot \sqrt{1 - \cos\delta} \cdot \sin\gamma \quad (3.67)$$

$$Q_{Sr} = \sqrt{2} \cdot I_S \cdot k \cdot \sqrt{1 - \cos\delta} \cdot \frac{\sin\delta}{\sqrt{2} \cdot \sqrt{1 - \cos\delta}} \quad (3.68)$$

$$Q_{Sr} = I_S \cdot k \cdot \sin\delta \quad (3.69)$$

From (3.69), the reactive power generated by series APF mainly depends on the power angle  $\delta$ . The higher the value of  $\delta$ , the higher will be the reactive power compensation through series connected controller, but at the same time higher will be the magnitude of series injected voltage by (3.34)

Similarly the real and reactive power of the shunt controller is determined as follows; reactive power flow:

$$P'_{Sh} = V'_L \cdot I'_{Sh} \cdot \cos\phi'_{Sh_L} = k \cdot \cos\phi'_{Sh_L} \cdot \sin\phi'_{Sh_L} \quad (3.70)$$

$$Q'_{Sh} = V'_L \cdot I'_{Sh} \cdot \sin\phi'_{Sh_L} = k \cdot I'_{Sh} \cdot \sin\phi'_{Sh_L} \quad (3.71)$$

$$Q_L = Q_{Sr} + Q'_{Sh} \quad (3.72)$$

Thus, the shunt controller only supply a maximum of reactive power to the load of  $Q_{Sh,max}$  and the remaining reactive power will be supplied by the series controller so that the operation of both series and shunt controllers do not be disturbed. As the load reactive demand increases beyond the  $Q_{Sh,max}$  it will be compensated with the series controller. Accordingly,

$$\begin{aligned} Q_{Sr} &= Q_{L,max} - Q_{Sh,max} \\ &= I_S \cdot k \cdot \sin\delta \end{aligned} \quad (3.73)$$

Therefore, the instantaneous value of  $\delta$  is calculated as follow;

$$\therefore \sin\delta = \frac{Q_{Sr}}{I_S \cdot k} \quad (3.74)$$

$$\sin\delta = \frac{Q_{sr}}{P_S} \quad (3.75)$$

$$\therefore \delta = \sin^{-1}\left(\frac{Q_{sr}}{P_S}\right) = \sin^{-1}\left(\frac{Q_{Sr}}{P_L}\right) \quad (3.76)$$

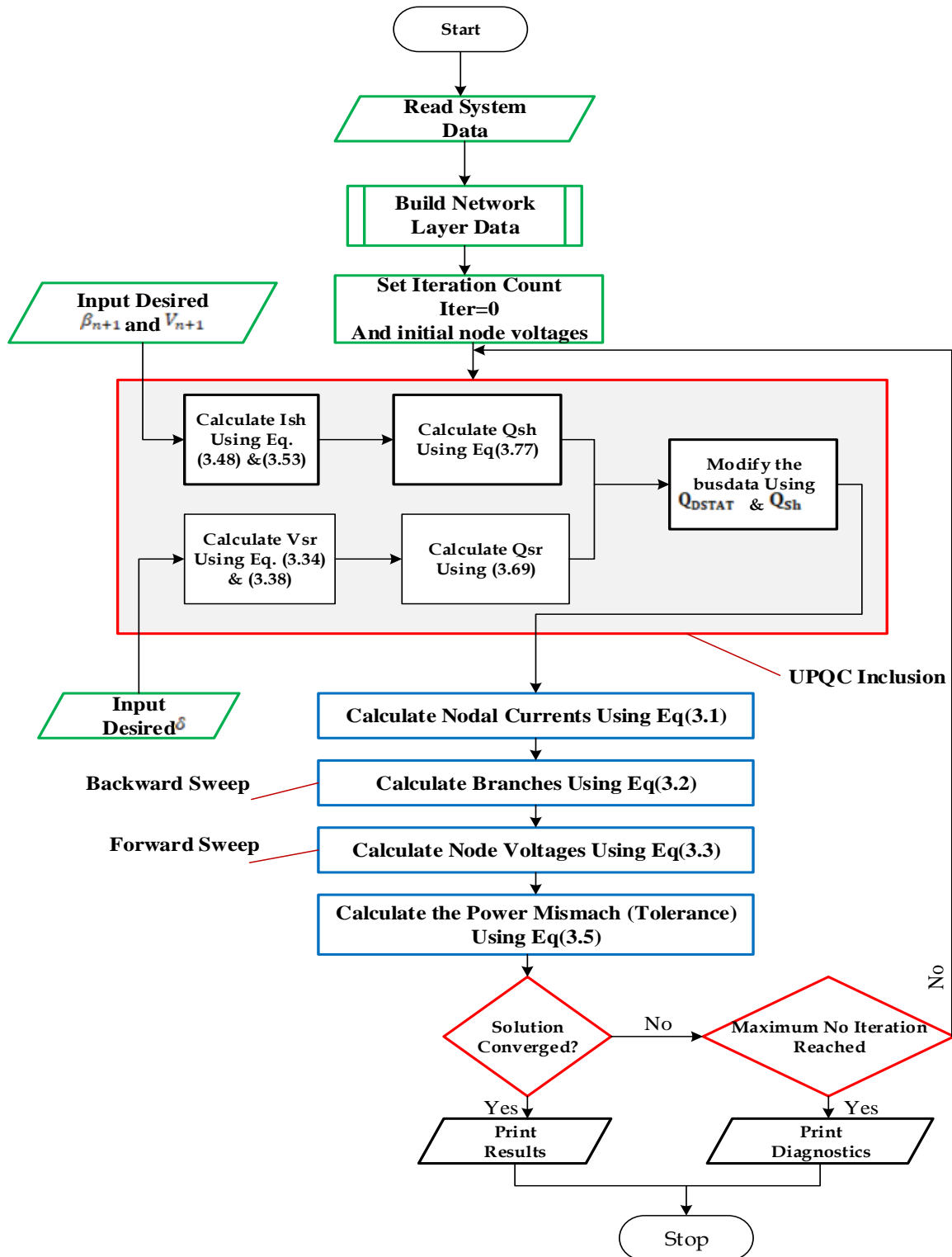


Figure 3-20:- Forward backward sweep algorithm flow chart with installation of UPQC

### 3.6 Optimal Sizing and Placing of FACTS Device

#### 3.6.1 Loss Sensitivity Index

There are different methods to find the candidate bus or weakest bus among all buses. In this thesis, power loss sensitivity index is used to identify the weakest candidate buses. By computing the loss sensitivity Index, its values are arranged in descending order and buses with highest value of Loss Sensitivity Index are chosen as candidate buses for installation of DSTATCOM, SVC and UPQC devices of selected feeder radial distribution system. To calculate Loss Sensitivity index the following single line diagram is used.

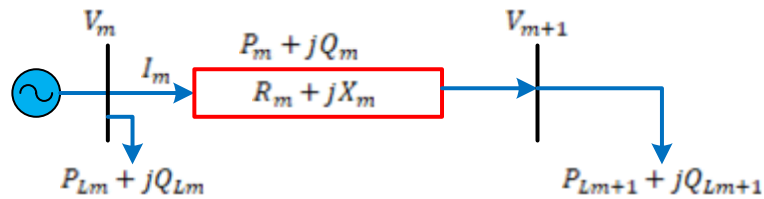


Figure 3-21:-Two-bus systems for LSI analysis

The voltage at node m+1 is given by

$$V_{m+1} = V_m + I_m * (R_m + jX_m) \quad (3.77)$$

And the branch current is calculated with the following equation'

The real and reactive power loss in the line section between buses m and m + 1 is calculated by using the following equation

$$P_{loss(m, m+1)} = \left( \frac{P_m^2 + Q_m^2}{|V_m|^2} \right) * R_m \quad (3.78)$$

$$Q_{loss(m, m+1)} = \left( \frac{P_m^2 + Q_m^2}{|V_m|^2} \right) * X_m \quad (3.79)$$

$$\text{Loss Sensitivity Index (LSI)} = \frac{\partial P_{loss(m,n)}}{\partial Q_{mn}} = \frac{2Q_{mn}R_{mn}}{|V_m|^2} \quad (3.80)$$

The LSI values are sorted in descending order for all the lines and the buses which have the higher value has more chance for selecting candidate location to install the FACTS Devices

### 3.6.2 Size and placement optimization process

This thesis aimed to reduce power loss and improve voltage profile of the distribution system and the optimization process for sizing and placing of the devices are as follows. First, based on the Loss Sensitivity Index (LSI) value the buses are sorted from worst (highest LSI) to best (lowest LSI). The user selects the number of candidate buses at which the FACTS devices are to be installed; in this case it is 5. Thus the 5 buses with the highest LSI (83, 36, 33, 81, and 54) will be chosen. Next, the PSO is initialized to search for the optimum value of the FACTS device size. The swarm size was initialized to 2000 and each particle has a dimension of 5 equal to the size of the candidate buses. The location of the particle  $i$ ,  $X_i^t$  at time step (iteration number  $t$ ) represents the possible value of the installed device parameter value at the five candidate buses [83, 36, 33, 81, and 54], i.e.

$$X_i^t = [X_{1i}^t, X_{2i}^t, X_{3i}^t, X_{4i}^t, X_{5i}^t] \quad (3.81)$$

For SVC,  $X$  represents the susceptance of the SVC at the respective bus, for DSTATCOM and UPQC,  $X$  represents the angle of the voltage  $\beta_{i+1}$ , at the respective bus. Each value of  $X$  is initialized within the limits given by upper and lower bound values. At any iteration  $t$ , the personal best  $p_{best}^t$  of each particle is calculated which represents the best position  $X_i^t$  that gives the minimum value of the cost function  $F$  calculated as the weighted sum of the Voltage cost, Power loss cost and the capital cost using:

$$F = w_1 V_{cost} + w_2 P_{loss\_cost} + w_3 Capital_{cost} \quad (3.82)$$

Where,  $w_1$ ,  $w_2$ ,  $w_3$  are weighting coefficients that are determined considering the importance of the objectives functions. The summation of these weighing coefficients must be One (1). For this thesis objective function analysis, the weighting coefficient values considered are  $w_1 = 0.5$ ,  $w_2 = 0.25$  and  $w_3 = 0.25$

The values of  $V_{cost}$ ,  $P_{loss\_cost}$ , and  $Capital_{cost}$  are calculated by running the BFS load flow by modifying the system data according to the device incorporated in the load flow simulation. That means:

- First using the current iteration value  $X_i^t$  the appropriate device is included in the load flow by modifying the busdata of the system accordingly.

- Then, load flow was performed on the new modified system data which gives the bus voltages, line losses and the size of the installed device from which the above costs are calculated.  $V_{cost}$  is the sum of the difference between the ideal bus voltage value (1 p.u.) and the system bus voltages from the load flow. The other two costs  $P_{loss\_cost}$ , and  $Capital_{cost}$  are self-explanatory.

This new best position  $p_{best}^t$  is then compared to the previous iteration (t-1). If the current  $p_{best}^t$  is better than the previous personal best  $p_{best}^{t-1}$ , it will be kept as the new personal best position (value), otherwise the previous value will be used as the personal best. The global best  $g_{best}^t$  will then be selected as the best of all the personal best values of all the particles (2000 in this case). Now using the personal and global best positions, the velocity is calculated to move each particle in the swarm to their next position for the next iteration. The same will be repeated in the next iteration each time updating the  $p_{best}^t$  and  $g_{best}^t$  until the maximum number of iterations are reached or the solution converges. If convergence is achieved, the global best values  $g_{best}^t$  will be used as the optimum values of the susceptance for SVC, or voltage angle injection for DSTATCOM and UPQC.

## **CHAPTER 4**

### **SIMULATION STUDIES AND ANALYSIS OF RESULTS**

#### **4.1 Introduction**

Radially configured real distribution network structure has been considered for integration of DTATCOM, SVC and UPQC devices and power loss reduction and voltage profile improvement performance of each devices have been analyzed in MATLAB software under reduced full load condition (75% of full load), at full load condition (100% loading) and overloaded condition (125% of full load) in order to check the effect and response of these devices under varies loading conditions.

Accordingly, backward-forward load flow analysis has been implemented to study the existing system performance of Sebbata-I distribution substation 15 kV outgoing feeder-12 before and after installation of DSTATCOM, SVC and UPQC devices. To accomplish the backward-forward load flow analysis, 1.05pu is considered as the upper limit and 0.95pu is taken as lower voltage limits, while the 15 kV & 10 MVA are used as system base voltage and base power respectively. The optimization process starts first by sorting out the buses having the worst (highest LSI value) to best (lowest LSI value) and candidate buses at which the FACTS devices are to be installed are determined accordingly. Thus, in this thesis five buses (i.e. 83, 36, 33, 81, and 54) having the highest LSI are selected as weak buses for placement of FACTS devices. Next, the PSO is initialized to search for the optimum value of the FACTS device size.

Accordingly, section 4.2 discuss on distribution system performance simulation analysis before installation of FACTS devices, section 4.3 performance enhancement using installation of FACTS devices, section 4.4 Cost benefit analysis without and with integration of FACTS devices and section 4.5 Summary of the overall simulation result have been discussed in depth in this section

#### **4.2 Distribution System Performance Analysis before Installation of FACTS devices**

Before installation of the FACTS devices, load flow analysis has been performed in order to assess the performance of the system and to identify the active and reactive power losses, each bus voltage profile, and power loss sensitivity index of Sebeta-I substation Feeder-12 radially

configured distribution system. Accordingly, the simulation result of the system parameters has been discussed as follow;

**4.2.1 Active and Reactive Power Losses Simulation Studies and Result Analysis**

To understand the status of Sebbata-I substation 15 kV outgoing feeder-12 radial Distribution System, backward-forward power flow analysis was performed and the system power losses have been carried out without installation of DSTATCOM, SVC and UPQC devices. The total load connected to this feeder was decreased by 25% and also increased by 25% which means the load flow has been computed at 75% of the full load, at full load (100%) and at 125% of full load conditions and the effect of each FACTS device have been examined.

The overall system power loss at various loading conditions before compensation of FACTS devices has been depicted both in tabular and bar graph as follow;

Table 4-1:- Active and Reactive Power losses at 75%, 100% and 125% of full load

From Bus	To Bus	Total losses at 75% of full load		Total losses at 100% Loading		Total losses at 125% Loading	
		MW	MVar	MW	MVar	MW	MVar
1	2	0.015972	0.016498	0.029093	0.030051	0.046623	0.048158
2	3	5.95E-05	3.51E-05	0.000106	6.25E-05	0.000166	9.78E-05
3	4	6.54E-06	3.85E-06	1.16E-05	6.86E-06	1.82E-05	1.07E-05
2	5	3.6E-06	1.37E-06	6.41E-06	2.44E-06	1E-05	3.82E-06
2	6	0.002447	0.002527	0.004461	0.004607	0.007156	0.00739
6	7	1.34E-07	7.93E-08	2.4E-07	1.41E-07	3.75E-07	2.21E-07
6	8	0.064185	0.06626	0.117031	0.120816	0.187747	0.193819
8	9	0.000412	0.000243	0.000739	0.000436	0.001167	0.000688
9	10	0.000192	0.000113	0.000345	0.000203	0.000545	0.000321
10	11	6.58E-05	3.88E-05	0.000118	6.97E-05	0.000187	0.00011
11	12	3.09E-05	1.82E-05	5.55E-05	3.27E-05	8.76E-05	5.16E-05
10	13	5.92E-05	2.25E-05	0.000106	4.04E-05	0.000168	6.37E-05
13	14	3.3E-05	1.26E-05	5.92E-05	2.26E-05	9.34E-05	3.56E-05
8	15	0.006229	0.006433	0.011373	0.011745	0.018271	0.018869
15	16	0.000104	6.12E-05	0.000186	0.00011	0.000294	0.000174
16	17	4.61E-05	2.72E-05	8.29E-05	4.89E-05	0.000131	7.72E-05
15	18	0.019681	0.020325	0.035958	0.037134	0.057806	0.059698
18	19	3.07E-05	1.81E-05	5.53E-05	3.26E-05	8.76E-05	5.16E-05
19	20	1.38E-05	8.13E-06	2.49E-05	1.46E-05	3.93E-05	2.32E-05

Table 4-1: Active and Reactive Power losses (cont....)

From Bus	To Bus	Total losses 75% of full load		Total losses at 100% Loading		Total losses at 125% Loading	
		MW	MVar	MW	MVar	MW	MVar
18	21	0.028028	0.016529	0.051224	0.030208	0.082376	0.04858
21	22	0.014231	0.008393	0.026024	0.015348	0.041879	0.024698
22	23	3.39E-05	2E-05	6.14E-05	3.62E-05	9.77E-05	5.76E-05
23	24	1.51E-05	8.87E-06	2.72E-05	1.6E-05	4.33E-05	2.55E-05
24	25	2.63E-05	1.55E-05	4.77E-05	2.81E-05	7.58E-05	4.47E-05
25	26	1.87E-05	1.1E-05	3.39E-05	1.99E-05	5.39E-05	3.17E-05
26	27	2.83E-06	1.67E-06	5.11E-06	3.01E-06	8.13E-06	4.8E-06
24	28	3.7E-06	2.18E-06	6.7E-06	3.95E-06	1.07E-05	6.29E-06
28	29	3.58E-06	2.11E-06	6.47E-06	3.81E-06	1.03E-05	6.07E-06
22	30	0.004091	0.004225	0.007487	0.007733	0.012058	0.012454
30	31	0.017039	0.017598	0.031188	0.032211	0.050235	0.051883
31	32	0.002059	0.002127	0.003769	0.003893	0.006072	0.006272
32	33	0.000215	0.000127	0.000391	0.000231	0.000624	0.000368
33	34	1.49E-05	8.78E-06	2.7E-05	1.59E-05	4.32E-05	2.55E-05
32	35	0.002949	0.00305	0.005402	0.005587	0.008709	0.009007
35	36	0.000331	0.000126	0.000601	0.000229	0.000961	0.000365
35	37	0.011725	0.012108	0.021508	0.022211	0.034723	0.035859
37	38	5.55E-05	5.73E-05	0.000101	0.000104	0.000162	0.000167
38	39	9.76E-06	5.76E-06	1.78E-05	1.05E-05	2.85E-05	1.68E-05
37	40	0.013758	0.008112	0.025252	0.014889	0.040792	0.024052
40	41	0.005021	0.00296	0.009216	0.005433	0.01489	0.008777
41	42	0.001968	0.001161	0.003614	0.002132	0.005839	0.003445
42	43	0.000905	0.000345	0.001661	0.000633	0.002681	0.001023
43	44	1.29E-05	4.9E-06	2.35E-05	8.96E-06	3.78E-05	1.44E-05
43	45	0.002501	0.000953	0.004593	0.001751	0.007423	0.00283
45	46	0.000619	0.000236	0.001137	0.000434	0.001839	0.000701
46	47	0.000472	0.000178	0.000867	0.000327	0.001402	0.000528
47	48	0.000151	8.87E-05	0.000276	0.000163	0.000447	0.000263
48	49	3.12E-05	1.84E-05	5.72E-05	3.37E-05	9.25E-05	5.45E-05
49	50	3.02E-05	1.78E-05	5.54E-05	3.26E-05	8.96E-05	5.28E-05
47	51	0.000281	0.000107	0.000516	0.000196	0.000834	0.000318
51	52	1.49E-05	8.79E-06	2.74E-05	1.62E-05	4.43E-05	2.61E-05
52	53	1.18E-05	6.95E-06	2.17E-05	1.28E-05	3.5E-05	2.07E-05
53	54	1.13E-05	6.64E-06	2.07E-05	1.22E-05	3.34E-05	1.97E-05
42	55	0.000825	0.003986	0.001515	0.007319	0.002449	0.011829
55	56	3.31E-05	1.95E-05	6.06E-05	3.58E-05	9.75E-05	5.76E-05
56	57	1.98E-05	1.17E-05	3.63E-05	2.14E-05	5.84E-05	3.44E-05

Table 4-1: Active and Reactive Power losses (cont....)

From Bus	To Bus	Total losses 75% full load		Total losses 100% Loading		Total losses 125% Loading	
		MW	MVar	MW	MVar	MW	MVar
55	58	0.000292	0.000334	0.000536	0.000613	0.000866	0.00099
58	59	0.001478	0.001525	0.002715	0.0028	0.004389	0.004527
59	60	0.001295	0.001338	0.002379	0.002457	0.003847	0.003973
60	61	0.000121	0.000124	0.000221	0.000229	0.000358	0.00037
61	62	9.99E-06	5.89E-06	1.83E-05	1.08E-05	2.95E-05	1.74E-05
61	63	0.001512	0.00089	0.002779	0.001636	0.004495	0.002646
63	64	0.000431	0.000255	0.000793	0.000468	0.001283	0.000757
64	65	3.92E-06	2.31E-06	7.2E-06	4.25E-06	1.16E-05	6.86E-06
64	66	0.000973	0.000574	0.001791	0.001056	0.0029	0.001711
66	71	3.43E-05	2.02E-05	6.31E-05	3.72E-05	0.000102	6.03E-05
71	72	0	0	0	0	0	0
66	67	0.000111	6.55E-05	0.000204	0.00012	0.000331	0.000195
67	68	8.62E-05	5.09E-05	0.000159	9.37E-05	0.000257	0.000152
68	69	1.67E-05	9.86E-06	3.08E-05	1.82E-05	4.99E-05	2.94E-05
68	70	5.09E-06	3.01E-06	9.37E-06	5.53E-06	1.52E-05	8.96E-06
60	73	0.003706	0.002185	0.006808	0.004014	0.011007	0.006491
73	74	0.001548	0.000913	0.002844	0.001677	0.004599	0.002712
74	75	7.11E-05	4.19E-05	0.000131	7.7E-05	0.000211	0.000124
75	76	0.000153	9.01E-05	0.000281	0.000165	0.000454	0.000267
76	77	0.000186	7.1E-05	0.000342	0.00013	0.000553	0.000211
77	78	0.000354	0.000135	0.00065	0.000248	0.001051	0.000401
78	79	2.6E-05	9.9E-06	4.77E-05	1.82E-05	7.71E-05	2.94E-05
79	80	1.2E-05	7.08E-06	2.2E-05	1.3E-05	3.56E-05	2.1E-05
79	81	6.6E-06	3.9E-06	1.21E-05	7.16E-06	1.96E-05	1.16E-05
74	82	0.001651	0.000973	0.003033	0.001789	0.004907	0.002894
82	83	0.000742	0.000436	0.001364	0.000802	0.002207	0.001298
83	84	7.68E-05	4.53E-05	0.000141	8.33E-05	0.000229	0.000135
84	85	0.000374	0.000221	0.000688	0.000406	0.001115	0.000657
85	86	2.71E-05	1.6E-05	4.98E-05	2.94E-05	8.06E-05	4.75E-05
86	87	8.09E-06	8.35E-06	1.49E-05	1.54E-05	2.41E-05	2.49E-05
85	88	2.14E-05	1.26E-05	3.93E-05	2.32E-05	6.36E-05	3.75E-05
84	89	8.19E-06	4.83E-06	1.51E-05	8.88E-06	2.43E-05	1.44E-05

From the simulation result, at 75% of the full load condition the total active and reactive power losses became 232.4291 kW and 205.6556 kVAr respectively. And also, at full load (100%) condition the total active and reactive power losses are 424.8793 kW and 375.8355 kVAr

respectively. Whereas, at 125% loading conditions, the simulation analysis reveals that the distribution network has 683.4434 kW of real loss and 604.3812 kVAr of losses. This indicates that the distribution system requires power compensating devices to enhance the performance of the distribution network to an appropriate level.

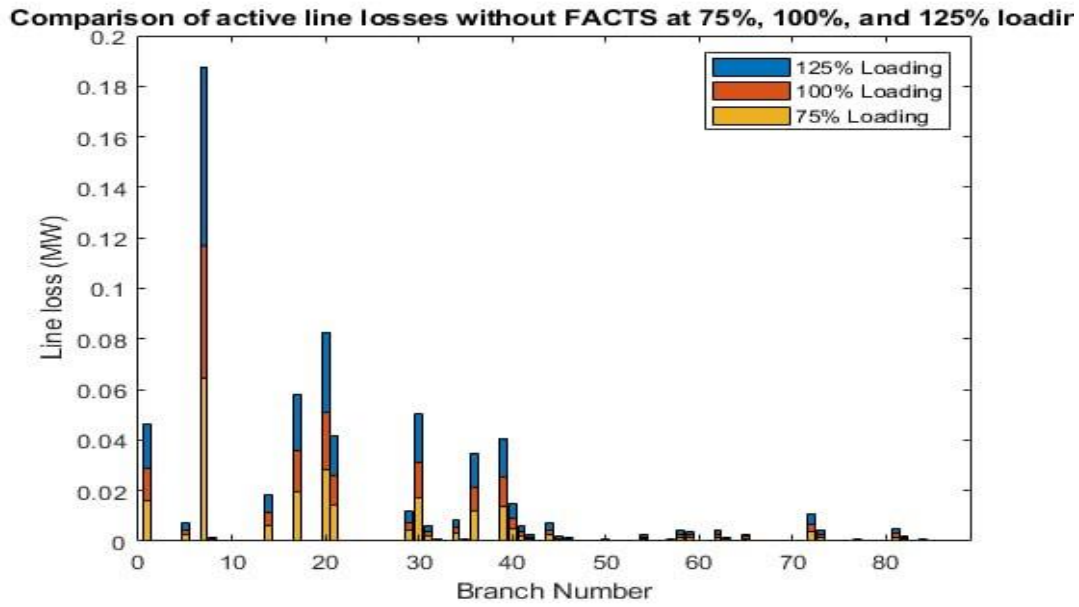


Figure 4-1:- Active power losses at 75%, 100% and 125% loading conditions

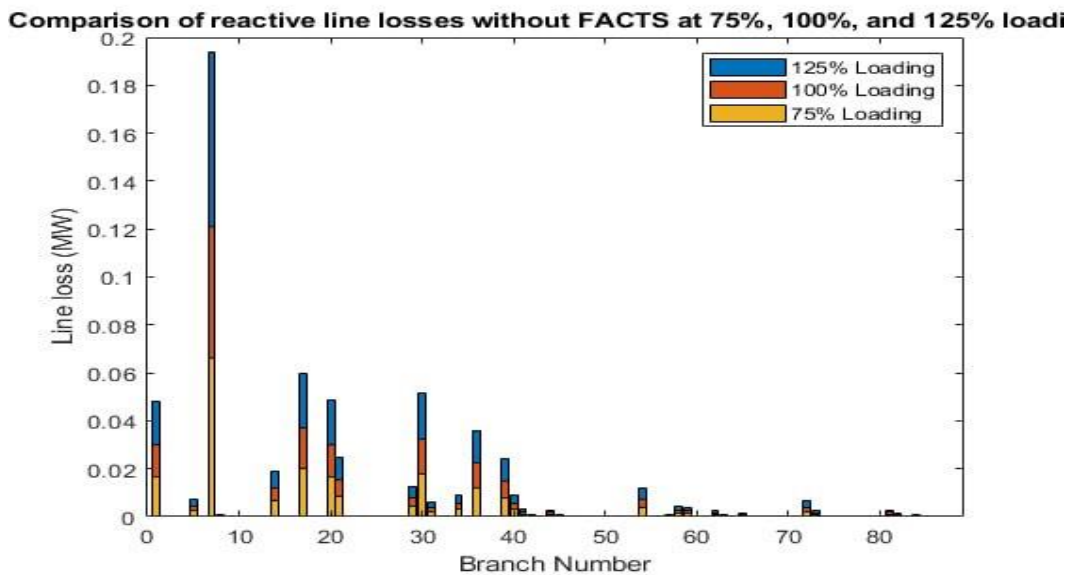


Figure 4-2: Reactive power loss at 75%, 100% and 125% loading conditions

**4.2.2 Voltage Profile before Installation of FACTS Devices**

In order to determine the voltage drop, Sebbata-I substation 15 kV outgoing feeder-12 radially configured distribution system parameters were examined using backward-forward load flow method and all buss voltage level are depicted below;

Table 4-2:- Base case Voltage Profile at 75%, 100% and 125% loading conditions

Bus No	Voltage Profile			Bus No	Voltage Profile		
	75% of full load	Loading 100%	Loading 125%		75% of full load	Loading 100%	Loading 125%
1	1	1	1	46	0.957727	0.942829	0.927467
2	0.997593	0.996751	0.995887	47	0.957047	0.941906	0.926294
3	0.99733	0.9964	0.995447	48	0.956623	0.941331	0.925564
4	0.997268	0.996317	0.995343	49	0.956497	0.941161	0.925347
5	0.997565	0.996713	0.995839	50	0.956247	0.940822	0.924917
6	0.997209	0.996232	0.995229	51	0.956089	0.940608	0.924644
7	0.997204	0.996225	0.995221	52	0.956018	0.940512	0.924522
8	0.987092	0.982571	0.977925	53	0.955952	0.940423	0.924408
9	0.986445	0.981704	0.976835	54	0.955878	0.940323	0.924281
10	0.986107	0.98125	0.976265	55	0.961742	0.94827	0.934385
11	0.985872	0.980936	0.97587	56	0.961496	0.947936	0.933962
12	0.985637	0.98062	0.975474	57	0.96126	0.947618	0.933558
13	0.985924	0.981006	0.975958	58	0.961617	0.9481	0.93417
14	0.985759	0.980784	0.97568	59	0.960994	0.947256	0.933096
15	0.986024	0.981127	0.976094	60	0.960426	0.946486	0.932118
16	0.985653	0.980631	0.975471	61	0.960231	0.946222	0.931781
17	0.985315	0.980177	0.9749	62	0.960113	0.946061	0.931578
18	0.98251	0.976377	0.970072	63	0.957991	0.943185	0.927919
19	0.982308	0.976106	0.96973	64	0.957293	0.942238	0.926715
20	0.982122	0.975857	0.969418	65	0.957253	0.942184	0.926646
21	0.978354	0.97076	0.962948	66	0.954733	0.938765	0.922295
22	0.976136	0.96776	0.959143	67	0.95435	0.938247	0.921635
23	0.976061	0.967659	0.959016	68	0.953866	0.93759	0.920799
24	0.976023	0.967608	0.958952	69	0.953728	0.937402	0.92056

Table 4-2: Base case Voltage Profile (Cont...)

Bus No	Voltage Profile			Bus No	Voltage Profile		
	75% of full load	Loading 100%	Loading 125%		75% of full load	Loading 100%	Loading 125%
25	0.97593	0.967482	0.958793	70	0.953777	0.937469	0.920645
26	0.97583	0.967348	0.958623	71	0.954349	0.938245	0.921633
27	0.975792	0.967297	0.958559	72	0.954349	0.938245	0.921633
28	0.975992	0.967566	0.958898	73	0.958621	0.944039	0.929006
29	0.975946	0.967504	0.958821	74	0.957806	0.942935	0.927602
30	0.975291	0.966617	0.957692	75	0.95769	0.942777	0.927401
31	0.971745	0.961818	0.951602	76	0.957363	0.942334	0.926838
32	0.971308	0.961228	0.950853	77	0.956985	0.941822	0.926186
33	0.970856	0.960619	0.950083	78	0.956063	0.940572	0.924597
34	0.970731	0.96045	0.94987	79	0.955983	0.940464	0.92446
35	0.970628	0.960307	0.949683	80	0.955894	0.940344	0.924307
36	0.97023	0.95977	0.949005	81	0.955941	0.940406	0.924387
37	0.967487	0.956053	0.944279	82	0.95653	0.941204	0.925401
38	0.967275	0.955767	0.943916	83	0.955899	0.940349	0.924313
39	0.9672	0.955666	0.943788	84	0.955728	0.940118	0.924019
40	0.96427	0.951694	0.938738	85	0.954621	0.938616	0.922108
41	0.963071	0.95007	0.936675	86	0.954487	0.938434	0.921877
42	0.962589	0.949417	0.935844	87	0.95441	0.93833	0.921743
43	0.961723	0.948243	0.934352	88	0.954464	0.938403	0.921837
44	0.961631	0.94812	0.934196	89	0.955656	0.940019	0.923893
45	0.958543	0.943934	0.928873				

The output of the simulation depicted that, the system has a minimum voltage of 0.953728pu, 0.937402pu and 0.92056pu at 75% of full load, at full load (100%) and 125% loading conditions respectively

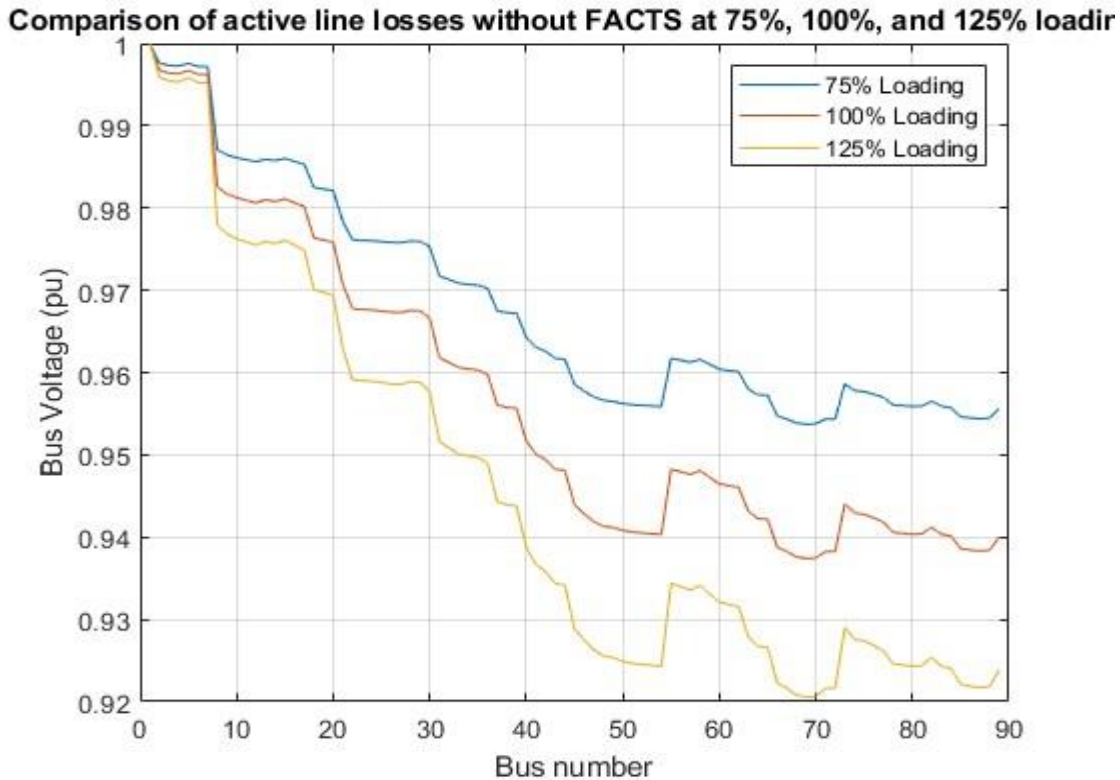


Figure 4-3:-Base Case Voltage profile at 75% of full load, 100% and 25% loading conditions

The figure above clearly reveals that, the voltage drops has been increasing proportionally with the increase of the feeder length from the source or substation to the far end user. At reduced load conditions (i.e. at 75% of full load) the voltage profile of the system has a sign of enhancement while it has a sign of decrement at full load (100% loading) and overloading (125% loading) conditions. Hence, the voltage profiles of the buses near to the substation are higher whereas the voltage profiles of buses away from the source are lower. The result obtained show that voltage magnitudes need some improvement to have more power flow capability in the feeder. From a power system point of view, for a distribution system network, the voltage profile should be better and must be in the distribution system voltage standard level. Improving the distribution system voltage profile makes the system losses to be reduced and enhanced the system performance. Therefore, installation of optimal size of DSTATCOM, SVC and UPQC devices on the feeder can increase the voltage profile to the required level.

**4.2.3 Loss Sensitivity Index Result before installation of FACTS Devices**

In power system studies, the Loss Sensitivity Index (LSI) analysis is a conventional procedure to find out the locations with maximum impact on the system real power losses with respect to the node reactive power. The power loss sensitivity index value is determined by the power flow analysis method before the installation of the FACTS devices on the selected feeder. And the calculated loss sensitivity factors of all lines are arranged in descending order (i.e. highest to lowest value) of the system under the case study. And buses which have maximum value of LSI are considered as weak buses and voltage improvement devices must be installed at these locations. The Loss Sensitivity Index of each buses of the selected feeder before compensation is depicted below;

Table 4-3:- Loss Sensitivity Index at 75% of full load, 100% and 125% loading conditions

Bus No	Loss Sensitivity Index			Bus No	Loss Sensitivity Index		
	75% of full load	100% Loading	125% Loading		75% of full load	100% Loading	125% Loading
1	0	0	0	46	0.001703	0.003171	0.0052
2	0	0	0	47	0	0	0
3	0.000199	0.000364	0.000586	48	0.003023	0.005629	0.009234
4	0.000183	0.000336	0.00054	49	0.003666	0.006828	0.011201
5	0.000179	0.000329	0.000531	50	0.003635	0.006769	0.011106
6	0	0	0	51	0.00152	0.002832	0.004648
7	4.78E-05	8.76E-05	0.000141	52	0.000936	0.001744	0.002863
8	0	0	0	53	0.000803	0.001495	0.002454
9	0.000538	0.000989	0.001602	54	0.004379	0.008156	0.013381
10	0	0	0	55	0	0	0
11	0.001261	0.002319	0.003754	56	0.001245	0.002316	0.003795
12	0.001146	0.002107	0.00341	57	0.002089	0.003885	0.006366
13	0.001013	0.001863	0.003016	58	0.002242	0.00417	0.006833
14	0.001553	0.002856	0.004624	59	0.002882	0.005362	0.008787
15	0	0	0	60	0	0	0
16	0.001272	0.002343	0.003799	61	0	0	0
17	0.001216	0.002238	0.003629	62	0.002156	0.004013	0.00658
18	0	0	0	63	0.001549	0.002886	0.004736
19	0.000786	0.001449	0.002355	64	0.003797	0.007075	0.011612
20	0.000811	0.001497	0.002431	65	0.00271	0.005049	0.008289
21	0.004483	0.008276	0.013454	66	0	0	0
22	0	0	0	67	0.0033	0.006156	0.010118

Table 4-3: Base Case Loss Sensitivity Index (Cont....)

Bus No	Loss Sensitivity Index			Bus No	Loss Sensitivity Index		
	75% of full load	100% Loading	125% Loading		75% of full load	100% Loading	125% Loading
23	0.000825	0.001523	0.002478	68	0	0	0
24	0	0	0	69	0.003532	0.00659	0.010831
25	0.001472	0.002719	0.004423	70	0.001719	0.003208	0.005274
26	0.001888	0.003486	0.00567	71	0.002628	0.004902	0.008056
27	0.001134	0.002094	0.003406	72	0	0	0
28	0.000607	0.001121	0.001823	73	0.003706	0.006901	0.011322
29	0.001195	0.002208	0.00359	74	0	0	0
30	0.000722	0.001334	0.00217	75	0.003895	0.007255	0.011907
31	0.001867	0.003455	0.005632	76	0.000805	0.0015	0.002462
32	0	0	0	77	0.002707	0.005045	0.008282
33	0.006524	0.012077	0.019691	78	0.001492	0.002781	0.004567
34	0.002284	0.004228	0.006894	79	0	0	0
35	0	0	0	80	0.003977	0.007412	0.012172
36	0.01342	0.024851	0.04053	81	0.0044	0.0082	0.013465
37	0	0	0	82	0.003604	0.006718	0.011031
38	0.004032	0.007479	0.012219	83	0.019344	0.036025	0.0591
39	0.002593	0.004811	0.007861	84	0	0	0
40	0.002005	0.003724	0.006093	85	0	0	0
41	0.002609	0.004848	0.007934	86	0.002229	0.004158	0.006834
42	0	0	0	87	0.004146	0.007734	0.01271
43	0.002554	0.004748	0.007775	88	0.004167	0.007772	0.012772
44	0.003149	0.005855	0.009587	89	0.003243	0.006046	0.009932
45	0.000605	0.001126	0.001846				

Therefore, in the optimization process the simulation result of loss sensitivity index is utilized to install the FACTS devices so as to enhance the system performance. Accordingly, buses with maximum LSI Value are preferred to install DSTATCOM, SVC and UPQC devices as the voltage dip occurs at these points and distributed to the entire system. Considering only the first five buses having maximum Loss Sensitivity Index (LSI) as candidate buses for installation of the FACTS devices, the bus number and its corresponding LSI value at different loading conditions has been depicted in the following table;

Table 4-4:- Candidate buses LSI value at 75% of full load, 100% and 125% loading conditions

Candidate bus	Maximum LSI Value before installation of FACTS Devices		
	75% of full load	100% loading	125% loading
83	0.0193	0.0360	0.0591
36	0.0134	0.0249	0.0405
33	0.0065	0.0121	0.0197
81	0.0044	0.0082	0.0135
54	0.0044	0.0082	0.0135

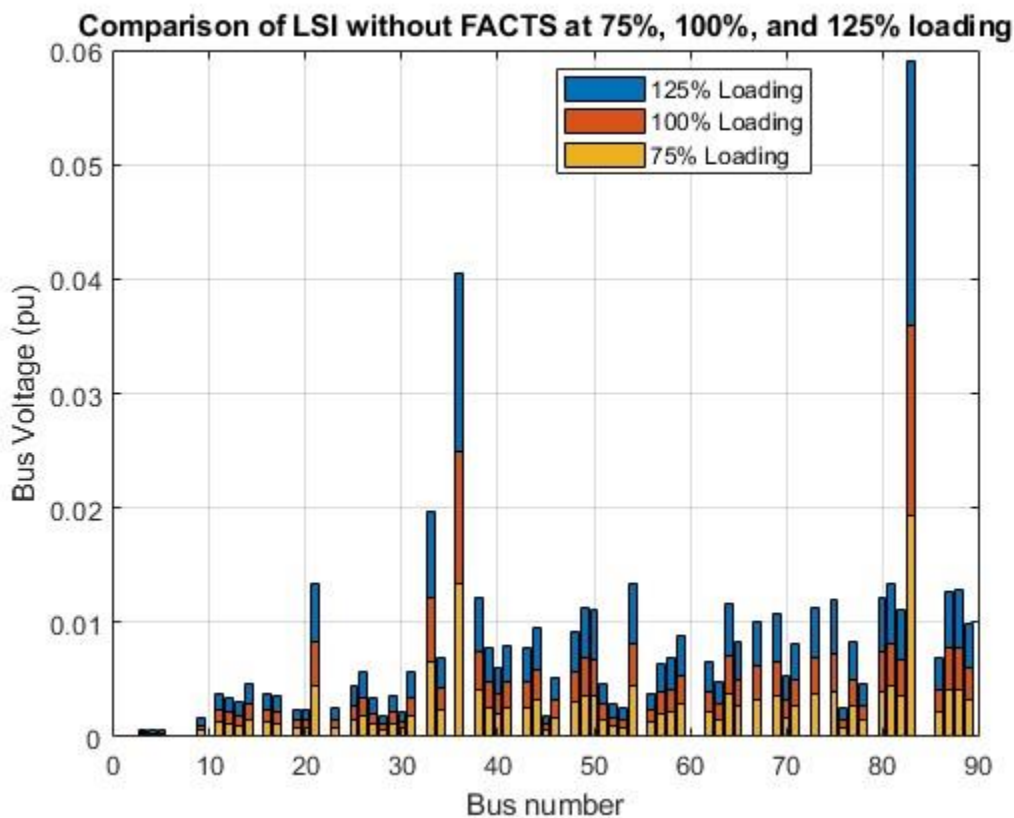


Figure 4-4:- Base case LSI at 75% of full load, 100% and 25% loading conditions

From fable 4-4 and figure 4.4 above, it is clear that bus numbers 83, 36, 33, 81 and 54 have the highest loss sensitivity index vales in the system. Therefore, these buses are considered as candidate buses for the installation of DSTATCOM, SVC and UPQC devices in order to compensate the power losses and improve the voltage profile of the system.

Before installation of FACTS devices, the overall performance simulation output summarized as follow;

Table 4-5:- Summary of Simulation Result before Installation of FACTS Devices

<b>Parameters</b>	<b>75% of full load</b>	<b>100% Loading</b>	<b>125% Loading</b>
Total Active Power Loss (kW)	232.4291	424.8793	683.4434
Total Reactive Power Loss (kVAr)	205.6556	375.8355	604.3812
Minimum Voltage (pu)	0.953728	0.937402	0.92056
Maximum Loss Sensitivity Index	0.019344	0.036025	0.059100
Identified Candidate Buses	83,36,33,81,54	83,36,33,81,54	83,36,33,81,54

The simulation analysis indicates that Sebbata-I substation 15 kV outgoing feeder-12 radially configured distribution system has active power losses of 232.43 kW, 424.88 kW and 683.44 kW at 75% of full load, 100% and 125% loading conditions respectively. The system minimum voltages are 0.953728pu, 0.937402pu and 0.92056pu at 75% of full load, 100% and 125% loading conditions respectively. This clearly shows that at reduced full load condition the voltage profile of the system has a sign of improvement when compared with full load and overloading conditions.

And also, the maximum loss sensitivity indexes of the system are 0.019344, 0.036025 and 0.059100 at 75% of full load, 100% and 125% loading conditions respectively. Again at reduced full load condition the loss sensitivity index of the system is lower than that of full load and overloading conditions.

The overall simulation result reveal that the Sebbata-I substation 15 kV outgoing feeder-12 radial distribution system parameters need improvement across the system line and the required compensation work can be done in order to improve the system performance can be done by installation FACTS controller.

### 4.3 Performance Enhancement Using FACTS Devices

In this section different types of FACTS controllers have been integrated on the Sebbata-I substation 15 kV outgoing feeder-12 which is a radially configured system and the effect of the installed FACTS devices has been investigated with regard of minimizing the line power losses, and improving the voltage profile of a system.

#### 4.3.1 Power Loss Reduction Performance of FACTS Devices

In order to check the response of the FACTS devices under reduced load condition, the total load of Sebbata-I substation 15 kV outgoing feeder-12 radial distribution system has been decreased by 25% ( i.e. at 75% of full load condition ) and the FACTS devices response has been examined under this loading scenario. Accordingly, at 75% of full load condition, with installation of DSTATCOM, SVC and UPQC devices at the identified candidate buses of 83, 36, 33, 81 and 54, the total active power loss has been reduced from 232.43 kW to 120.73 kW, 152.67 kW, and 81.71 kW respectively. This implies that the total active power loss has been reduced by 48.06%, 34.49% and 64.85% active power loss respectively. Similarly, after installation of DSTATCOM, SVC and UPQC devices the reactive power losses reduced from 205.66 kVAr to 110.61 kVAr, 131.80 kVAr, and 73.77 kVAr which represent 46.22%, 35.79% and 64.85% reactive power loss respectively.

The size of DSTATCOM, SVC and UPQC devices were decided based on PSO algorithm and the candidate buses for allocation of the devices were determined with loss sensitivity index. Accordingly, the sizes of the DSTATCOM, SVC and UPQC devices for each candidate buses are shown on the table below

Table 4-6:-Sizes of FACTS devices for each candidate buses at 75% of full load

Candidate bus	83	36	33	81	54
Installed DSTATCOM Size (kVAr)	480.60	498.53	240.30	223.80	102.60
Installed SVC Size (kVAr)	1027.2	1017.6	1017.0	1012.7	1025.9
Installed UPQC Size (kVAr)	528.66	548.38	264.33	246.18	112.86

As it can be seen from the above table, the size of the SVC devices identified to be installed to meet intended objectives are much higher than that of DSTATCOM and UPQC devices and this has an adverse effect on the investment cost of this device. And also the sizes of the DSTATCOM devices are lower than that of UPQC devices. The simulation output for system power losses after installation of these FACTS devices on the Sebeta-I substation Feeder-12 radial distribution system at 75% of full load condition is depicted both in tabular and graphically as follow;

Table 4-7:-Power losses after installation of FACTS Devices at 75% of full load

From Bus	To Bus	Total Line losses at 75% of full load					
		DSTATCOM		SVC		UPQC	
		MW	MVar	MW	MVar	MW	MVar
1	2	0.009526	0.009839	0.009948	0.010275	0.006703	0.006924
2	3	0.0000594	0.000035	0.0000594	0.000035	0.0000594	0.000035
3	4	0.0000065	0.0000038	0.0000065	0.0000038	0.0000065	0.0000038
2	5	0.0000036	0.0000014	0.0000036	0.0000014	0.0000036	0.0000014
2	6	0.001455	0.001502	0.001521	0.001571	0.001013	0.001046
6	7	0.0000001	0.00000008	0.0000001	0.0000000	0.00000013	0.00000008
6	8	0.038151	0.039385	0.039882	0.041172	0.026526	0.027384
8	9	0.000407	0.00024	0.000407	0.00024	0.000406	0.000239
9	10	0.00019	0.000112	0.00019	0.000112	0.000189	0.000111
10	11	0.000065	0.0000384	0.0000651	0.0000384	0.0000648	0.0000382
11	12	0.0000305	0.000018	0.0000305	0.000018	0.0000304	0.0000179
10	13	0.0000585	0.0000222	0.0000585	0.0000222	0.0000583	0.0000221
13	14	0.0000326	0.0000124	0.0000326	0.0000124	0.0000325	0.0000124
8	15	0.003691	0.003812	0.003865	0.003992	0.002515	0.002598
15	16	0.000102	0.0000604	0.000103	0.0000604	0.000102	0.0000602
16	17	0.0000456	0.0000269	0.0000456	0.0000269	0.0000454	0.0000268
15	18	0.01169	0.012073	0.012247	0.012648	0.007909	0.008168
18	19	0.0000302	0.0000178	0.0000303	0.0000178	0.0000301	0.0000177
19	20	0.0000136	0.000008	0.0000136	0.000008	0.0000135	0.000008
18	21	0	0	0.017467	0.010301	0	0
21	22	0.008489	0.005006	0.008811	0.005196	0.005487	0.003236
22	23	0.0000331	0.0000195	0.0000333	0.0000196	0.0000327	0.0000193
23	24	0.0000147	0.0000087	0.0000148	0.0000087	0.0000145	0.0000086
24	25	0.0000257	0.0000151	0.0000258	0.0000152	0.0000254	0.000015
25	26	0.0000183	0.0000107	0.0000183	0.0000108	0.0000181	0.0000106
26	27	0.0000028	0.0000016	0.0000028	0.0000016	0.0000027	0.0000016
24	28	0.0000036	0.0000021	0.0000036	0.0000021	0.0000036	0.0000021

Table 4-7: - Power losses after installation FACTS devices (Cont...)

From Bus	To Bus	Total Line losses at 75% of full load					
		DSTATCOM		SVC		UPQC	
		MW	MVar	MW	MVar	MW	MVar
28	29	0.0000035	0.0000021	0.0000035	0.0000021	0.0000035	0.0000020
22	30	0.002363	0.002441	0.002528	0.002611	0.001532	0.001582
30	31	0.00981	0.010132	0.01053	0.010875	0.006363	0.006572
31	32	0.001176	0.001215	0.001273	0.001315	0.000765	0.00079
32	33	0	0	0.000489	0.000289	0	0
33	34	0.0000143	0.0000084	0.0000145	0.0000086	0.0000142	0.0000084
32	35	0.001672	0.001729	0.001842	0.001906	0.001004	0.001038
35	36	0	0	0.000333	0.000126	0	0
35	37	0.006604	0.00682	0.007695	0.007947	0.003566	0.003683
37	38	0.0000538	0.0000556	0.000054	0.0000558	0.000053	0.0000547
38	39	0.0000095	0.0000056	0.0000095	0.0000056	0.0000093	0.0000055
37	40	0.007465	0.004401	0.008871	0.005231	0.0038	0.00224
40	41	0.002695	0.001589	0.003222	0.001899	0.001348	0.000795
41	42	0.001042	0.000615	0.001256	0.000741	0.00051	0.000301
42	43	0.000875	0.000334	0.000879	0.000335	0.000859	0.000328
43	44	0.0000124	0.0000047	0.0000125	0.0000048	0.0000122	0.0000047
43	45	0.002417	0.000921	0.002427	0.000925	0.002374	0.000905
45	46	0.000599	0.000228	0.000601	0.000229	0.000588	0.000224
46	47	0.000456	0.000172	0.000458	0.000173	0.000448	0.000169
47	48	0.000145	0.0000858	0.000146	0.0000861	0.000143	0.0000842
48	49	0.0000301	0.0000177	0.0000302	0.0000178	0.0000296	0.0000174
49	50	0.0000292	0.0000172	0.0000293	0.0000173	0.0000286	0.0000169
47	51	0.000271	0.000103	0.000272	0.000104	0.000266	0.000102
51	52	0.0000144	0.0000085	0.0000145	0.0000085	0.0000142	0.0000083
52	53	0.0000114	0.0000067	0.0000114	0.0000068	0.0000112	0.0000066
53	54	0.0000109	0.0000064	0.0000109	0.0000064	0.0000107	0.0000063
42	55	0.000379	0.00183	0.000506	0.002446	0.000148	0.000715
55	56	0.000032	0.0000189	0.0000321	0.000019	0.0000314	0.0000185
56	57	0.0000192	0.0000113	0.0000192	0.0000113	0.0000188	0.0000111
55	58	0.000131	0.00015	0.000179	0.000205	0.0000498	0.000057
58	59	0.000653	0.000674	0.000907	0.000935	0.000245	0.000253
59	60	0.000563	0.000582	0.000798	0.000825	0.00021	0.000217
60	61	0.000116	0.00012	0.000117	0.000121	0.000114	0.000118
61	62	0.0000096	0.0000057	0.0000097	0.0000057	0.0000095	0.0000056
61	63	0.001458	0.000858	0.001464	0.000862	0.00143	0.000842
63	64	0.000416	0.000245	0.000418	0.000246	0.000408	0.000241
64	65	0.0000038	0.0000022	0.0000038	0.0000022	0.0000037	0.0000022

Table 4-7: - Power losses after installation FACTS devices (Cont...)

From Bus	To Bus	Total Line losses at 75% of full load					
		DSTATCOM		SVC		UPQC	
		MW	MVar	MW	MVar	MW	MVar
64	66	0.000938	0.000553	0.000942	0.000556	0.00092	0.000543
66	71	0.0000331	0.0000195	0.0000332	0.0000196	0.0000324	0.0000191
71	72	0	0	0	0	0	0
66	67	0.000107	0.0000631	0.000108	0.0000634	0.000105	0.0000619
67	68	0.0000831	0.0000491	0.0000834	0.0000493	0.0000815	0.0000481
68	69	0.0000161	0.0000095	0.0000162	0.000096	0.0000158	0.0000093
68	70	0.0000049	0.0000029	0.0000049	2.91E-06	0.0000048	0.0000028
60	73	0.001506	0.000888	0.002578	0.00152	0.00082	0.000483
73	74	0.000634	0.000374	0.001135	0.000669	0.000418	0.000247
74	75	0.000038	0.0000224	0.000102	6E-05	0.0000193	0.0000114
75	76	0.0000689	0.0000406	0.000375	0.000221	0.0000295	0.0000174
76	77	0.0000801	0.0000305	0.000525	0.0002	0.0000336	0.0000128
77	78	0.000126	0.0000482	0.00174	0.000663	0.0000647	0.0000247
78	79	0.000084	0.0000032	0.000185	0.0000706	0.0000066	0.0000025
79	80	0.0000115	0.0000068	0.0000115	0.0000068	0.0000113	0.0000066
79	81	0	0	0.000189	0.000112	0	0
74	82	0.000888	0.000524	0.001007	0.000594	0.000958	0.000565
82	83	0	0	0.000473	0.000278	0	0
83	84	0.0000716	0.000042	0.0000741	0.0000437	0.0000709	0.0000418
84	85	0.000349	0.000206	0.000361	0.000213	0.000345	0.000204
85	86	0.0000252	0.0000149	0.0000261	0.0000154	0.000025	0.0000147
86	87	0.0000075	0.0000078	0.0000078	0.00008	0.0000075	0.0000077
85	88	0.0000199	0.0000117	0.0000206	0.0000122	0.0000197	0.0000116
84	89	0.0000076	0.0000045	0.000079	0.0000047	0.0000076	0.0000045

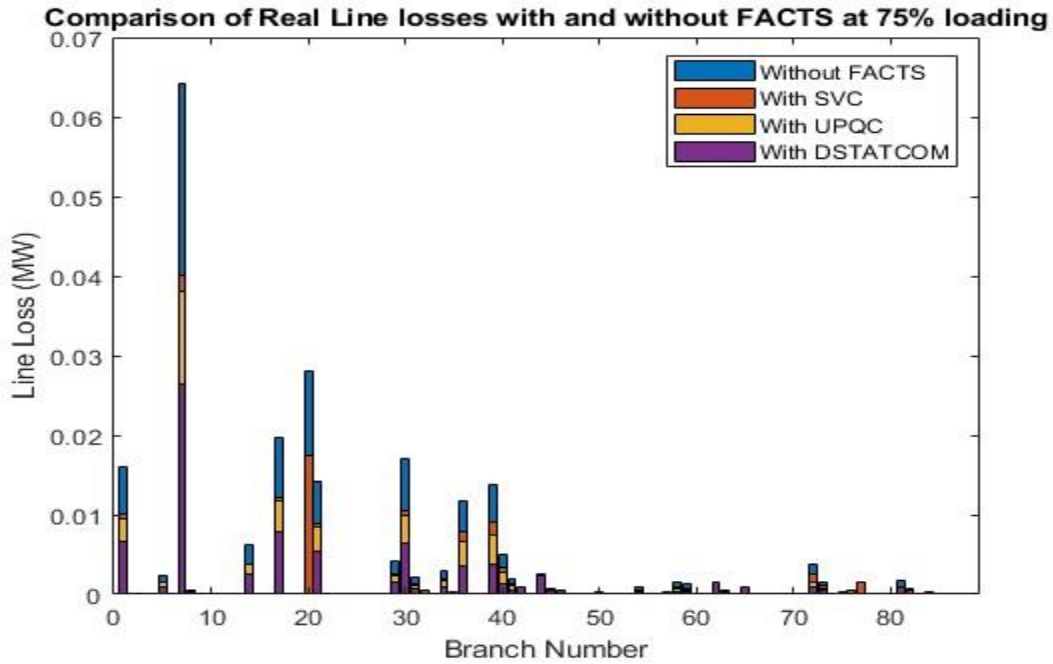


Figure 4-5:- Active power losses with and without FACTS Devices at 75% of full load

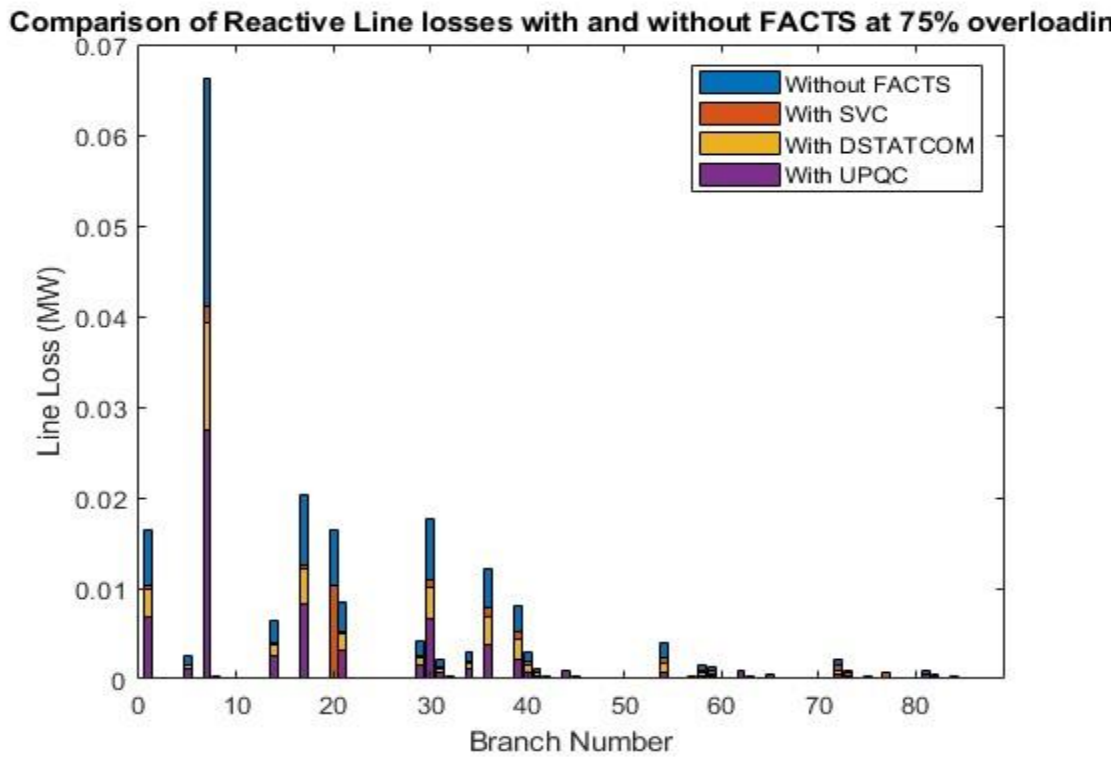


Figure 4-6:- Reactive power losses with and without FACTS Devices at 75% of full load

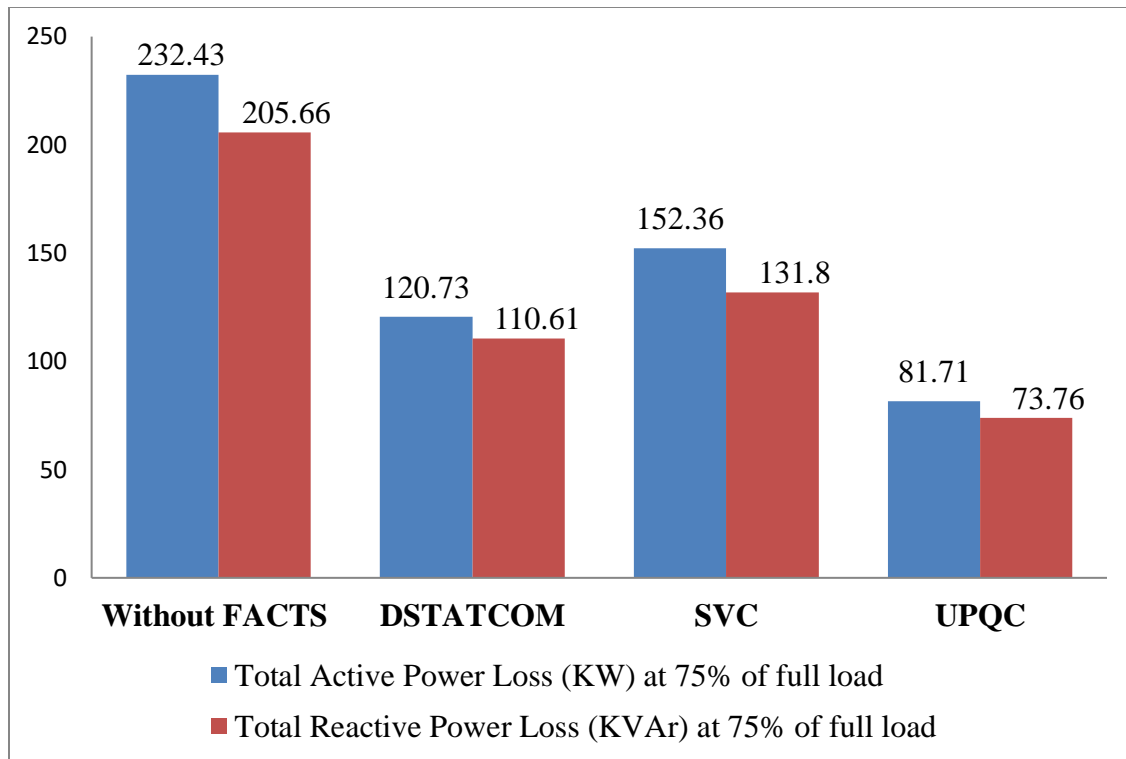


Figure 4-7:-Total Active and reactive Power losses with and without FACTS devices at 75% of full load

Similarly, in order to check the response of the FACTS devices under full load (100% loading) condition, total power load of Sebbata-I substation 15 kV outgoing feeder-12 radial distribution system has been loaded at full load (100%) condition. Then, the active and reactive power loss of the system was analyzed in MATLAB software similar to the above.

Accordingly, the total system power losses without and with installation of FACTS controllers have been computed using BFS load flow approach.

The size of FACTS devices were decided based on PSO algorithm and the candidate buses for allocation of the devices were determined with loss sensitivity index. Consequently, the sizes of the DSTATCOM, SVC and UPQC are shown on the table below;

Table 4-8:-Installed FACTS Devices values at the candidate buses at 100% loading

Candidate bus	83	36	33	81	54
Installed DSTATCOM Size (kVAr)	640.80	664.70	320.40	298.40	136.80
Installed SVC Size (kVAr)	1043.0	1028.10	1027.20	1020.20	1041.70
Installed UPQC Size (kVAr)	704.88	731.17	352.44	328.24	150.48

Again, the sizes of SVC devices are higher than DSTATCOM and UPQC devices which have negative impact on the investment cost of this device.

At 100% loading scenario, with installation of DSTATCOM, SVC and UPQC devices, the total base case active power loss was reduced from 424.88 kW to 214.61 kW, 282.49 kW and 145.66 kW respectively. Similarly, the reactive power losses improved from 375.84 kVAr to 196.55 kVAr, 246.35 kVAr and 131.46 kVAr after installation of DSTATCOM, SVC and UPQC devices respectively. These represent reduction of real and reactive power loss by 49.49%, 33.51%, and 65.72% and by 47.70%, 34.45%, and 65.02% after installation of DSTATCOM, SVC and UPQC devices respectively.

This indicates that at 100% loading scenario the power losses reduction performance of UPQC device is higher than DSTATCOM and SVC devices while the power loss reduction performance of DSTATCOM is better than SVC devices.

The active and reactive power loss for each branch is presented both in tables and bar graphs as follows;

Table 4-9:- Power losses after installation of FACTS Devices at full load (100% loading)

From Bus	To Bus	Total Line losses at 100% loading					
		DSTATCOM		SVC		UPQC	
		MW	MVar	MW	MVar	MW	MVar
1	2	0.016934	0.017491	0.018935	0.019558	0.01194	0.012333
2	3	0.000106	0.0000623	0.000106	0.0000624	0.000106	0.0000623
3	4	0.0000116	0.0000068	0.0000116	0.0000068	0.0000116	0.0000068
2	5	0.0000064	0.0000024	0.0000064	0.0000024	0.0000064	0.0000024
2	6	0.002586	0.002671	0.002876	0.00297	0.001804	0.001863
6	7	0.0000002	0.0000001	0.0000002	0.0000001	0.0000002	0.0000001

Table 4-9: - Power losses (Cont...)

From Bus	To Bus	Total Line losses at 100% loading					
		DSTATCOM		SVC		UPQC	
		MW	MVar	MW	MVar	MW	MVar
6	8	0.067818	0.070011	0.07539	0.077828	0.047248	0.048776
8	9	0.000728	0.000429	0.000731	0.000431	0.000725	0.000427
9	10	0.000339	0.0002	0.000341	0.000201	0.000338	0.000199
10	11	0.000116	0.0000686	0.000117	0.0000689	0.000116	0.0000683
11	12	0.0000546	0.0000322	0.0000548	0.0000323	0.0000543	0.000032
10	13	0.000105	0.0000397	0.000105	0.0000399	0.000104	0.0000396
13	14	0.0000582	0.0000222	0.0000585	0.0000223	0.000058	0.0000221
8	15	0.00656	0.006775	0.007186	0.007422	0.00448	0.004627
15	16	0.000183	0.000108	0.000184	0.000109	0.000182	0.000107
16	17	0.0000815	0.000048	0.0000819	0.0000482	0.0000811	0.0000478
15	18	0.020777	0.021457	0.022549	0.023286	0.014088	0.014549
18	19	0.0000541	0.0000319	0.0000545	0.0000321	0.0000538	0.0000317
19	20	0.0000243	0.0000143	0.0000245	0.0000144	0.0000242	0.0000142
18	21	0	0	0.031971	0.018854	0	0
21	22	0.01509	0.008899	0.016765	0.009887	0.009782	0.005769
22	23	0.0000589	0.0000347	0.0000601	0.0000354	0.0000582	0.0000343
23	24	0.0000261	0.0000154	0.0000267	0.0000157	0.0000258	0.0000152
24	25	0.0000458	0.000027	0.0000467	0.0000275	0.0000452	0.0000267
25	26	0.0000325	0.0000191	0.0000332	0.0000195	0.0000321	0.0000189
26	27	0.0000049	0.0000029	0.0000050	0.0000030	0.0000049	0.0000029
24	28	0.0000064	0.0000038	0.0000066	0.0000039	0.0000064	0.0000038
28	29	0.0000062	0.0000037	0.0000063	0.0000037	0.0000061	0.0000036
22	30	0.004199	0.004337	0.004746	0.004902	0.002729	0.002819
30	31	0.017431	0.018003	0.019739	0.020387	0.011338	0.01171
31	32	0.002089	0.002158	0.002377	0.002455	0.001362	0.001407
32	33	0	0	0.00051	0.000301	0	0
33	34	0.0000255	0.000015	0.0000263	0.0000155	0.0000252	0.0000149
32	35	0.002969	0.003071	0.003557	0.003679	0.001789	0.00185
35	36	0	0	0.000437	0.000166	0	0
35	37	0.011716	0.012099	0.015063	0.015556	0.006367	0.006575
37	38	0.0000962	0.0000994	0.0000983	0.000101	0.0000946	0.0000977
38	39	0.0000169	0.0000098	0.0000173	0.0000102	0.0000166	0.0000098
37	40	0.013233	0.007803	0.017349	0.01023	0.006781	0.003999
40	41	0.004777	0.002816	0.006298	0.003713	0.002406	0.001418
41	42	0.001846	0.001089	0.002452	0.001447	0.000909	0.000536
42	43	0.001573	0.0006	0.001609	0.000614	0.00154	0.000588
43	44	0.0000223	0.0000085	0.0000228	0.0000087	0.0000218	0.0000083

4-9: - Power losses (Cont...)

From Bus	To Bus	Total Line losses at 100% loading					
		DSTATCOM		SVC		UPQC	
		MW	MVar	MW	MVar	MW	MVar
43	45	0.004349	0.001658	0.004449	0.001696	0.004259	0.001624
45	46	0.001077	0.000411	0.001102	0.00042	0.001055	0.000402
46	47	0.000821	0.000309	0.00084	0.000316	0.000804	0.000303
47	48	0.000262	0.000154	0.000268	0.000158	0.000256	0.000151
48	49	0.0000542	0.0000319	0.0000554	0.0000327	0.0000531	0.0000313
49	50	0.0000525	0.0000309	0.0000537	0.0000316	0.0000514	0.0000303
47	51	0.000488	0.000186	0.0005	0.00019	0.000478	0.000182
51	52	0.0000259	0.0000153	0.0000265	0.0000156	0.0000254	0.000015
52	53	2.05E-05	0.0000121	0.000021	0.0000124	0.0000201	0.0000118
53	54	0.0000196	0.0000115	0.00002	0.0000118	0.0000192	0.0000113
42	55	0.000668	0.003226	0.000962	0.004647	0.000263	0.001269
55	56	0.0000573	0.0000338	0.0000586	0.0000346	0.0000561	0.0000331
56	57	0.0000343	0.0000202	0.0000351	0.0000207	0.0000336	0.0000198
55	58	0.000231	0.000264	0.000337	0.000385	0.0000884	0.000101
58	59	0.00115	0.001186	0.001697	0.00175	0.000434	0.000448
59	60	0.000991	0.001023	0.001479	0.001527	0.000372	0.000384
60	61	0.000209	0.000216	0.000214	0.000221	0.000204	0.000211
61	62	0.0000173	0.0000102	0.0000177	0.0000104	0.0000169	0.00000996
61	63	0.002622	0.001544	0.002684	0.00158	0.002563	0.001509
63	64	0.000748	0.000441	0.000766	0.000452	0.000732	0.000432
64	65	0.0000068	0.000004	0.00000696	0.0000041	0.0000066	0.00000392
64	66	0.001689	0.000997	0.001729	0.00102	0.001651	0.000974
66	71	0.0000596	0.0000351	0.000061	0.000036	0.0000582	0.0000343
71	72	0	0	0	0	0	0
66	67	0.000193	0.000114	0.000197	0.000116	0.000188	0.000111
67	68	0.00015	0.0000884	0.000153	0.0000905	0.000146	0.0000864
68	69	0.000029	0.0000171	0.0000297	0.0000175	0.0000284	0.0000167
68	70	0.0000088	0.0000052	0.00000905	0.0000053	0.0000086	0.0000051
60	73	0.002639	0.001556	0.004182	0.002466	0.001448	0.000854
73	74	0.001112	0.000656	0.00176	0.001037	0.00074	0.000436
74	75	0.0000673	0.0000397	0.000118	0.0000699	0.0000343	0.0000202
75	76	0.000122	0.0000717	0.000394	0.000232	0.0000522	0.0000308
76	77	0.000141	0.0000538	0.000542	0.000207	0.0000594	0.0000227
77	78	0.000221	0.0000843	0.001735	0.000662	0.000114	0.0000434
78	79	0.0000146	0.0000056	0.000183	6.99E-05	0.0000117	0.00000445
79	80	0.0000207	0.0000122	0.0000212	0.0000125	0.0000201	0.0000119
79	81	0	0	0.000191	0.000113	0	0

4-9: - Power losses (Cont...)

From Bus	To Bus	Total Line losses at 100% loading					
		DSTATCOM		SVC		UPQC	
		MW	MVar	MW	MVar	MW	MVar
74	82	0.001572	0.000927	0.001825	0.001076	0.001701	0.001003
82	83	0	0	0.000823	0.000484	0	0
83	84	0.000127	0.0000751	0.000136	8.01E-05	0.000126	0.0000744
84	85	0.000621	0.000366	0.000662	0.00039	0.000615	0.000362
85	86	0.0000449	0.0000265	0.0000479	0.0000282	0.0000445	0.0000262
86	87	0.0000134	0.0000138	0.0000143	0.0000148	0.0000133	0.0000137
85	88	0.0000355	0.0000209	0.0000378	0.0000223	0.0000351	0.0000207
84	89	0.0000136	0.0000801	0.0000145	0.0000085	0.0000134	0.0000079

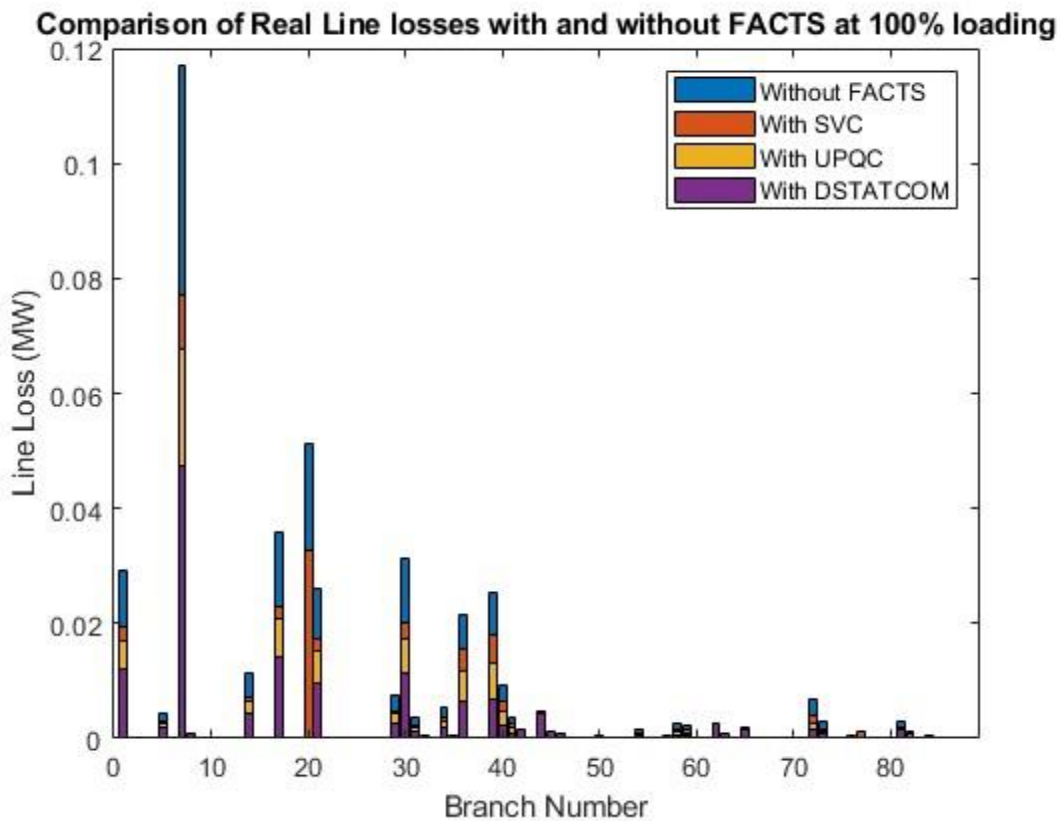


Figure 4-8:- Real line losses before and after installation of FACTS Devices at full load

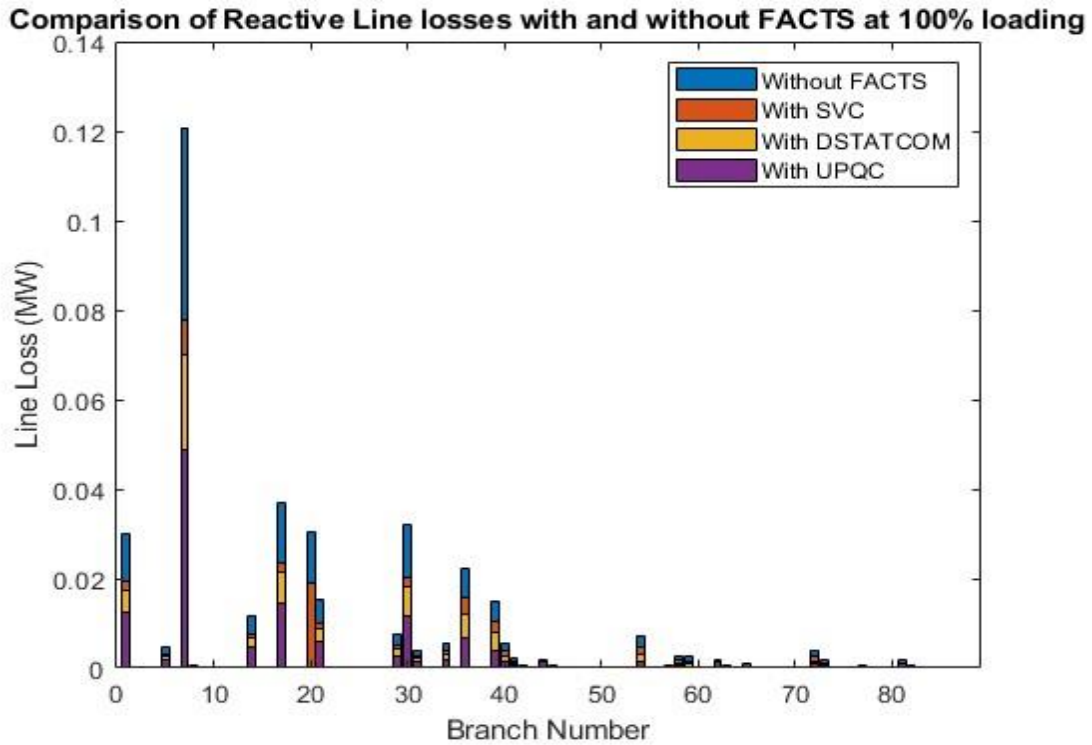


Figure 4-9:- Reactive losses before and after installation of FACTS Devices at full load

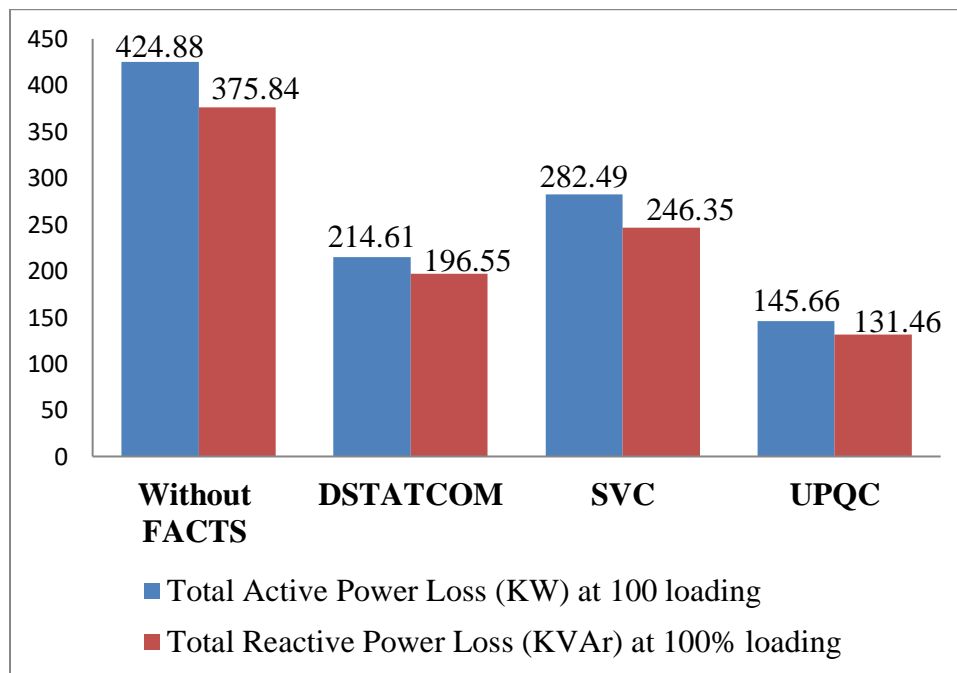


Figure 4-10:-Total Active and reactive Power losses with and without FACTS devices

Therefore, at full load (100%) condition, after installation of DSTACOM, SVC and UPQC devices the active power losses of the system is reduced significantly. And also the percentage of power loss reduction performance of UPQC device is higher than of DSTATCOM and SVC devices. When the performance of DSTACOM is compared with SVC, DSTATCOM has higher performance than SVC device.

In similar manner, in order to show the response of DSTATCOM, SVC and UPQC devices under peak load condition, each bus active and reactive power load was increased by 25% of full load condition.

Then, the active and reactive power loss of Sebbata-I substation 15 kV outgoing feeder-12 was analyzed in MATLAB software similar to the above. The total active and reactive power loss before and after installation of DSTATCOM, SVC and UPQC device are analyzed using forward-backward load flow approach in order to see the effect of FACTS devices under peak load condition.

The size of DSTATCOM, SVC and UPQC devices were decided based on PSO algorithm and the candidate buses were determined with loss sensitivity Index. Accordingly, sizes and candidate buses for this scenario are shown on the table below;

Table 4-10:- Installed FACTS Devices values at the candidate buses at 125% loading

Candidate bus	83	36	33	81	54
Installed DSTATCOM Size (kVAr)	801.00	830.88	400.50	171.00	373.00
Installed SVC Size (kVAr)	1059.9	1039.1	1037.9	1058.5	1028.0
Installed UPQC Size (kVAr)	881.10	913.96	440.55	188.10	410.30

At this load condition, again the size of the SVC is higher than UPQC and DSTATCOM devices which directly affect the investment cost of SVC device.

The active and reactive power loss for each branch is presented both in tables and bar graphs as follows;

Table 4-10:- Power losses of the selected test system with FACTS device at 125% loading

From Bus	To Bus	Total Line losses at 125% loading					
		DSTATCOM		SVC		UPQC	
		MW	MVar	MW	MVar	MW	MVar
1	2	0.026472	0.027344	0.031893	0.032943	0.018692	0.019307
2	3	0.000165	0.0000975	0.000166	0.0000976	0.000165	0.0000974
3	4	0.0000182	0.0000107	0.0000182	0.0000107	0.0000181	0.0000107
2	5	0.0000099	0.0000038	0.00001	0.0000038	0.0000099	0.0000038
2	6	0.004042	0.004174	0.004842	0.005	0.002823	0.002916
6	7	0.0000004	0.00000022	0.00000037	0.0000002	0.00000037	0.00000022
6	8	0.105996	0.109424	0.126905	0.131009	0.073965	0.076357
8	9	0.001144	0.000674	0.001153	0.00068	0.001137	0.000671
9	10	0.000533	0.000314	0.000538	0.000317	0.000531	0.000313
10	11	0.000183	0.000108	0.000184	0.000109	0.000182	0.000107
11	12	0.0000858	0.0000506	0.0000865	0.000051	0.0000853	0.0000503
10	13	0.000164	0.0000624	0.000166	0.000063	0.000164	0.0000621
13	14	9.15E-05	0.0000349	0.0000923	0.0000352	0.0000911	0.0000347
8	15	0.010247	0.010583	0.012065	0.01246	0.007013	0.007243
15	16	0.000288	0.00017	0.000291	0.000171	0.000286	0.000169
16	17	0.000128	0.0000755	0.000129	0.0000762	0.000127	0.000075
15	18	0.032444	0.033506	0.037773	0.039009	0.022053	0.022774
18	19	0.0000851	0.0000502	0.0000861	0.0000508	0.0000845	0.0000498
19	20	0.0000382	0.0000225	0.0000387	0.0000228	0.0000379	0.0000223
18	21	0	0	0.053486	0.031543	0	0
21	22	0.023557	0.013893	0.028324	0.016704	0.015325	0.009038
22	23	0.0000922	0.0000544	0.0000955	0.0000563	0.0000911	0.0000537
23	24	0.0000409	0.0000241	0.0000424	0.000025	0.0000404	0.0000238
24	25	0.0000716	0.0000422	0.0000742	0.0000437	0.0000707	0.0000417
25	26	0.0000509	0.0000299	0.0000527	0.000031	0.0000503	0.0000296
26	27	0.0000077	0.00000452	0.0000079	0.0000047	0.0000759	0.00000447
24	28	0.0000101	0.00000593	0.0000104	0.000062	0.0000099	0.00000587
28	29	0.0000097	0.00000573	0.0000101	0.0000059	0.0000096	0.00000566
22	30	0.006555	0.006771	0.008	0.008263	0.004274	0.004415
30	31	0.02721	0.028102	0.033263	0.034354	0.017755	0.018338
31	32	0.003261	0.003369	0.004002	0.004134	0.002133	0.002204
32	33	0	0	0.000578	0.000341	0	0
33	34	0.0000398	0.0000235	0.000042	0.0000248	0.0000394	0.0000232
32	35	0.004635	0.004794	0.00603	0.006237	0.002803	0.002899
35	36	0	0	0.000618	0.000235	0	0
35	37	0.018311	0.01891	0.025506	0.026341	0.009989	0.010316
37	38	0.000151	0.000156	0.000157	0.000162	0.000148	0.000153

Table 4-10: Power loss of selected system with FACTS at 125% loading (Cont...)

From Bus	To Bus	Total Line losses at 125% loading					
		DSTATCOM		SVC		UPQC	
		MW	MVar	MW	MVar	MW	MVar
38	39	0.0000266	0.0000157	0.0000276	1.63E-05	0.0000261	0.0000154
37	40	0.020673	0.012189	0.029432	0.017354	0.010637	0.006272
40	41	0.007461	0.004398	0.010689	0.006301	0.003774	0.002224
41	42	0.002883	0.001701	0.004164	0.002457	0.001426	0.000841
42	43	0.002484	0.000948	0.002593	0.000989	0.002427	0.000926
43	44	0.0000351	0.0000134	0.0000366	0.000014	0.0000343	0.0000131
43	45	0.006876	0.002621	0.007178	0.002736	0.006718	0.002561
45	46	0.001703	0.000649	0.001778	0.000678	0.001664	0.000634
46	47	0.001298	0.000489	0.001355	0.00051	0.001268	0.000478
47	48	0.000414	0.000244	0.000432	0.000255	0.000404	0.000238
48	49	0.0000857	0.0000505	0.0000894	0.0000527	0.0000837	0.0000493
49	50	0.000083	0.0000489	0.0000866	0.000051	0.0000811	0.0000478
47	51	0.000773	0.000294	0.000806	0.000307	0.000755	0.000287
51	52	0.000041	0.0000242	0.0000428	0.0000253	0.0000401	0.0000236
52	53	0.0000324	0.0000191	0.0000339	0.00002	0.0000317	0.0000187
53	54	0.000031	0.0000183	0.0000323	0.0000191	0.0000302	0.0000178
42	55	0.001038	0.005013	0.001629	0.00787	0.00041	0.00198
55	56	0.0000903	0.0000533	0.0000942	0.0000556	0.0000881	0.000052
56	57	0.0000541	0.0000319	0.0000564	0.0000333	0.0000528	0.0000311
55	58	0.000358	0.00041	0.00057	0.000651	0.000138	0.000157
58	59	0.001785	0.001841	0.002864	0.002954	0.000676	0.000698
59	60	0.001537	0.001588	0.002488	0.00257	0.000578	0.000597
60	61	0.00033	0.000341	0.000345	0.000357	0.000322	0.000332
61	62	0.0000272	0.000016	0.0000284	0.0000168	0.0000265	0.0000156
61	63	0.004144	0.00244	0.004333	0.002551	0.00404	0.002379
63	64	0.001183	0.000698	0.001237	0.00073	0.001153	0.00068
64	65	0.0000107	0.00000633	0.0000112	0.0000066	0.0000105	0.0000062
64	66	0.002673	0.001577	0.002795	0.001649	0.002606	0.001537
66	71	0.0000942	0.0000556	0.0000985	0.000058	0.0000918	0.0000542
71	72	0	0	0	0	0	0
66	67	0.000305	0.00018	0.000319	0.000188	0.000297	0.000175
67	68	0.000237	0.00014	0.000248	0.000146	0.000231	0.000136
68	69	0.000046	0.0000271	0.0000481	0.0000283	0.0000448	0.0000264
68	70	0.000014	0.0000083	0.0000146	0.0000864	0.0000136	0.0000081
60	73	0.004077	0.002404	0.006694	0.003947	0.002246	0.001324
73	74	0.001718	0.001013	0.002759	0.001627	0.001149	0.000678
74	75	0.000104	0.0000611	0.000151	0.0000893	0.0000536	0.0000316

Table 4-10: Power loss of selected system with FACTS at 125% loading (Cont...)

From Bus	To Bus	Total Line losses at 125% loading					
		DSTATCOM		SVC		UPQC	
		MW	MVar	MW	MVar	MW	MVar
75	76	0.000185	0.000109	0.000445	0.000263	0.0000812	0.0000479
76	77	0.000214	0.0000816	0.0006	0.000229	0.0000923	0.0000352
77	78	0.000331	0.000126	0.001804	0.000688	0.000176	0.000067
78	79	0.0000217	0.00000828	0.000187	0.0000712	0.000018	0.000069
79	80	0.0000326	0.00000192	0.0000341	0.0000201	0.0000316	0.0000186
79	81	0	0	0.000194	0.000115	0	0
74	82	0.002452	0.001446	0.003059	0.001804	0.002655	0.001566
82	83	0	0	0.001359	0.000799	0	0
83	84	0.000199	0.000117	0.000219	0.000129	0.000197	0.000116
84	85	0.000971	0.000572	0.00107	0.000631	0.000961	0.000567
85	86	0.0000702	0.0000414	0.0000774	0.0000456	0.0000695	0.000041
86	87	0.000021	0.0000217	0.0000231	0.0000239	0.0000208	0.0000214
85	88	0.0000554	0.0000327	0.0000611	0.000036	0.0000549	0.0000324
84	89	0.0000212	0.0000125	0.0000234	0.0000138	0.000021	0.0000124

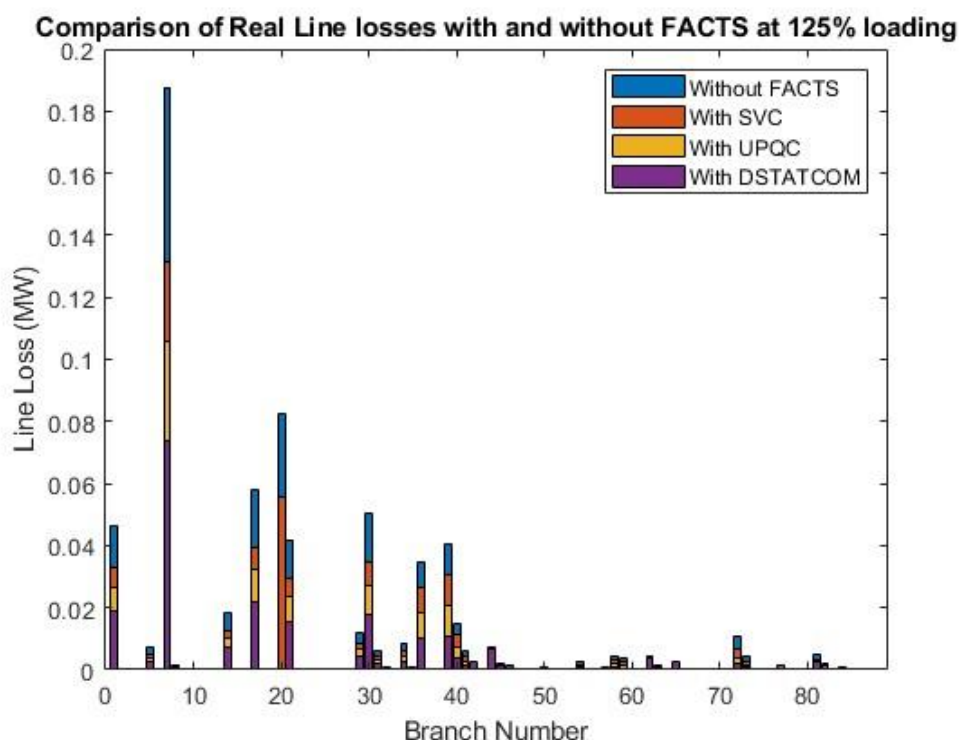


Figure 4-11:- Active power losses with and without FACTS Devices at 125% overloading

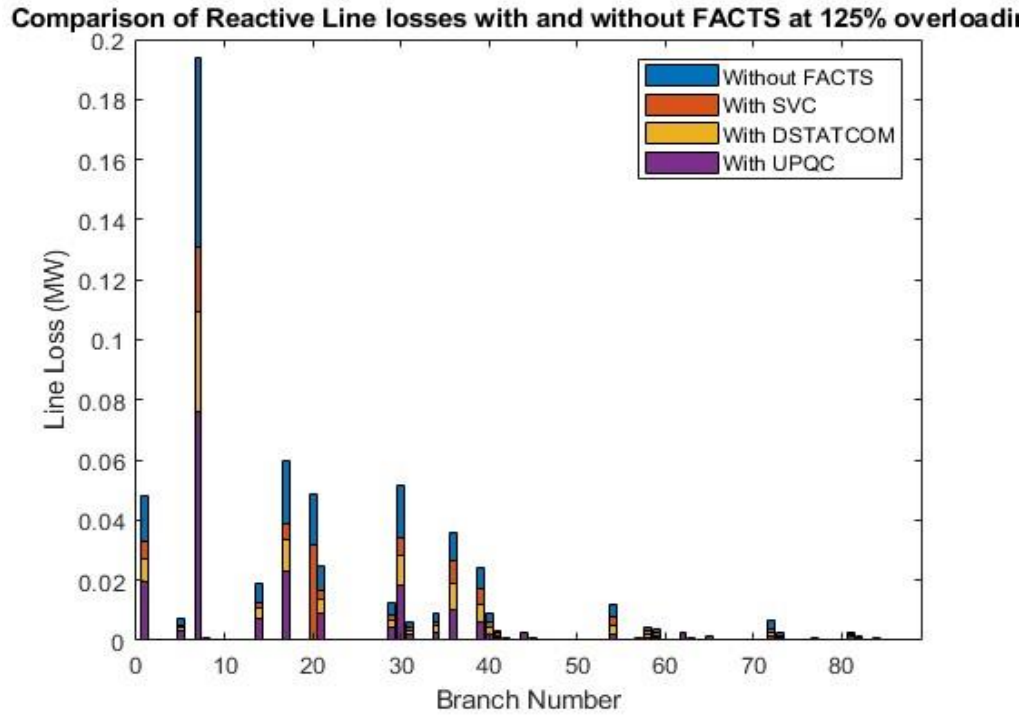


Figure 4-12:- Reactive loss before and after installation of FACTS Devices at 125% overloading

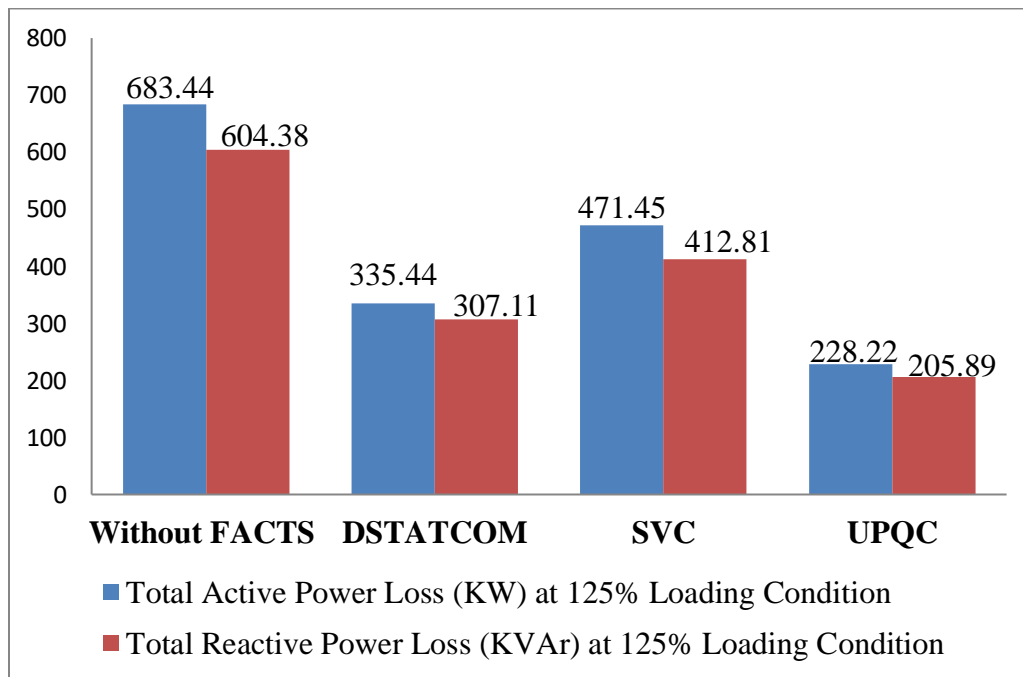


Figure 4-13:- Total active and reactive Power losses with and without FACTS devices at 125% loading

Under this loading scenario, after installation of DSTATCOM, SVC and UPQC devices, the total real line loss reduced from 683.44 kW to 335.44 kW, 471.45 kW, and 228.22 kW with installation of DSTATCOM, SVC and UPQC devices respectively. Likewise, the base case reactive power loss was reduced from 604.38 kVAr to 307.11 kVAr, 412.81 kVAr, and 205.89 kVAr with installation of DSTATCOM, SVC and UPQC devices respectively

The reduction of the real and reactive power losses represent 50.92%, 31.02%, 66.01% and 49.19%, 31.70% and 65.93%/ with installation of DSTATCOM, SVC and UPQC devices respectively.

The MATLAB simulation analysis shows that the real and reactive power loss reduction performance of the UPQC devices is 64.85%, 65.72%, 66.01% and 64.13%, 65.02%, 65.93% at 75% of full load, 100 % and 125% overloading conditions respectively. Whereas the power loss reduction performance of DSTATCOM device is 48.06 %, 49.49 %, 50.92 % and 46.22%, 47.70% , 49.19% at 75% of full load, 100 % and 125% overloading respectively. And also the power losses reduction performance of SVC device is 34.45%, 33.51%, 31.02 % and 35.91%, 34.45%, 31.70% at 75% of full load, 100 % and 125% loading conditions respectively.

Based on this simulation results, the power losses reduction performance of UPQC device is much greater when compared with DSTATCOM and SVC devices. And also by comparing the power losses reduction performance of DSTATCOM and SVC, DSTATCOM device has better power reduction performance than SVC device.

### **4.3.2 Voltage Profile Improvement**

At 75% of full load condition, with installation of DSTATCOM, SVC and UPQC devices at the determined candidate bus locations, the system voltage profile has been examined in order to check the effect of these devices. Accordingly, with installation of DSTATCOM, SVC and UPQC devices, Sebbata-I substation 15 kV outgoing feeder-12 radial distribution system is examined and the output is depicted in the table below;

Table 4-11:- Voltage Profile Improvement with installation FACTS devices at 75% of full load

Bus No	Loading 75% of full load			Bus No	Loading 75% of full load		
	DSTATCOM	SVC	UPQC		DSTATCOM	SVC	UPQC
1	1	1	1	46	0.974162	0.971258	0.983075
2	0.998616	0.998511	0.998913	47	0.973492	0.970587	0.982412
3	0.998353	0.998249	0.99865	48	0.973076	0.970169	0.981999
4	0.998291	0.998186	0.998588	49	0.972952	0.970045	0.981877
5	0.998587	0.998483	0.998884	50	0.972706	0.969799	0.981633
6	0.998402	0.99828	0.998748	51	0.972551	0.969643	0.98148
7	0.998397	0.998275	0.998743	52	0.972481	0.969573	0.98141
8	0.992802	0.992221	0.994452	53	0.972417	0.969508	0.981346
9	0.992159	0.991577	0.99381	54	0.972344	0.969435	0.981274
10	0.991822	0.99124	0.993474	55	0.97869	0.975806	0.987787
11	0.991589	0.991007	0.993241	56	0.978448	0.975563	0.987547
12	0.991355	0.990772	0.993007	57	0.978217	0.97533	0.987318
13	0.991641	0.991059	0.993293	58	0.978628	0.975736	0.987763
14	0.991476	0.990894	0.993129	59	0.978314	0.975383	0.987643
15	0.992254	0.99162	0.994054	60	0.97804	0.975071	0.987552
16	0.991886	0.991252	0.993686	61	0.977848	0.974879	0.987362
17	0.991550	0.990915	0.99335	62	0.977732	0.974762	0.987247
18	0.990524	0.989709	0.992834	63	0.975649	0.972673	0.985184
19	0.990324	0.989508	0.992634	64	0.974963	0.971985	0.984505
20	0.990140	0.989324	0.992451	65	0.974924	0.971946	0.984466
21	0.990000	0.986936	0.995000	66	0.972449	0.969464	0.982015
22	0.988308	0.985343	0.993825	67	0.972074	0.969088	0.981644
23	0.988234	0.985268	0.993751	68	0.971599	0.968611	0.981173
24	0.988197	0.985231	0.993714	69	0.971463	0.968475	0.981038
25	0.988104	0.985138	0.993622	70	0.971511	0.968523	0.981087
26	0.988006	0.985039	0.993524	71	0.972073	0.969086	0.981643
27	0.987968	0.985001	0.993487	72	0.972073	0.969086	0.981643
28	0.988166	0.985200	0.993683	73	0.977248	0.974053	0.987577
29	0.988121	0.985155	0.993638	74	0.976927	0.973622	0.987654
30	0.987736	0.984856	0.993502	75	0.976842	0.973589	0.987596
31	0.985346	0.982828	0.992164	76	0.976629	0.973569	0.987483
32	0.985054	0.982583	0.992004	77	0.976372	0.973466	0.987345
33	0.990000	0.982549	0.995000	78	0.975827	0.973406	0.987167
34	0.989877	0.982426	0.994878	79	0.975785	0.973415	0.987163
35	0.984598	0.982146	0.991741	80	0.975698	0.973327	0.987077
36	0.990000	0.981922	0.995000	81	0.972073	0.973491	0.995000
37	0.982467	0.979884	0.990241	82	0.977248	0.972794	0.988128

Table 4-11: Voltage Profile Improvement with installation of FACTS devices (Cont....)

Bus No	Loading 75% of full load			Bus No	Loading 75% of full load		
	DSTATCOM	SVC	UPQC		DSTATCOM	SVC	UPQC
38	0.982258	0.979675	0.990034	83	0.976927	0.972405	0.995000
39	0.982184	0.9796	0.989961	84	0.976842	0.972237	0.994836
40	0.980143	0.97736	0.98863	85	0.976629	0.971149	0.993772
41	0.979284	0.976425	0.988042	86	0.976372	0.971017	0.993643
42	0.978941	0.976052	0.987812	87	0.975827	0.970941	0.993569
43	0.978090	0.975198	0.986968	88	0.975785	0.970994	0.993622
44	0.978000	0.975108	0.986879	89	0.975698	0.972166	0.994766
45	0.974964	0.972063	0.98387				

At 75% of full load condition, with installation of DSTATCOM, SVC and UPQC devices at the determined candidate bus locations, the base case voltage profile is enhanced from 0.9537pu to 0.9715pu, 0.9695pu, and 0.9810pu respectively. Summary of the minimum voltage profile with and without installation of DSTATCOM, SVC and UPQC devices at 75% of full load condition has been depicted as follow:

Table 4-12:- Summary of minimum Voltage with and without FACTS at 75% of full load

	Without FACTS Devices	DSTATCOM	SVC	UPQC
Minimum Voltage (pu)	0.9537	0.9715	0.9695	0.9810
Bus Number	69	69	69	69

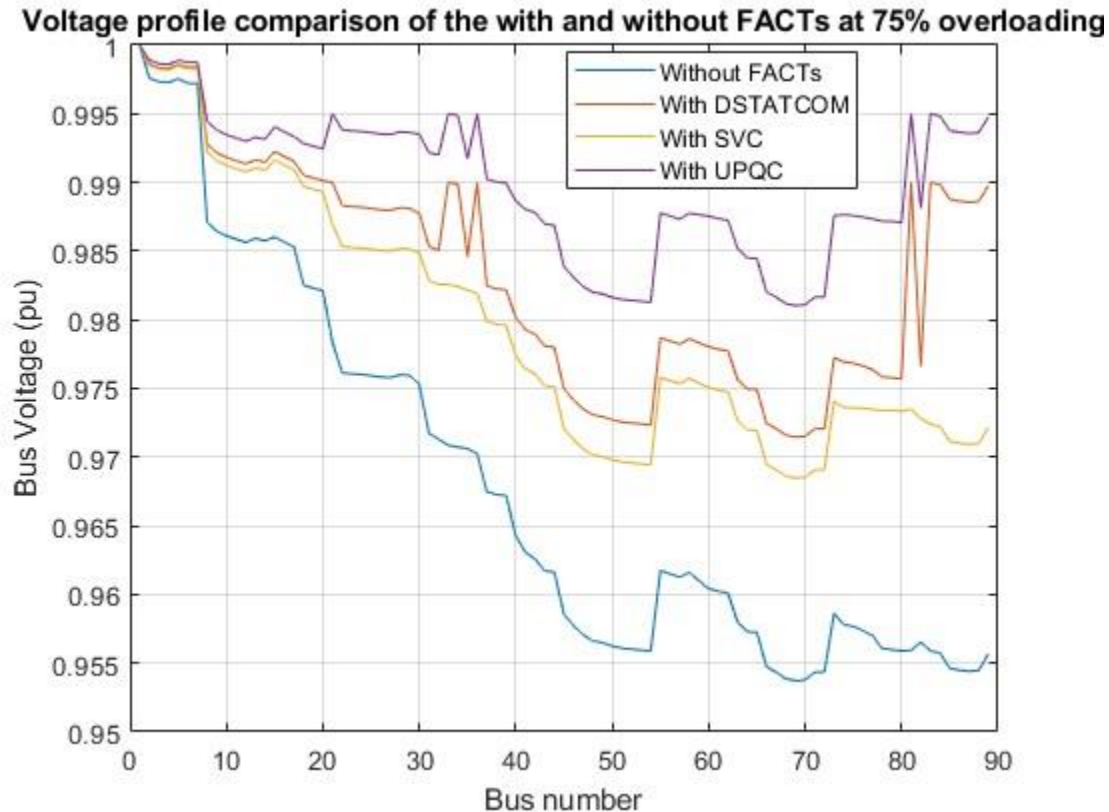


Figure 4-14:-Voltage profile comparison with and without FACTS at 75% of full load

As shown in the figure above, before installation of FACTS devices the buses closest to the source have higher voltage profile and as the length of the feeder increases the voltage profile becomes lower at the far end. Then, after installation of DSTATCOM, SVC and UPQC devices, the voltage profile of the system has been improved from 0.95374pu to 0.9715pu, 0.9695pu and 0.9810pu respectively. This clearly reveals that voltage profile enhancing performance of UPQC device is greater than DSTATCOM and SVC devices.

Again, at full load ( 100% loading ) condition, Sebbata-I substation 15 kV outgoing feeder-12 lines and bus data were simulated using MATLAB software in forward-backward load flow algorithm and the voltage profile at each bus of the feeder after installation of DSTATCOM, SVC and UPQC devices have been examined. Consequently, the minimum voltage before installation of the FACTS devices was 0.937p.u which is below the standard IEEE distribution system minimum voltage level has been enhanced to 0.9652p.u, 0.9538p.u, and 0.9763p.u with

installation of DSTATCOM, SVC and UPQC devices respectively. The simulation result for all buses through the feeder has been shown both in tabular and graph as follow;

Table 4-13:-Voltage Profile Improvement with FACTS Devices at 100% loading

Bus No	Loading 100%			Bus No	Loading 100%		
	DSTATCOM	SVC	UPQC		DSTATCOM	SVC	UPQC
1	1	1	1	46	0.968845	0.956401	0.979034
2	0.998154	0.997668	0.998548	47	0.967948	0.955492	0.978145
3	0.997804	0.997317	0.998197	48	0.967388	0.954926	0.977592
4	0.997721	0.997234	0.998114	49	0.967223	0.954758	0.977428
5	0.998117	0.99763	0.99851	50	0.966893	0.954424	0.977102
6	0.997869	0.997301	0.998328	51	0.966685	0.954213	0.976896
7	0.997863	0.997295	0.998322	52	0.966591	0.954118	0.976803
8	0.990414	0.98769	0.992595	53	0.966504	0.95403	0.976717
9	0.989554	0.986828	0.991737	54	0.966407	0.953931	0.97662
10	0.989104	0.986377	0.991288	55	0.974925	0.962344	0.985344
11	0.988792	0.986064	0.990977	56	0.974601	0.962015	0.985023
12	0.988479	0.98575	0.990664	57	0.974291	0.961701	0.984716
13	0.988861	0.986133	0.991046	58	0.974843	0.96223	0.985311
14	0.988642	0.985913	0.990827	59	0.974428	0.961655	0.985151
15	0.989686	0.986713	0.992064	60	0.974065	0.961141	0.985029
16	0.989194	0.98622	0.991574	61	0.973808	0.960881	0.984774
17	0.988744	0.985768	0.991125	62	0.973653	0.960723	0.98462
18	0.987390	0.983564	0.990442	63	0.970859	0.957891	0.981858
19	0.987122	0.983295	0.990174	64	0.969939	0.956959	0.980948
20	0.986877	0.983048	0.989930	65	0.969887	0.956906	0.980897
21	0.990000	0.979336	0.995000	66	0.966566	0.95354	0.977613
22	0.987743	0.976965	0.993428	67	0.966063	0.95303	0.977115
23	0.987644	0.976865	0.993329	68	0.965425	0.952383	0.976485
24	0.987594	0.976815	0.993280	69	0.965242	0.952198	0.976304
25	0.987471	0.97669	0.993157	70	0.965307	0.952264	0.976369
26	0.987339	0.976557	0.993026	71	0.966061	0.953028	0.977114
27	0.987289	0.976506	0.992976	72	0.966061	0.953028	0.977114
28	0.987553	0.976773	0.993238	73	0.973029	0.959481	0.985065
29	0.987493	0.976712	0.993179	74	0.972612	0.95876	0.985169
30	0.986979	0.97618	0.992994	75	0.972498	0.958686	0.985093
31	0.983786	0.9729	0.991201	76	0.972215	0.958546	0.984941
32	0.983397	0.9725	0.990987	77	0.971875	0.958308	0.984757
33	0.990000	0.972307	0.995000	78	0.971153	0.957914	0.984522
34	0.989836	0.97214	0.994837	79	0.971098	0.957893	0.984516
35	0.982788	0.971823	0.990633	80	0.970982	0.957774	0.984401

Table 4-13: Voltage Profile (Cont....)

Bus No	Loading 100%			Bus No	Loading 100%		
	DSTATCOM	SVC	UPQC		DSTATCOM	SVC	UPQC
36	0.990000	0.971460	0.995000	81	0.990000	0.957953	0.995000
37	0.979949	0.968452	0.988627	82	0.972233	0.957479	0.985807
38	0.979670	0.968170	0.988350	83	0.990000	0.956867	0.995000
39	0.979571	0.968069	0.988252	84	0.989780	0.956639	0.994781
40	0.976855	0.964796	0.986473	85	0.988354	0.955163	0.993362
41	0.975712	0.963439	0.985686	86	0.988181	0.954985	0.993190
42	0.975256	0.962896	0.985378	87	0.988082	0.954882	0.993092
43	0.974114	0.961739	0.984248	88	0.988152	0.954954	0.993161
44	0.973994	0.961617	0.984129	89	0.989687	0.956542	0.994688
45	0.969921	0.957491	0.980099				

The simulation result clearly reveals that, after installation of DSTATCOM, SVC and UPQC devices at the determined candidate bus locations, the base case voltage profile of the system is enhanced from 0.937p.u to 0.9652, 0.9538, and 0.9763 respectively.

Summary of the minimum voltage profile with and without integration of DSTATCOM, SVC and UPQC devices at 100% loading condition has been depicted as follow:

Table 4-14:-Summary of minimum Voltage with and without FACTS at 100% loading

	Without FACTS Devices	DSTATCOM	SVC	UPQC
Minimum Voltage (pu)	0.9374	0.9652	0.9538	0.9763
Bus Number	69	69	69	69

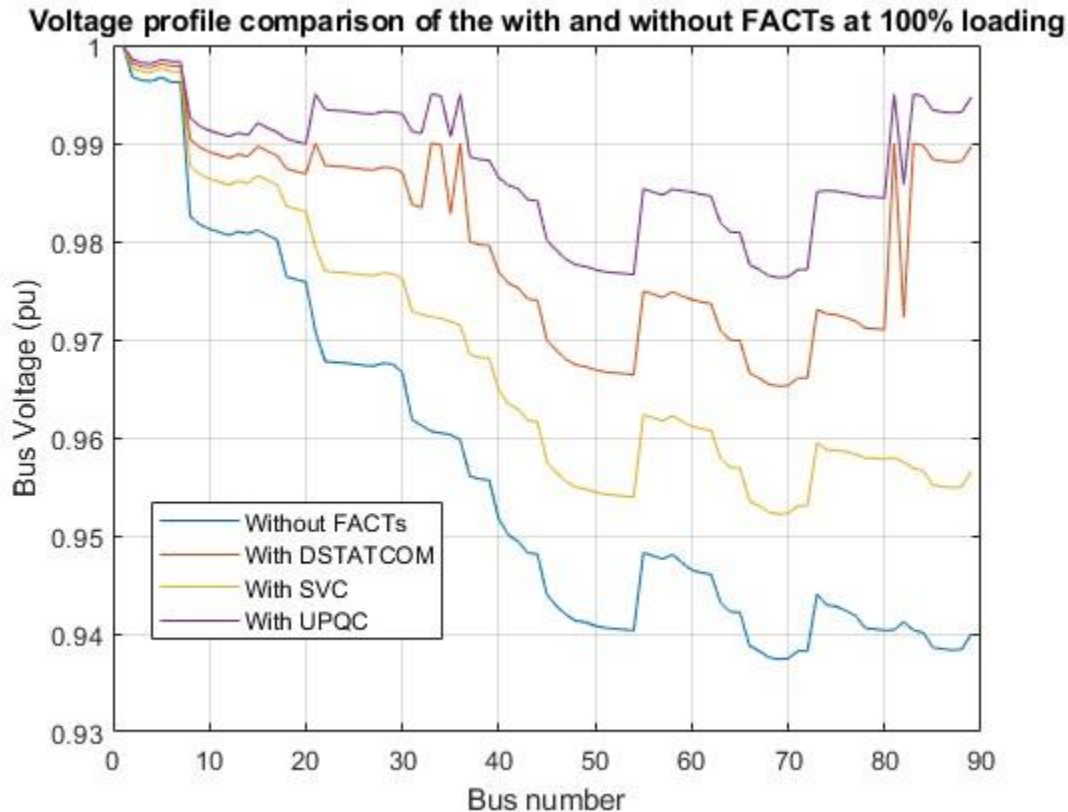


Figure 4-15:-Voltage profile comparison with and without FACTS at 100% loading

As shown in the figure above, before installation of FACTS devices buses closest to the source have higher voltage profile and as the length of the feeder increases the voltage profile becomes lower at the far end. Then after installation of DSTATCOM, SVC and UPQC devices, the distribution system voltage profile enhanced from 0.9374pu to 0.965pu, 0.952pu and 0.9763pu respectively. This clearly reveals that voltage profile enhancing performance of UPQC device is much greater than DSTATCOM and SVC devices.

On the other hand, by increasing the full load by 25%, the response of the DSTATCOM, SVC and UPQC devices have been tested and analyzed using a backward-forward power flow algorithm in MATLAB. Accordingly, for this loading scenario, the minimum base case voltage profile has been enhanced from 0.9206pu to 0.9590pu, 0.9354pu, and 0.9715pu with installation of DSTATCOM, SVC and UPQC devices respectively. The simulation result for the voltage

profile before and after installation of devices at 125% overloading is presented in both tabular and graphical form as follow;

Table 4-15:-Voltage Profile Improvement with FACTS Devices at 125% loading

Bus No	Loading at 125%			Bus No	Loading at 125%		
	DSTATCOM	SVC	UPQC		DSTATCOM	SVC	UPQC
1	1	1	1	46	0.963523	0.941094	0.974957
2	0.997686	0.996802	0.998181	47	0.962394	0.939938	0.973842
3	0.997248	0.996363	0.997743	48	0.96169	0.939218	0.973147
4	0.997144	0.996259	0.997639	49	0.961482	0.939004	0.972941
5	0.997639	0.996754	0.998134	50	0.961068	0.93858	0.972531
6	0.997329	0.996297	0.997906	51	0.960805	0.938311	0.972272
7	0.997321	0.996289	0.997898	52	0.960688	0.938191	0.972156
8	0.987992	0.983038	0.990735	53	0.960579	0.938079	0.972048
9	0.986914	0.981954	0.989659	54	0.960456	0.937953	0.971926
10	0.986350	0.981387	0.989097	55	0.971174	0.94848	0.982880
11	0.985959	0.980994	0.988707	56	0.970767	0.948063	0.982478
12	0.985566	0.980599	0.988315	57	0.970378	0.947665	0.982093
13	0.986046	0.981081	0.988793	58	0.971071	0.948320	0.982838
14	0.985770	0.980804	0.988519	59	0.970555	0.947516	0.982638
15	0.987082	0.981674	0.990072	60	0.970104	0.946793	0.982485
16	0.986465	0.981054	0.989457	61	0.969781	0.946462	0.982165
17	0.985901	0.980487	0.988895	62	0.969586	0.946261	0.981972
18	0.984213	0.97725	0.988047	63	0.966073	0.942661	0.978504
19	0.983877	0.976911	0.987713	64	0.964916	0.941475	0.977362
20	0.983569	0.976601	0.987406	65	0.964850	0.941408	0.977297
21	0.990000	0.971524	0.995000	66	0.960673	0.937125	0.973173
22	0.987181	0.968353	0.993027	67	0.960040	0.936476	0.972547
23	0.987057	0.968226	0.992904	68	0.959237	0.935653	0.971755
24	0.986995	0.968163	0.992843	69	0.959008	0.935418	0.971528
25	0.986841	0.968006	0.992689	70	0.959090	0.935502	0.971609
26	0.986676	0.967838	0.992526	71	0.960038	0.936474	0.972545
27	0.986613	0.967774	0.992463	72	0.960038	0.936474	0.972545
28	0.986943	0.968110	0.992791	73	0.968827	0.944469	0.982534
29	0.986868	0.968033	0.992716	74	0.968315	0.943447	0.982667
30	0.986228	0.967260	0.992483	75	0.968174	0.943329	0.982571
31	0.982245	0.962687	0.990228	76	0.967825	0.943068	0.982381
32	0.981760	0.962128	0.989959	77	0.967406	0.942689	0.982152
33	0.990000	0.961773	0.995000	78	0.966526	0.941948	0.981859
34	0.989795	0.961562	0.994796	79	0.966460	0.941897	0.981853

Table 4-15: (Cont...)

Bus No	Loading at 125%			Bus No	Loading at 125%		
	DSTATCOM	SVC	UPQC		DSTATCOM	SVC	UPQC
35	0.981000	0.961204	0.989515	80	0.966314	0.941746	0.981708
36	0.990000	0.960699	0.995000	81	0.990000	0.941939	0.995000
37	0.977450	0.956687	0.986998	82	0.967858	0.941698	0.983470
38	0.977100	0.95633	0.986651	83	0.990000	0.940853	0.995000
39	0.976976	0.956203	0.986529	84	0.989725	0.940564	0.994727
40	0.973582	0.95186	0.984298	85	0.987942	0.938687	0.992952
41	0.972153	0.950067	0.983312	86	0.987726	0.93846	0.992737
42	0.971584	0.949348	0.982925	87	0.987601	0.938329	0.992613
43	0.970149	0.947878	0.981507	88	0.987689	0.938421	0.992701
44	0.969998	0.947724	0.981358	89	0.989608	0.940441	0.994610
45	0.964876	0.942479	0.976295				

Summary of the minimum voltage profile with and without installation of DSTATCOM, SVC and UPQC devices at 125% loading condition has been depicted as follow:

Table 4-16:- Minimum Voltage with and without FACTS at 125% overloading

	Without FACTS Devices	DSTATCOM	SVC	UPQC
Minimum Voltage (pu)	0.9206	0.9590	0.9377	0.9715
Bus Number	69	69	69	69

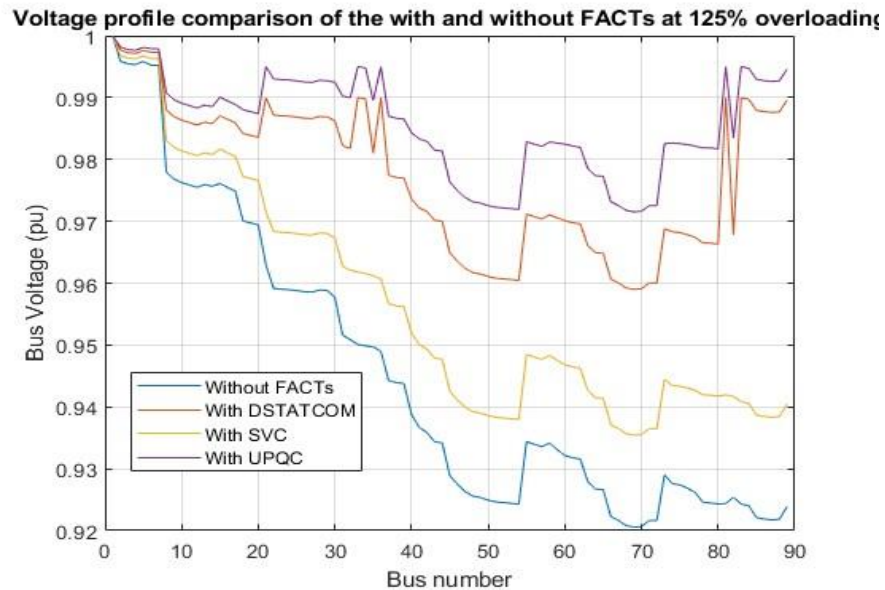


Figure 4-16:-Voltage profile comparison with and without FACTS at 125% loading

As it can be seen on the figure above, the voltage profile of the system has been improved with installation of DSTATCOM, SVC and UPQC devices, but, comparatively the voltage profile enhancement performance of the UPQC devices is much better than DSTATCOM and SVC devices.

**4.3.3 Loss Sensitivity Index Improvement After installation of FACTS devices**

At 75% of full load condition, the Loss Sensitivity Index of each buses of Sebbata-I substation feeder-12 radial distribution system has been examined with installation of DSTATCOM, SVC and UPQC devices at determined locations and sizes and the result is depicts below;

Table 4-17:- Loss Sensitivity Index with installation FACTS at 75% of full load

Bus No	Loading 75% of full load			Bus No	Loading 75% of full load		
	DSTATCOM	SVC	UPQC		DSTATCOM	SVC	UPQC
1	0	0	0	46	0.001274	0.000421	0.001231
2	0	0	0	47	0	0	0
3	0.000149	4.71E-05	0.000144	48	0.002275	0.000793	0.002202
4	0.000138	4.6E-05	0.000134	49	0.002758	0.000958	0.002669
5	0.000130	3.03E-05	0.000125	50	0.002738	0.000959	0.002649
6	0	0	0	51	0.001153	0.000426	0.001117
7	3.46E-05	7.72E-06	3.33E-05	52	0.000712	0.000266	0.00069
8	0	0	0	53	0.000611	0.00023	0.000592
9	0.000390	9.23E-05	0.000376	54	0.003302	0.001166	0.003196
10	0	0	0	55	0	0	0
11	0.000927	0.000249	0.000894	56	0.000885	0.000169	0.000849
12	0.000846	0.000238	0.000816	57	0.001484	0.000284	0.001424
13	0.000746	0.000203	0.000719	58	0.001586	0.000287	0.001522
14	0.001143	0.00031	0.001102	59	0.002036	0.000359	0.001953
15	0	0	0	60	0	0	0
16	0.000908	0.000171	0.000872	61	0	0	0
17	0.000873	0.000179	0.000839	62	0.001528	0.00028	0.001466
18	0	0	0	63	0.001124	0.00028	0.001082
19	0.000552	7.92E-05	0.000529	64	0.002762	0.000706	0.00266
20	0.000572	8.61E-05	0.000548	65	0.001975	0.000517	0.001903
21	0	0.002094	0.000304	66	0	0	0
22	0	0	0	67	0.002459	0.000789	0.002376
23	0.00057	5.92E-05	0.000545	68	0	0	0
24	0	0	0	69	0.002639	0.000865	0.002551
25	0.001018	0.000109	0.000974	70	0.001291	0.000441	0.001249

Table 4-17: Cont...

Bus No	Loading 75% of full load			Bus No	Loading 75% of full load		
	DSTATCOM	SVC	UPQC		DSTATCOM	SVC	UPQC
26	0.001306	0.000142	0.001249	71	0.001959	0.000632	0.001893
27	0.000787	9.09E-05	0.000752	72	0	0	0
28	0.00042	4.57E-05	0.000402	73	0.002586	0.000349	0.002475
29	0.000826	8.8E-05	0.00079	74	0	0	0
30	0.000497	4.96E-05	0.000475	75	0.002701	0.000294	0.002584
31	0.001277	0.000117	0.001219	76	0.00056	5.37E-05	0.000536
32	0	0	0	77	0.001877	9.01E-05	0.001795
33	0	0.002497	0.000438	78	0.001029	7.25E-05	0.000984
34	0.001543	5.62E-05	0.00147	79	0	0	0
35	0	0	0	80	0.002726	0.000281	0.002603
36	0	0.001446	0.000926	81	0	0.005192	0.000299
37	0	0	0	82	0.002467	0.000269	0.002355
38	0.002797	0.00037	0.002675	83	0	0.003187	0.001393
39	0.001804	0.000254	0.001727	84	0	0	0
40	0.001412	0.000239	0.001353	85	0	0	0
41	0.001843	0.000325	0.001768	86	0.00154	0.000234	0.001473
42	0	0	0	87	0.002854	0.0004	0.002727
43	0.001827	0.000385	0.001755	88	0.002866	0.000397	0.002738
44	0.002252	0.000473	0.002164	89	0.002208	0.000244	0.002106
45	0.00045	0.000142	0.000434				

After installation FACTS devices the Loss Sensitivity Index of the system has been reduced or improved significantly.

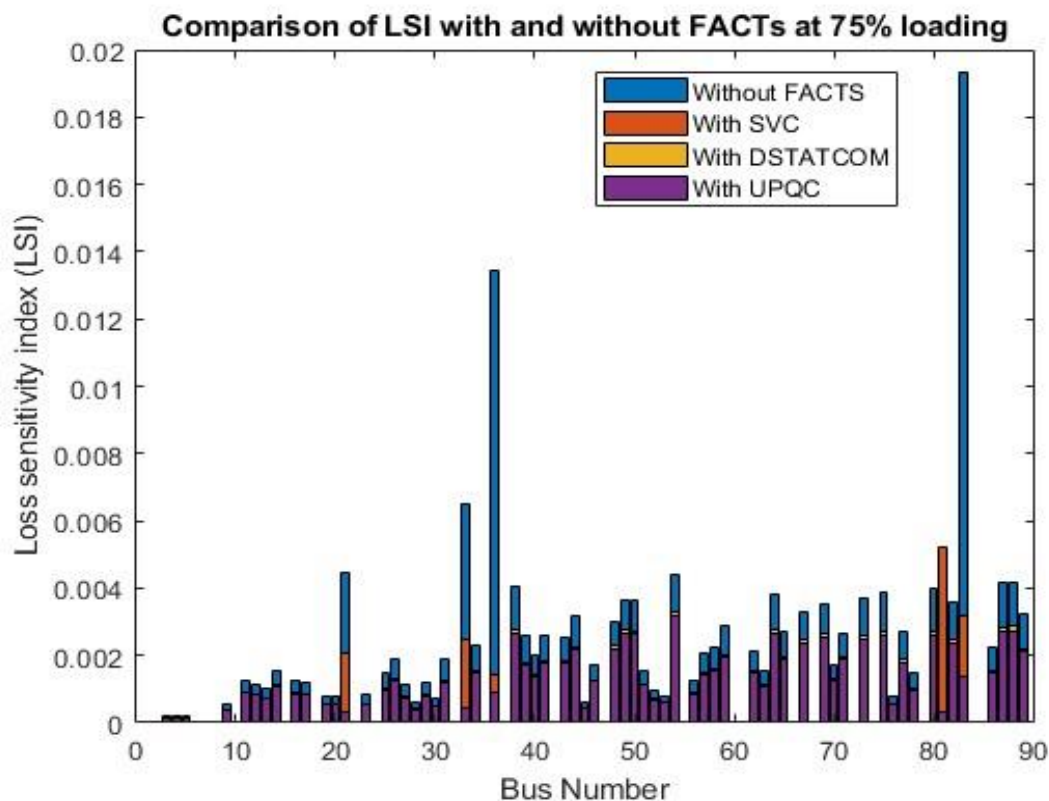


Figure 4-17:- LSI With and without FACTS devices at 75% of full load

In the same way, at full load (100%), the loss sensitivity index of the system has been analyzed with installation of DSTATCOM, SVC and UPQC devices in order to see the effect of the devices. The overall LSI simulation result has been shown both in tabular and graph as follow;

Table 4-18:-Loss Sensitivity Index with FACTS at full load

Bus No	Loading 100%			Bus No	Loading 100%		
	DSTATCOM	SVC	UPQC		DSTATCOM	SVC	UPQC
1	0	0	0	46	0.002367	0.00141	0.002288
2	0	0	0	47	0	0	0
3	0.000273	0.000161	0.000264	48	0.00423	0.002565	0.004157
4	0.000253	0.000152	0.000245	49	0.005127	0.003105	0.005025
5	0.000239	0.000129	0.000231	50	0.00509	0.003092	0.004989
6	0	0	0	51	0.002145	0.001327	0.002077
7	6.36E-05	3.4E-05	6.12E-05	52	0.001323	0.000823	0.001282
8	0	0	0	53	0.001135	0.000707	0.0011
9	0.000719	0.000389	0.000693	54	0.006205	0.003739	0.006005

Table 4-18: Cont...

Bus No	Loading 100%			Bus No	Loading 100%		
	DSTATCOM	SVC	UPQC		DSTATCOM	SVC	UPQC
10	0	0	0	55	0	0	0
11	0.001705	0.000954	0.001645	56	0.001642	0.000841	0.001577
12	0.001556	0.000882	0.001502	57	0.002755	0.001411	0.002644
13	0.001372	0.000771	0.001324	58	0.002946	0.00149	0.002826
14	0.002102	0.001179	0.002028	59	0.003782	0.001902	0.003693
15	0	0	0	60	0	0	0
16	0.001674	0.000857	0.001609	61	0	0	0
17	0.001609	0.000839	0.001547	62	0.002838	0.001439	0.002723
18	0	0	0	63	0.00209	0.001141	0.002012
19	0.001019	0.000494	0.000977	64	0.005135	0.002825	0.00501
20	0.001055	0.000516	0.001012	65	0.003673	0.002034	0.003604
21	0	0.006761	0.000561	66	0	0	0
22	0	0	0	67	0.004577	0.002696	0.004487
23	0.001053	0.000485	0.001007	68	0	0	0
24	0	0	0	69	0.004913	0.002915	0.004813
25	0.001881	0.000871	0.001799	70	0.002404	0.001446	0.002325
26	0.002413	0.00112	0.002308	71	0.003647	0.002152	0.003589
27	0.001453	0.00068	0.00139	72	0	0	0
28	0.000776	0.00036	0.000742	73	0.004805	0.002293	0.004664
29	0.001527	0.000706	0.00146	74	0	0	0
30	0.000919	0.000422	0.000879	75	0.005087	0.00231	0.004866
31	0.002364	0.001075	0.002257	76	0.001042	0.000467	0.000997
32	0	0	0	77	0.003488	0.001449	0.003401
33	0	0.008443	0.00081	78	0.001913	0.000631	0.001829
34	0.002855	0.001197	0.002721	79	0	0	0
35	0	0	0	80	0.005135	0.001564	0.004903
36	0	0.003655	0.001715	81	0	0.017231	0.000557
37	0	0	0	82	0.004585	0.002132	0.004441
38	0.005184	0.002482	0.005024	83	0	0.006003	0.00259
39	0.003345	0.001618	0.003201	84	0	0	0
40	0.002619	0.001308	0.002511	85	0	0	0
41	0.00342	0.001723	0.003345	86	0.002866	0.001411	0.002805
42	0	0	0	87	0.005375	0.002578	0.005135
43	0.003391	0.001777	0.003324	88	0.005398	0.002584	0.005157
44	0.004181	0.002189	0.004082	89	0.004106	0.001922	0.003981
45	0.000835	0.00049	0.000807				

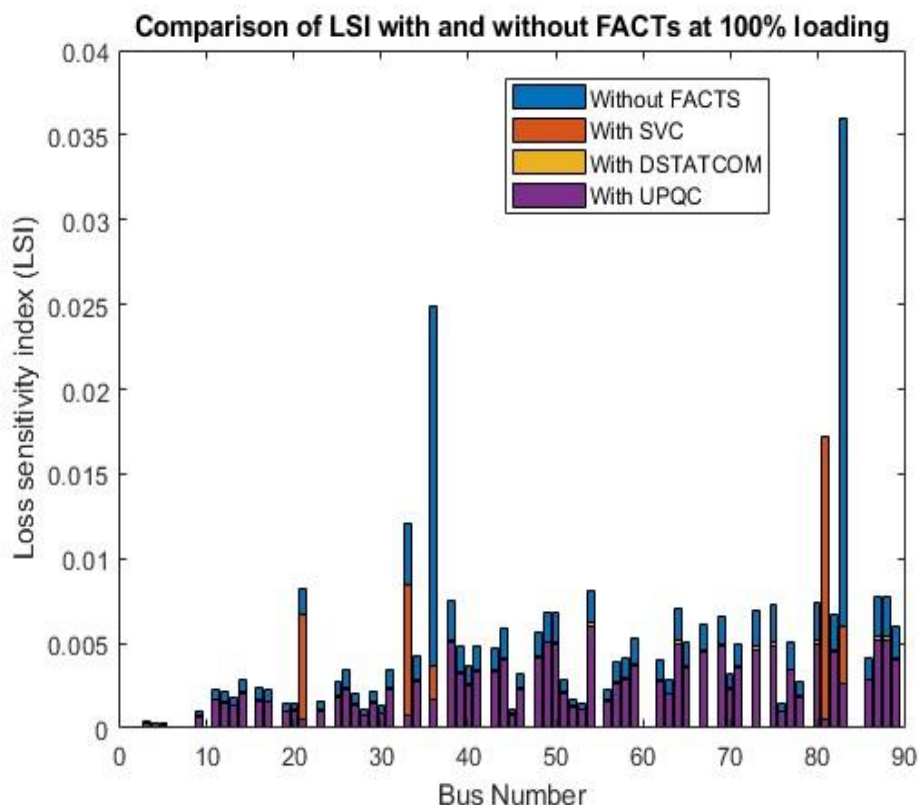


Figure 4-18: LSI with and without FACTS devices at 100% loading

Similarly, increasing the full load by 25%, the loss sensitivity index of the system has been analyzed with installation of DSTATCOM, SVC and UPQC devices in order to see the effect of the devices. The simulation result has been shown both in tabular and graph as follow;

Table 4-19:- Loss Sensitivity Index with FACTS at 125% overloading

Bus No	Loading 125%			Bus No	Loading 125%		
	DSTATCOM	SVC	UPQC		DSTATCOM	SVC	UPQC
1	0	0	0	46	0.003873	0.002928	0.003744
2	0	0	0	47	0	0	0
3	0.00044	0.000331	0.000425	48	0.006924	0.005278	0.0067
4	0.000408	0.000309	0.000395	49	0.008393	0.006394	0.008121
5	0.000387	0.00028	0.000373	50	0.008332	0.006356	0.008063
6	0	0	0	51	0.003511	0.002702	0.003401
7	0.000103	7.42E-05	9.91E-05	52	0.002167	0.001671	0.002099
8	0	0	0	53	0.001859	0.001435	0.001801
9	0.001165	0.000842	0.001123	54	0.01005	0.007677	0.009726

Table 4-19: Cont...

Bus No	Loading 125%			Bus No	Loading 125%		
	DSTATCOM	SVC	UPQC		DSTATCOM	SVC	UPQC
10	0	0	0	55	0	0	0
11	0.002762	0.002027	0.002665	56	0.002686	0.001895	0.002578
12	0.002519	0.001859	0.002433	57	0.004504	0.003178	0.004324
13	0.002222	0.001633	0.002144	58	0.004817	0.00338	0.004621
14	0.003404	0.0025	0.003285	59	0.006186	0.00433	0.005933
15	0	0	0	60	0	0	0
16	0.002718	0.001917	0.002612	61	0	0	0
17	0.002611	0.001857	0.002512	62	0.004643	0.00326	0.004455
18	0	0	0	63	0.003421	0.002482	0.003294
19	0.001657	0.001142	0.001589	64	0.008409	0.006123	0.008099
20	0.001715	0.001186	0.001646	65	0.006016	0.004393	0.005795
21	0	0.010432	0.000913	66	0	0	0
22	0	0	0	67	0.007504	0.005638	0.007251
23	0.001712	0.001156	0.001638	68	0	0	0
24	0	0	0	69	0.008055	0.006073	0.007786
25	0.00306	0.00207	0.002927	70	0.003942	0.002991	0.003813
26	0.003925	0.002657	0.003755	71	0.005979	0.004496	0.005778
27	0.002363	0.001605	0.002262	72	0	0	0
28	0.001262	0.000854	0.001207	73	0.007862	0.005375	0.007527
29	0.002484	0.001679	0.002376	74	0	0	0
30	0.001496	0.001009	0.00143	75	0.008216	0.005523	0.007859
31	0.003851	0.002592	0.003678	76	0.001705	0.001129	0.001632
32	0	0	0	77	0.00571	0.003638	0.005461
33	0	0.012823	0.00132	78	0.003133	0.001791	0.002994
34	0.004653	0.003019	0.004435	79	0	0	0
35	0	0	0	80	0.008296	0.004622	0.007921
36	0	0.002207	0.002795	81	0	0.028368	0.000912
37	0	0	0	82	0.007506	0.005106	0.007165
38	0.008462	0.005814	0.008096	83	0	0.003229	0.004241
39	0.005459	0.003767	0.005226	84	0	0	0
40	0.004278	0.002989	0.004101	85	0	0	0
41	0.005588	0.003917	0.00536	86	0.004694	0.00328	0.004487
42	0	0	0	87	0.008695	0.00604	0.008306
43	0.005543	0.003952	0.005326	88	0.008732	0.006061	0.008341
44	0.006833	0.00487	0.006566	89	0.006722	0.0046	0.006412
45	0.001366	0.001025	0.00132				

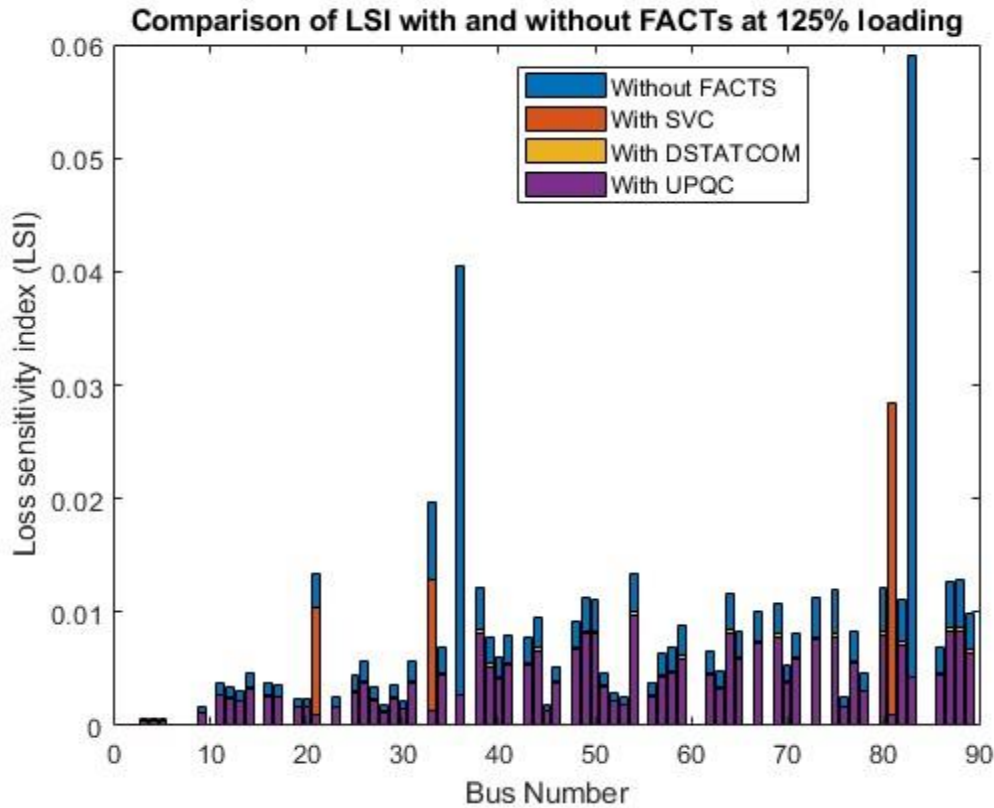


Figure 4-19:- LSI with and without FACTS devices at 125% loading

#### 4.4 Cost Benefit Analysis for Installation of FACTS Devices

The cost benefit analysis considered for installation of the FACTS devices includes the financial calculation of the energy lost, and the capital cost incurred for the purchasing of the devices. And also, the installation and maintenance cost of each device have been considered in the cost analysis. In the process of energy lost cost calculation, the energy rate which is 2.4810 ETB/kWhr under the new power tariff is considered based on unit price data collected on May 5, 2023 G.C. from Ethiopian Utility office. Accordingly, the cost of energy loss is calculated by:

$$\text{Cost of power lost} = P_{\text{cost}} = (P_{\text{loss}}) * (E_r * T) \quad (4.1)$$

Where  $P_{\text{loss}}$  is the total active power losses,  $E_r$  is energy rate (ETB/kWh), T is net time period. In this cost calculation, an average of 422 hours yearly operational period has been considered to be elapsed due to power interruption and has been deducted from total yearly operating hours of 8760 hours (i.e. 8760hours - 422hours = 8338 hours). And also the unit cost of each device is the

aggregate cost of all cost factors which includes the average market price of the device, profit, tax, maintenance cost, installation and transportation cost.

Cost of investment required for installation of each FACTS devices are calculated by multiplying the unit cost per the kVAr with total size of respective FACTS devices. Installation cost, maintenance cost, profit and tax expenses have been considered and included in the investment cost. The devices are purchased in foreign currency (Dollar ) and Ethiopian National Bank exchange rate on May 5, 2023 G.C, which is One USD is equal to 54.34 ETB is considered for calculation. The cost of installing DSTATCOM, SVC and UPQC devices in a distribution network is calculated as follows:

$$\text{FACTS}_{\text{Cost}} = U_{\text{cap}} * Q_{\text{Var}}$$

Where  $U_{\text{cap}}$  is cost/kVAr of FACTS devices, and  $Q_{\text{Var}}$  is the respective FACTS size to be integrated at each candidate buses

#### **4.4.1 Cost Analysis for Distribution Static VAR Compensator (DSTACOM) Installation**

The total real power loss calculation with installation of DSTATCOM at 75% of full load and 100% and 125% loading conditions have been are calculated as follow:

Table 4-20:- Cost analysis before and after installation of DSTATCOM

	<b>75% of full Load</b>	<b>100% loading</b>	<b>125% loading</b>
Total Line Loss without FACTS (kW)	232.43	424.88	683.44
Total Line Losses with DSTATCOM (kW)	120.73	214.61	335.44
Total Line losses reduction (in kW)	111.69	210.27	348.00
% age of Loss Reduction	48.06	49.49	50.92
Annual average Operational Period (hr)	8,338	8,338	8,338
Total Energy saved (in kWhr)	931,354.60	1,753,231.26	2,901,624.00
Energy Unit Cost (ETB/kWhr)	2.4810	2.4810	2.4810
Total Energy Saved (in Birr)	2,310,690.76	4,349,766.76	7,198,929.14

As it can be seen from the table herein above, with installation of DSTATCOM device the selected feeder line loss is reduced by 48.06%, 49.49% and 50.92% at 75% of full load, 100% and 125% loading respectively.

This implies that by installing DSTATCOM device, the utility can save a total energy of 931,354.60 kWhr, 1,753,231.26 kWhr and 2,901,624.00 kWhr at 75% of full load, 100% and 125% loading conditions respectively. Accordingly, a total of 2,310,690.76 ETB, 4,349,766.76 ETB and 7,198,929.14 ETB can be saved annually at 75% of full load, 100% and 125% loading conditions respectively.

The investment cost analysis of the determined sizes of DSTATCOM devices for reducing the power loss and improving the system voltage profile at 75% of full load, 100% and 125% loading conditions have been calculated as follow:

Table 4-21:-Investment cost analysis for DSTATCOM device installation

Unit cost (\$/KVAR)	Candidate bus	DSTATCOM (size in KVAR)			Device cost at each loading conditions		
		75%	100%	125%	75%	100%	125%
70	83	480.6	640.8	801	33,642.00	44,856.00	56,070.00
70	36	498.5	664.7	830.9	34,896.75	46,529.00	58,161.25
70	33	240.3	320.4	400.5	16,821.00	22,428.00	28,035.00
70	81	223.8	298.4	171	15,666.00	20,888.00	11,970.00
70	54	102.6	136.8	373	7,182.00	9,576.00	26,110.00
Subtotal of DSTATCOM device Cost (in USD)					108,207.75	144,277.00	180,346.25
Installation Cost (10%)					10,820.78	14,427.70	18,034.63
Maintenance Cost (2%)					2,164.16	2,885.54	3,606.93
Total Cost (in USD)					121,192.68	161,590.24	201,987.80
Exchange Rate					54.34	54.34	54.34
<b>Total Cost (in ETB)</b>					<b>6,585,610.23</b>	<b>8,780,813.64</b>	<b>10,976,017.05</b>

As it can be understood clearly from the table above, for installation of DSTATCOM devices on Sebbata-I substation feeder-12 at total of 6,585,610.23 ETB, 8,780,813.64 ETB and 10,976,017.05 ETB is required as investment cost at 75% of full load, 100% and 125% loading scenarios respectively. When the investment cost of DSTATCOM is compared with the annual

total cost wasted due to power loss, the investment cost of DSTATCOM device is feasible for implementation.

### **Payback Period**

In order to assess the feasibility of the cost of FACTS devices installation on the system, calculating the payback period for each device must be done and the length of time it takes to recover the invested cost for this purpose shall be determined prior to the decision. Accordingly, the installed devices payback period is calculated as follow;

$$\text{Payback Period (in Years)} = \frac{\text{Net Investment Cost}}{\text{Net Annual Saving Cost}}$$

Accordingly, investment return period for DSTATCOM devices at 75% of full load, 100% and 125% overloading calculated as follow:

$$\text{Payback Period (at 75\% of Full Load)} = \frac{6,585,610.23}{2,310,690.76} = 2.85\text{years}$$

$$\text{Payback Period (at 100 loading )} = \frac{8,780,813.64}{4,349,766.76} = 2.02 \text{ years}$$

$$\text{Payback Period (at 125\% loading )} = \frac{10,976,017.05}{7,198,929.14} = 1.52 \text{ years}$$

The payback period for DSTATCOM device are 2.85 years, 2.02 years and 1.52 years at 75% of full load, 100% and 125% loading scenarios respectively.

#### 4.4.2 Cost Analysis for Static VAR (SVC) Compensator Installation

Similarly, the total real power loss improvement due to installation of SVC at 75% of full load, 100% and 125% is calculated and depicted in tabular form as follow:

Table 4-22:-Cost analysis before and after installation of SVC device

	<b>75% of full Load</b>	<b>100% loading</b>	<b>125% loading</b>
Total Line Loss without FACTS (kW)	232.43	424.88	683.44
Total Line Losses with SVC (kW)	152.36	282.49	471.45
Total Line losses reduction (in kW)	80.16	142.39	211.99
% age of Loss Reduction	34.45	33.51	31.02
Annual average Operational Period (hr)	8,338	8,338	8,338
Total Energy saved (in kWhr)	667,623.66	1,187,247.82	1,767,572.62
Energy Unit Cost (ETB/kWhr)	2.4810	2.4810	2.4810
Total Energy Saved (in Birr)	1,656,374.30	2,945,561.84	4,385,347.67

It clearly shows that, with installation of SVC devices the selected feeder line loss is reduced by 34.45%, 33.51%, and 31.02% at 75% of full load, 100% and 125% loading conditions respectively. This implies that by installing SVC device the utility can save a total energy of 667,623.66 kWhr, 1,187,247.82 kWhr, and 1,767,572.62 kWhr at 75% of full load, 100% and 125% loading conditions respectively. Accordingly, a total of 1,656,374.30 ETB, 2,945,561.84ETB and 4,385,347.67 ETB can be saved annually at 75% of full load, 100% and 125% overloading conditions respectively. However, the power loss enhancement of SVC device is much less when compared with that of DSTATCOM device at respective loading scenarios

Whereas, the investment cost of SVC devices at 75% of full load, 100% and 125% loading conditions have been calculated as follow:

Table 4-23:-Investment cost analysis for SVC installation

Unit cost (\$/KVAR)	Candidate bus	SVC ( Size in KVAR)			Device cost at each loading conditions		
		75%	100%	125%	75%	100%	125%
48	83	1027.20	1043.00	1059.90	49,305.60	50,064.00	50,875.20
48	36	1017.60	1028.10	1039.10	48,844.80	49,348.80	49,876.80
48	33	1017.00	1027.20	1037.90	48,816.00	49,305.60	49,819.20
48	81	1012.70	1020.20	1058.50	48,609.60	48,969.60	50,808.00
48	54	1025.90	1041.70	1028.00	49,243.20	50,001.60	49,344.00
Subtotal of SVC device Cost (in USD)					244,819.20	247,689.60	250,723.20
Installation Cost (10%)					24,481.92	24,768.96	25,072.32
Maintenance Cost (2%)					4,896.38	4,953.79	5,014.46
Total Cost (in USD)					274,197.50	277,412.35	280,809.98
Exchange Rate					54.34	54.34	54.34
<b>Total Cost ( in ETB)</b>					<b>14,899,892.37</b>	<b>15,074,587.21</b>	<b>15,259,214.53</b>

For installation of SVC device at Sebbata-I substation feeder-12 distribution system, a total of 14,899,892.37 ETB, 15,074,587.21 ETB, and 15,259,214.53 ETB is required as investment cost at 75% of full load, 100% and 125% loading scenarios.

### Payback Period

The Payback Period for SVC device at 75% of full load, 100% and 125% overloading have been calculated as follow:

$$\text{Payback Period (at 75\% of full load)} = \frac{14,899,892.37}{1,656,374.30} = 9.00 \text{ years}$$

$$\text{Payback Period (at 100\% loading)} = \frac{15,074,587.21}{2,945,561.84} = 5.12 \text{ years}$$

$$\text{Payback Period (at 125\% loading)} = \frac{15,259,214.53}{4,385,347.67} = 3.48 \text{ years}$$

The payback period for SVC device device are 9.00 years, 5.12 years and 3.48 years at 75% of full load, 100% and 125% overloading scenarios which is greater than of DSTATCOM device

#### **4.4.3 Cost Analysis for Unified Power Quality Conditioner (UPQC) Installation**

Similarly, the total real power loss improvement due to installation of UPQC device at 75% of full load and at 100% and 125% loading conditions are calculated as follow:

Table 4-24:-Cost analysis before and after installation of UPQC device

	<b>75% of full load</b>	<b>100% loading</b>	<b>125% loading</b>
Total Line Loss without FACTS (kW)	232.43	424.88	683.44
Total Line Losses with UPQC (kW)	81.71	145.66	228.22
Total Line losses reduction (in kW)	150.72	279.22	455.22
%age of loss reduction	64.85	65.72	66.61
Annual average Operational Period (hr)	8,338	8,338	8,338
Total Energy saved (in kWhr)	1,256,703.11	2,328,136.36	3,795,624.36
Energy Unit Cost (ETB/kWhr)	2.481	2.481	2.481
Total Energy Saved (ETB)	3,117,880.42	5,776,106.31	9,416,944.04

With installation of UPQC device, the selected feeder line loss is reduced by 64.85%, 65.72%, and 66.61% at 75% of full load, 100% and 125% loading conditions respectively. This implies that by installing UPQC device, the utility can save a total energy of 1,256,703.11 kWhr, 2,328,136.36 kWhr, and 3,795,624.36 kWhr at 75% of full load, 100% and 125% loading conditions respectively. Accordingly, a total of 3,117,880.42 ETB, 5,776,106.31 ETB and 9,416,944.04 ETB can be saved annually at 75% of full load, 100% and 125% loading conditions respectively. Power loss reduction and costs saved with installation of UPQC device are much higher than of DSTATCOM and SVC devices. This implies that UPQC has better power loss reduction performance than of DSTATCOM and SVC devices at 75% of full load, 100% and 125% loading scenarios

The investment cost for installation of UPQC device at 75%, 100% and 125% loading conditions have been calculated as follow:

Table 4-25:-Investment cost analysis for UPQC installation

Unit cost (\$/KVar)	Candi date bus	UPQC ( Size in in KVar)			Device cost at each loading condition		
		75%	100%	125%	75%	100%	125%
85	83	528.66	704.88	881.10	44,936.10	59,914.80	74,893.50
85	36	548.38	731.17	913.96	46,612.30	62,149.45	77,686.60
85	33	264.33	352.44	440.55	22,468.05	29,957.40	37,446.75
85	81	246.18	328.24	188.10	20,925.30	27,900.40	15,988.50
85	54	112.86	150.48	410.30	9,593.10	12,790.80	34,875.50
Subtotal cost of UPQC device (in USD)					144,534.85	192,712.85	240,890.85
Installation Cost (10%)					14,453.49	19,271.29	24,089.09
Maintenance Cost (2%)					2,890.70	3,854.26	4,817.82
Total Cost (in USD)					161,879.03	215,838.39	269,797.75
Exchange Rate					54.34	54.34	54.34
<b>Total Cost ( in ETB)</b>					<b>8,796,506.60</b>	<b>11,728,658.22</b>	<b>14,660,809.84</b>

For installation of UPQC device at Sebbata-I substation feeder-12 distribution system, a total of 8,796,506.60 ETB, 11,728,658.22 ETB, and 14,660,809.84 ETB is required as investment cost at 75% of full load, 100% and 125% loading conditions.

**Payback Period**

The Payback Period for UPQC device at 75% of full load, 100% and 125% loading conditions have been calculated as follow:

$$\text{Payback Period (at 75\% of full load )} = \frac{8,796,506.60}{3,117,880.42} = 2.82\text{years}$$

$$\text{Payback Period (at 125\%)} = \frac{11,728,658.22}{5,776,106.31} = 2.03\text{years}$$

$$\text{Payback Period (at 150\%)} = \frac{46,569,631.27}{9,416,944.04} = 1.56\text{ years}$$

The payback period for UPQC device are 2.82 years, 2.03 years and 1.56 years at 75% of full load, 100% and 125% overloading scenarios which is less than of SVC devices

### 4.5 Summary of the Simulation Result

Simulation result obtained reveals that the system voltage profile is enhanced by 1.86%, 2.97% and 4.18% with installation of DSTATCOM device, by 1.65%, 1.75% and 1.86% with installation of SVC device and by 2.86%, 4.15% and 5.54% after installation of UPQC devices at 75% of full load, 100% and 125% loading conditions respectively. This clearly shows that the voltage enhancing performance of UPQC device at all loading scenarios is much greater than DSTATCOM and SVC devices.

However, with regard to improving the loss sensitivity index of the system installation of DSTATCOM much greater than UPQC and SVC devices and this is due to the fact that the amount of the injected reactive power for compensation greater for DSTATCOM devices. At 75% of full load condition, the active power loss reduced by 48.06%, 34.45%, and 64.85% with installation of DSTATCOM, SVC and UPQC devices respectively. At full load (100% loading), installation of DSTATCOM, SVC and UPQC devices has reduced the active power loss by 49.49%, 33.51% and 65.72% respectively. This implies that installation of UPQC devices at the identified candidate buses has saved energy loss much better than DSTACOM and SVC devices.

The overall cost benefit analysis before and after installation of DSTATCOM, SVC and UPQC devices at 75% of full load condition has been summarized in tabular as follow;

Table 4-26:- Comparison of FACTS performance at 75% of full load

	75% of full load			
	Without FACTS	DSTATCOM	SVC	UPQC
Active power loss (kW)	232.43	120.73	152.36	81.71
Reactive Power loss(kVAr)	205.66	110.61	131.80	73.77
Active power loss saved (in kW)		111.69	80.07	150.72
Minimum Voltage ( in pu)	0.9537	0.9715	0.9695	0.9810
Maximum Loss Sensitivity Index	0.0193	0.0033	0.0034	0.0032
% age of power Losses Reduction		48.06	34.49	64.85
Average annual Operation Period ( in hr)	8,338	8,338	8,338	8,338

Cont...

	<b>75% of full load</b>			
	<b>Without FACTS</b>	<b>DSTATCOM</b>	<b>SVC</b>	<b>UPQC</b>
Energy Unit Cost /kWh	2.481	2.481	2.481	2.481
Total Active Energy Saved (kWh)	-	931,354.60	667,623.66	1,256,703.36
Total Energy Losses (in ETB)		2,310,690.76	1,656,374.30	3,117,881.04
Total Investment Cost		6,585,610.23	14,899,892.37	8,796,506.60
Payback Period ( in years)		2.85	9	2.82

Similarly, at 100% loading conditions the system performance was enhanced and the real line loss was reduced by 49.49%, 33.51% and 65.72% with installation of DSTACOM, SVC and UPQC devices. Again for this load scenario the performance of the UPQC device is higher than DSTATCOM and SVC. The overall cost benefit analysis before and after installation of DSTATCOM, SVC and UPQC devices at 100% loading have been summarized in tabular as follow;

Table 4-27:-Comparison of FACTS Performance at 100% overloading

	<b>100% Loading</b>			
	<b>Without FACTS</b>	<b>DSTATCOM</b>	<b>SVC</b>	<b>UPQC</b>
Active power loss (kW)	424.88	214.61	282.49	145.66
Reactive Power loss(kVAr)	375.84	196.55	246.35	131.46
Active power loss saved (in kW)		210.27	142.39	279.22
Minimum Voltage ( in pu)	0.9374	0.9652	0.9538	0.9763
Maximum Loss Sensitivity Index	0.0360	0.0062	0.0162	0.0060
%age of power Losses Reduction		49.49	33.51	65.72
Average Annual Operation Period ( in hr)	8,338	8,338	8,338	8,338
Energy Unit Cost /kWh	2.481	2.481	2.481	2.481
Total Energy Saved (kWh)	-	1,753,231.26	1,187,247.82	2,328,136.36
Total Energy Save ( in ETB)	-	4,349,766.76	2,945,561.84	5,776,106.31
Total Investment Cost		8,780,813.64	15,074,587.21	11,728,658.22
Payback Period ( in years)		2.02	5.12	2.03

Likewise, at 125% loading the system performance was enhanced and the real line loss was reduced by 50.92%, 31.02% and 66.61% with installation of DSTACOM, SVC and UPQC devices. Again for this load scenario the performance of the UPQC device is higher than DSTATCOM and SVC.

The overall cost benefit analysis of the before and after installation of DSTATCOM, SVC and UPQC at 125% loading have been summarized in tabular as follow;

Table 4-28:-Comparison of FACTS Performance at 125% overloading

	<b>125% Loading</b>			
	<b>Without FACTS</b>	<b>DSTATCOM</b>	<b>SVC</b>	<b>UPQC</b>
Active power loss (kW)	683.44	335.44	471.45	228.22
Reactive Power loss(kVAr)	604.38	307.11	412.81	205.89
Active power loss saved (in kW)		348.00	211.99	455.23
Minimum Voltage ( in pu)	0.9206	0.9590	0.9377	0.9715
Maximum Loss Sensitivity Index	0.0591	0.0100	0.0298	0.0097
% age of power Losses Reduction		50.92	31.02	66.61
Average Annual Operation Period ( in hr)	8,338	8,338	8,338	8,338
Energy Unit Cost /kWh		2.481	2.4810	2.4810
Total Energy Saved (kWh)		2,901,624.00	1,767,572.62	3,795,624.36
Total Energy Save ( in ETB)		7,198,929.14	4,385,347.67	9,416,944.04
Total Investment Cost		10,976,017.05	15,259,214.53.	14,660,809.84
Payback Period ( in years)		1.52	3.48	1.56

Therefore, by comparing the performance of each FACTS devices on reducing the system real line loss and enhancing the voltage profile against the Energy cost save for Sebbata-I Substation, 15 kV outgoing feeder-12, installation of UPQC devices can perform much better than installing of DSTATCOM or SVC devices.

## **CHAPTER 5**

### **CONCLUSION, RECOMMENDATION AND FUTURE WORK**

Based on the result obtained from the MATLAB simulation result analysis without and with installation of DSTATCOM, SVC and UPQC devices for enhancing the performance of the power distribution system taking real radially configured distribution system as a test system, the final conclusion, recommendation and suggestion future works have been presented as follows;

#### **5.1 Conclusion**

In recent years, the importance of FACTS devices in transmission and distribution system is highly increasing as it provides tremendous technological advantages when used correctly. In this thesis, three different types of FACTS devices with different loads scenarios were studied in order to assess their system performance enhancing capabilities by taking Sebbata-I substation feeder-12 as a test system. From base case load flow analysis, bus numbers 83, 36, 33, 81 and 54 were identified to be the weakest candidate buses in terms of maximum LSI Values and were chosen for installation of the FACTS devices.

From the overall simulation studies, it is clearly indicated with integration of DSTATCOM device real line loss has been decreased from 232.43 kW, 424.88 kW, and 683.44 kW to 120.73 kW, 214.61kW and 335.44 kW, at 75% of full load, 100% and 125% loading conditions respectively. This implies that the active power loss is reduced by 48.06%, 49.49% and 50.92% at 75% of full load, 100% and 125% loading conditions respectively. Similarly, after installation of DSTACOM devices, the reactive power has been reduced from 205.66 kVAr, 375.84 kVAr, and 604.38 kVAr to 110.61 kVAr, 196.55 kVAr and 307.11 kVAr which represent 46.22%, 47.70%, 49.19%, at 75% of full load, 100%, and 125% loading conditions respectively.

Whereas, installing of SVC devices to this feeder has reduced the active power loss from 232.43 kW, 424.88 kW, 683.44 kW to 152.27 kW, 288.29 kW, and 471.45 kW which represent 34.45%, 33.51% and 31.02% reduction at 75% of full load, 100% and 125% loading conditions respectively. Likewise, after installation of SVC, the reactive power loss has been reduced from 205.66 kVAr, 375.84 kVAr and 604.38 kVAr to 131.80 kVAr, 246.75 kVAr and 412.81 kVAr at

75% of full load, 100% and 125% loading conditions respectively which represent 35.91%, 34.45% and 31.70% respectively.

The same feeder was analyzed with installation of UPQC devices and the active power loss has been reduced from 232.44 kW, 424.88 kW, and 683.44 kW to 81.70 kW, 145.66 kW, and 228.22 kW which represent 64.85%, 65.72%, and 66.61% loss reduction at 75% of full load, 100% and 125% loading respectively. Similarly, after installation of UPQC devices the reactive power loss of the system has been reduced from 205.66 kVAr, 375.84 kVAr and 604.38 kVAr to 73.77 kVAr, 131.46 kVAr, and 205.89 kVAr at 75% of full load, 100% and 125% loading conditions respectively which represent 64.13%, 65.02% and 65.93% respectively.

The above results clearly show that installation of DSTATCOM devices can save electrical energy of 931,354.60 kWhr, 1,753,231.26 kWhr, 2,901,624.00 kWhr, installation of SVC devices can save electrical energy of 667,623.66 kWhr, 1,187,247.82 kWhr, 1,767,572.62 kWhr and installation of UPQC device can save electrical energy of 1,256,703.36 kWhr, 2,328,136.36 kWhr, 3,795,624.36 kWhr at 75% of full load, 100% loading and 125% loading conditions respectively.

In terms of money, installation of DSTATCOM, SVC and UPQC devices can save 4,349,766.76 ETB, 2,945,561.84 ETB and 5,776,106.31 ETB per annum at full load (100%) loading condition respectively. Considering the investment cost, installation of DSTATCOM, SVC and UPQC device requires 8,780,813.64 ETB, 15,074,587.21 ETB and 11,728,658.22 ETB at full load (100%) load conditions respectively.

The simulation results indicate that all the three FACTS devices (i.e. DSTATCOM, SVC and UPQC devices) have significantly enhanced the performance of the radially configured distribution network. However, UPQC device has shown the highest reduction in voltage profile improvement, power losses and hence, it has better energy saving when compared to DSTATCOM and SVC devices. Therefore, if energy saving is the primary concern, UPQC devices may be the most suitable option. However, investment costs, which may vary from time to time, should also be considered before making a final decision.

## **5.2 Recommendation**

The output of this project can be taken as input by the Ethiopian Electric utility to have full understanding on the performance of the DSTATCOM, SVC and UPQC devices with regard of reducing the line loss and enhancing the voltage level of radially configured distribution networks. In addition, this thesis will help to analyze the corresponding cost benefit advantage obtained and payback period of each FACTS device before selecting and deciding on the type of FACTS devices to be installed on distribution network. Moreover, by installing FACTS devices will enhance the system performance so that the unnecessary energy wastage will be minimized. And hence, the amount of the energy saved can be used to fulfill the energy gap exist in the country

Furthermore, the output of this project enables the utilities to know the performance of DSTATCOM, SVC and UPQC devices installation for ensuring the voltage profile at end-users within IEEE standard limit range.

By comparing the performance of DSTATCOM, SVC and UPQC device for power loss reduction and improvement of the voltage profile of a radial distribution system, installation of UPQC device has better performance than DSTATCOM and SVC devices. Therefore, installation of UPQC device can save electrical energy and money for utility. Therefore, the EEU will be more cost-effective and reliable to operate and the consumers will be benefited as well.

### **5.3 Suggestion for Future Work**

This thesis work has been applied to the real distribution system of Sabbata-I Substation 15kV distribution feeder-12 and with consideration of five number of candidate buses for installation of the FACTS devices.

Varying the number of candidate buses for the installation of the devices as an optimizing variable for the PSO might have better performance improvement in the system though the cost of the devices is one factor to be considered.

The use of mixed FACTS devices at the different candidate buses (using two or more FACTS devices during a single optimization process) may also give improved results and should be investigated in future works. In addition, utilization of multi-objective optimization schemes, like Genetic Algorithm (GA), which can optimize each cost variable individually instead of using a weighted-approach used in this thesis can enable an improved choice of device sizing. The modeling and the load-flow analysis of the studied system is based on the assumption that the feeder is balanced as per the scope of the thesis. Therefore, phase load unbalanced and non-linear load conditions were not considered. The future work would be conducted with consideration of phase load imbalance and harmonics.

## **REFERENCES**

- [1] Kashem, M. A, et al. "A novel method for loss minimization in distribution networks." DRPT2000. International conference on electric utility deregulation and restructuring and power technologies. Proceedings (Cat. No. 00EX382). IEEE, 2000.
- [2] Fazel Abbasi<sup>1</sup>, Seyed Mehdi Hosseini, "Optimal DG allocation and sizing in presence of storage systems considering network configuration effects in distribution systems" IET Generation, Transmission & Distribution, P.N. 1-8,2015.
- [3] Wagner TP, Chikhani AY, Hackam R. "Feeder reconfiguration for loss reduction: an application of distribution automation", IEEE transactions on power Delivery. 1991-6 (4):1922-1933.
- [4] Nara K, Shiose A, Kitagawa M, Ishihara T. "Implementation of genetic algorithm for distribution systems loss minimum re-configuration." IEEE Transactions on Power systems, 1992
- [5] Dolloff, P.A., "Optimization in Electrical Distribution Systems: Discrete Ascent Optimal Programming", Ph.D. Thesis, Virginia Polytechnic Institute and State University, December, 1995.
- [6] Neagle, N.M., and D.R. Samson, "Loss Reduction from Capacitors Installed on Primary Feeders", IEE Trans., Vo1.75, Oct. 1956,
- [7] Cook, R.F., "Calculating Loss Reduction Afforded By Shunt Capacitor Application", IEEE Trans. on Power Delivery, Vol. 83, Dec. 1964
- [8] R. T., "Voltage Drop Calculations & Design of Urban Distribution Feeders," Int. J. Res. Eng. Technol., vol.04, no.24, pp. 43–53, 2015,
- [9] Sallam, Abdelhay A., and Om P. Malik. "Electric distribution systems." 2018
- [9] J. P. Navani, N. K. Sharma, and S. Sapra, "Technical and Non-Technical Losses in Power System and Its Economic Consequence in Indian Economy," pp. 757–761, 2015.
- [10] Ramesh, L., et al. "Minimization of power loss in distribution networks by different techniques." International Journal of Electrical and Computer Engineering 3.4, 2009
- [11] A. Chauhan, E. Engineering, S. Rajvanshi, and E. Engineering, "Non-Technical Losses in Power System: A Review," pp. 558–561, 2013.

- [12] L. Nkodo, C. Bernard, O. Hamandjoda, and F. F. Louis, "Detection and Solutions for Non-Technical Losses in Cameroon Electricity Network," 2018, not work
- [13] T. Zhang, R. Gao, and S. Sun, "Theories, Applications, and Trends of Non-technical Losses in power utilities using Machine Learning," 2018 2nd IEEE Adv. Inf. Manag. Autom. Control Conf., no. Imcec, pp. 2324–2329, 2018.
- [14] M. H. Chou, C. L. Su, Y. C. Lee, H. M. Chin, G. Parise, and P. Chavdarian, "Voltage-drop calculations and power cable designs for harbor electrical distribution systems with high voltage shore connection," IEEE Trans. Ind. Appl., vol. 53, no. 3, pp. 1807–1814, 2017
- [15] S. Nunoo, J. C. Attachie, and F. N. Duah, "An Investigation into the Causes and Effects of Voltage Drop on an 11 kV Feeder," no. May 2014.
- [16] T. Chen, L. Chiang, and N. Yang, "Examination of major factors affecting voltage variation on distribution feeders," Energy Build., vol. 55, pp. 494–499, 2012,
- [17] E. Jagdeep, "Real-Time Study on Technical and non-technical losses in Distribution System and reduction techniques," vol. 5, no. 3, pp. 276–279, 2018.
- [18] A. A. Sallam and O. M. P. Malik, "Distribution System Planning," no. Cm, pp. 23– 39, 2019.
- [19] G. Kour and R. K. Sharma, "Different Techniques of Loss Minimization in Distribution System," Int. J. Enhanc. Res. Sci. Technol. Eng., vol. 2, no. 2, pp. 1–5, 2013,
- [20] Shokri, Abdollah, Azah Mohamed Hussain Shareef, and Shervin Shokri. "Performance of Facts Devices to Improve Power Quality and Application of Static Synchronous Compensator." Research Journal of Applied Sciences, Engineering and Technology 7.10 (2014): 1994-2003.
- [21] Okeke, Therese Uzochukwuamaka, and Ramy Georgious Zaher. "Flexible AC transmission systems (FACTS)." 2013 international conference on new concepts in smart cities: fostering public and private alliances (SmartMILE). IEEE, 2013
- [22] Grunbaum, Rolf, Conny Wahlberg, and Ambra Sannino. "Use of FACTS for enhanced flexibility and efficiency in power transmission and distribution grids." 2010.
- [23] Gandotra, R., and K. Pal. "FACTS Technology: A Comprehensive Review on FACTS Optimal Placement and Application in Power System." Iranian Journal of Electrical and Electronic Engineering 18.3, 2022.

- [24] Zhang, Xiao-Ping, et al. "FACTS-devices and applications." Flexible AC Transmission Systems: Modelling and Control, 2012.
- [25] N. B. Kadandani, "An Overview of FACTS Controllers for Power Quality Improvement an Overview of FACTS Controllers for Power Quality Improvement," no. September 2015, pp. 9–17, 2018.
- [26] Balamurugan, P., T. Yuvaraj, and P. Muthukannan. "Optimal allocation of DSTATCOM in distribution network using whale optimization algorithm." Engineering, Technology & Applied Science Research 8.5, 2018.
- [27] A. R. Gupta and A. Kumar, "Energy Savings using DSTATCOM placement in Radial Distribution System," Procedia Comput. Sci., Vol. 70, pp. 558-564, 2015
- [28] Amin, Amal, Salah Kamel, and Juan Yu. "Developed analytical technique for optimal placement and sizing of DG and DSTATCOM in radial distribution systems." 2018 Twentieth International Middle East Power Systems Conference (MEPCON). IEEE, 2018
- [29] Gowtham, G., and A. Lakshmi Devi. "Power loss reduction and voltage profile improvement by DSTATCOM using PSO." International Journal of Engineering Research and Technology (IJERT) 4.2 , 2015
- [30] Yuvaraj, T., K. R. Devabalaji, and K. Ravi. "Optimal placement and sizing of DSTATCOM using harmony search algorithm." Energy Procedia 79, 2015.
- [31] Kaliaperumal Rukmani, Devabalaji, et al. "A new approach to optimal location and sizing of DSTATCOM in radial distribution networks using bio-inspired cuckoo search algorithm." Energies 13.18, 2020
- [32] Ahmed, Walaa, et al. "Probabilistic load flow solution considering optimal allocation of SVC in radial distribution system." 2018.
- [33] Ahmed, Walaa, et al. "Probabilistic load flow solution considering optimal allocation of SVC in radial distribution system." 2018.
- [34] Ramanaiah, M. Laxmidevi, and M. Damodar Reddy. "Performance of Unified Power Quality Conditioner in radial distribution networks using Particle Swarm Optimization Method." International Journal of Applied Engineering Research 12.24, 2017

- [35] Ramanaiah, M. Laxmidevi, and M. Damodar Reddy. "Optimal placement of unified power quality conditioner using ant lion optimization method." *International Journal of Applied Engineering Research* 12.13, 2017
- [36] Ganguly, "Multi-Objective Planning for Reactive Power Compensation of Radial Distribution Networks With Unified Power Quality Conditioner Allocation Using Particle Swarm Optimization," *IEEE Transactions on Power Systems*, vol. 29, no. 4, pp. 1801-1810, July 2014.
- [37] Sanam, Joseph, A. K. Panda, and Sanjib Ganguly. "Optimal phase angle injection for reactive power compensation of distribution systems with the allocation of multiple distributions STATCOM." *Arabian Journal for Science and Engineering* 42, 2017.
- [38] Sanam, Joseph, Sanjib Ganguly, and A. K. Panda. "Placement of DSTATCOM in radial distribution systems for the compensation of reactive power." *2015 IEEE Innovative Smart Grid Technologies-Asia (ISGT ASIA)*. IEEE, 2015.
- [39] Reddy, K. Subbarami, and V. Usha Reddy. "Optimal Placement of DSTATCOM in Radial Distribution System using Fuzzy and Penguins Search Optimization Algorithm." *Innovative research in electrical, electronics, instrumentation and control engineering* 3.11, 2015.
- [40] Mekhamer, S. F., et al. "Enhancing radial distribution system performance by optimal placement of DSTATCOM." *International Journal of Electrical and Computer Engineering* 10.3, 2020.
- [41] Hussain, SM Suhail, and N. Visali. "Identification of weak buses using Voltage Stability Indicator and its voltage profile improvement by using DSTATCOM in radial distribution systems." *IOSR Journal of Electrical and Electronics Engineering (IOSRJEEE)* 2.4, 2012.
- [42] Devi, S., and M. Geethanjali. "Optimal location and sizing of distribution static synchronous series compensator using particle swarm optimization." *International Journal of Electrical Power & Energy Systems* 62, 2014
- [43] Reddy, K. Subbarami, and V. Usha Reddy. "Optimal Placement of DSTATCOM in Radial Distribution System using Fuzzy and Penguins Search Optimization Algorithm." *Innovative research in electrical, electronics, instrumentation and control engineering* 3.11, 2015.

- [44] Hassan, Mohammed Osman, S. J. Cheng, and Zakaria Anwar Zakaria. "Steady-state modeling of SVC and TCSC for power flow analysis." Proceedings of the International Multi Conference of Engineers and Computer Scientists. Vol. 2. 2009.
- [45] Zamani-Gargari, Milad, Farshad Kalavani, and Kazem Zare. "Review of impacts of static var compensator allocation on radial distribution networks." IETE Journal of Research 65.1, 2019.
- [46] Vardani, Bharat. "Optimum location of svc in an ieee 33 bus radial distribution system using power sensitivity index." 2019 International Conference on Electrical, Electronics and Computer Engineering (UPCON). IEEE, 2019.
- [47] Zellagui, Mohamed, et al. "Multi-Objective Optimal Allocation of Hybrid Photovoltaic Distributed Generators and Distribution Static Var Compensators in Radial Distribution Systems Using Various Optimization Algorithms." Journal of Electrical Systems 18.1, 2022.
- [48] Khadkikar, Vinod, and Ambrish Chandra. "A new control philosophy for a unified power quality conditioner (UPQC) to coordinate load-reactive power demand between shunt and series inverters." IEEE Transactions on power delivery 23.4, 2008.
- [49] Hosseini, M., H. A. Shayanfar, and M. Fotuhi-Firuzabad. "Modeling of unified power quality conditioner (UPQC) in distribution systems load flow." Energy Conversion and Management 50.6, 2009.
- [50] Salimon, Sunday Adeleke, et al. "Load flow analysis of nigerian radial distribution network using backward/forward sweep technique." Journal of VLSI Design and its Advancement 2.3, 2019.
- [51] Issicaba, Diego, and Jorge Coelho. "Evaluation of the forward-backward sweep load flow method using the contraction mapping principle." International Journal of Electrical and Computer Engineering 6.6, 2016.
- [52] Eminoglu, Ulas, and M. Hakan Hocaoglu. "Distribution systems forward/backward sweep-based power flow algorithms: a review and comparison study." Electric Power Components and Systems 37.1, 2008.
- [53] Kawambwa, Shante, et al. "An improved backward/forward sweep power flow method based on network tree depth for radial distribution systems." Journal of Electrical Systems and Information Technology 8, 2021.

- [54] Mehruz, Shabana, and Sumit Kumar. "Two dimensional particle swarm optimization algorithm for load flow analysis." *International Journal of Computational Intelligence Systems* 7.6, 2014.
- [55] Kennedy, James, and Russell Eberhart. "Particle swarm optimization." *Proceedings of ICNN'95-international conference on neural networks*. Vol. 4. IEEE, 1995.
- [56] Y. Shi, R. Eberhart, "A modified particle swarm optimizer". *Proceedings of the IEEE World Congress on Computational Intelligence*, 1998.
- [57] S. Mirjalili, "Particle swarm optimization," *Stud. Comput. Intell.*, vol. 780, pp. 15–31, 2019.
- [58] M. A. Khanday and R. Malviya, "Optimal Placement and Sizing of STATCOM using PSO," *Int. Res. J. Eng. Technol.*, vol. 6, no. 08, pp. 1423–1428, 2019.
- [59] D. Venugopal and A. Jayalaxmi, "Optimal Placement of Facts Devices Using Particle Swarm Optimization Technique for the Increased Loadability of a Power System," *IOSR J. Electr. Electron. Eng.*, vol. 10, no. 2, pp. 20–26, 2015.
- [60] Kumar, T. Vinod, and I. Satish Kumar. "Implementation of Novel Optimization Algorithm for Optimal Placement and Sizing of Capacitor Banks in Radial Distribution Systems for Power Loss Minimization and Net Savings Maximization." *International Journal of Computer Applications* 108.11, 2014.
- [61] Mekhamer, S. F., et al. "Enhancing radial distribution system performance by optimal placement of DSTATCOM." *International Journal of Electrical and Computer Engineering* 10.3, 2020.
- [62] Iqbal, Fahad, Mohd Tauseef Khan, and Anwar Shahzad Siddiqui. "Optimal placement of DG and DSTATCOM for loss reduction and voltage profile improvement." *Alexandria Engineering Journal* 57.2, 2018.
- [63] Taher, Seyed Abbas, and Seyed Ahmadreza Afsari. "Optimal location and sizing of DSTATCOM in distribution systems by immune algorithm." *International Journal of Electrical Power & Energy Systems* 60, 2014.
- [64] Padmavathi, K., and K. Rama Sudha. "Optimal placement and sizing of DSTATCOM using firefly algorithm in the distribution system." *International Journal of Renewable Energy Technology* 10.1-2, 2019.

- [65] Chabok, Babak Safari, and Ahmad Ashouri. "Optimal placement of D-STATCOMs into the radial distribution networks in the presence of distributed generations." *American Journal of Electrical and Electronic Engineering* 4.2, 2016.
- [66] Shimohammadi, D. "A Compensation-based power flow method for weekly meshed distribution and transmission network." *IEEE Trans on Power System* 3.2, 1988.
- [67] Houzhong Zhang, Xiangtian Yang, Xiaoqiang Sun and Jiasheng Liang, "Optimal Design of Shift Point Strategy for DCT Based on Particle Swarm Optimization," in *Machines* 2021,, Basel, Switzerland, 2021.
- [68] Gupta, Ankita, Harmeet Singh Gill, and Isha Bansal. "Effectiveness of high voltage in distribution system: High voltage distribution system." *IOSR Journal of Electrical and Electronic Engineering* 1.5, 2012
- [69] A Case Study of Analysis of Technical and Non-Technical Losses in Power System and its Impact on Power Sector; J.P Navani, N.K Sharma, Sonal Sapra; 2012
- [70] Reducing Technical and Non-Technical Losses in the Power Sector; Background Paper for the World Bank Group Energy Sector Strategy; July 2009
- [71] Detection of frauds and other non-technical losses in a power utility using Pearson coefficient, Bayesian networks and decision trees; Inigo Monedero, Felix Biscarri, Carlos Leon, Juan I. Guerrero, Jesus Biscarri, Rocio Millan; December 2011
- [72] Vivek, Raval, and Sanjay R. Vyas. "Distribution System Planning using Network Reconfiguration for Loss Reduction." 2018.
- [73] Jain, Meetu, et al. "An Overview of Variants and Advancements of PSO Algorithm." *Applied Sciences* 12.17, 2022
- [74] Juneja, Mudita, and S. K. Nagar. "Particle swarm optimization algorithm and its parameters: A review." 2016 International Conference on Control, Computing, Communication and Materials (ICCCCM). IEEE, 2016.
- [75] Transmission and Distribution Losses (Power); M S Bhalla; 2000
- [76] Jain, Meetu, et al. "An overview of variants and advancements of PSO algorithm." *Applied Sciences* 12.17 (2022): 8392.

- [77] Vujosevic, I., E. Spahic, and D. Rakocevic. "One method for the estimation of voltage drops in distribution systems." IEEE Power Engineering Society Summer Meeting, Vol. 1. IEEE, 2002.
- [78] Narain, Aishvarya, and S. K. Srivastava. "An Overview of Facts Devices used for Reactive Power Compensation Techniques." power 2, 2015

## APPENDICES

### Appendix A: Power Interruption Data

Total Interruption Data During 2022							
Feeder	Peak Load (MW)	Cause of Interruption					
		OI	SC	EF	UF	Total	Hr.
F1	5.9	27	2	9	0	38	95.8
F2	11.4	235	155	230	8	628	757.83
F3	11.80	40	79	38	0	157	211.25
F4	12.5	152	36	109	59	356	502.39
F5	1.5	181	21	34	0	236	606.37
F6	8.5	258	69	52	0	379	552.28
F7	9.3	215	166	202	0	583	942.13
F8	5.2	25	1	0	0	26	64.7
F9	11.4	120	143	70	0	333	581.17
F10	9.4	171	28	71	0	270	524.97
F11	10.6	213	131	125	11	480	1051.68
F12	14.3	129	102	97	0	328	536.03
F13	9.3	190	98	158	0	446	692.41
F14	2.5	30	4	28	0	62	249.1
F15	13.1	100	58	69	0	227	358.99
Total Interruption data during 2021							
Feeder	Peak Load (MW)	Cause of Interruption					
		OI	SC	EF	UF	Total	HR
1	11.47	31	25	60	0	116	147.477
2	12.5	188	119	284	0	591	702.86
3	12.8	53	45	64	0	162	155.89
4	16.4	108	41	171	0	320	451.99
5	8.7	123	26	37	0	186	466.26
6	4.6	129	44	58	0	231	362.07
7	7.8	114	188	110	0	412	516.54
8	5.4	129	26	92	0	247	247.95
9	9.3	99	107	66	0	272	326.17
10	8.4	101	35	86	0	222	313.34
11	12	156	104	203	3	466	519.58
12	12.7	104	106	105	0	315	309.56
13	8.05	116	85	104	0	305	319.44
14	2.4	31	11	28	0	70	92.99
15	13.69	100	66	70	0	236	294.09

**Appendix B: Substation Transformer Data**

No	Station Name	Voltage Ratio (KV)	Equipment	Rating (MVA)	Peak Load	Remark
1	SEBETA-I	230/132	AT1	125	91	
		230/132	AT1	125	-	
		230/132	AT3	125	91	
		132/45/15	Transformer-1	25/25/10	21.1/14.2/6.9	
		132/45/15	Transformer-2	12/12/4.0	11.2/11.2/0	15kv idle
		132/15	Transformer-3	50	41	
		132/15	New transformer	50	45.57	

**Appendix C: Capacity of the Outgoing feeders of Sabbata-1 Substation**

Feeder Name	Cable			CT Ratio				Relay Setting		
	C.S.A (mm <sup>2</sup> )	Type	C.C.C(A)	MW	Ratio	A	MW	Setting	A	MW
F1	3 core 120	CU	325	7.6	800/5	800	18.7	0.42XIn	336	7.9
F2	2X240	AL	834	19.5	800/5	800	18.7	0.8*In	640	
F3	1X300	CU	599	140	800/1	800	18.7	1Xin	800	18.7
F4	2X240	AL	1064	24.9	800/5	800	18.7	0.82XIn	656	15.3
F	3 core 120	CU	325	7.6	800/5	800	18.7	0.62XIn	496	11.6
F6	2X240	AL	834	19.5	800/5	800	18.7	0.4*In	320	
F7	3 core 240	CU	455	10.6	1200/5	1200	28.1	0.35XIn	420	9.8
F8	2X240	AL	834	19.5	800/5	800	18.7	0.4XIn	320	7.5
F9	1X300	CU	599	14	800/1	800	18.7	0.6*In	480	11.2
F10	2X240	AL	834	19.5	800/5	800	18.7	0.6XIn	480	11.2
F11	2X240	AL	834	19.5	800/5	800	18.7	0.6XIn	480	11.2

## Comparative Studies of Facts Devices for Reduction of Power Loss and Voltage Profile Improvement in RDS

F12	1X300	CU	599	14	800/1	800	18.7	0.8*In	640	14.9
F13	2X240	AL	834	19.5	800/5	800	18.7	0.55XIn	440	10.3
F14	1X300	CU	599	14	800/1	800	18.7	0.5*In	400	9.4
F15	1X300	CU	599	14	800/1	800	18.7	0.91XIn	728	17

### Appendix D: Length and Capacity of Each Feeder

Name of the feeder	Distance Coverage (in Km)	Number of transformer	Peak Load	
			Current (A)	Power (MW)
F1	10.8	57	270	6.3
F2	40.12	170	506	11.8
F3	25.7	82	440	10.29
F4	27.3	64	642	15.01
F5	19.8	8	28	0.6
F6	20.1	2	38	0.8
F7	19.5	70	250	5.8
F8	16.9	8	153	3.5
F9	24.4	74	287	6.71
F10	1.3	77	296	6.9
F11	24.2	123	460	10.7
F12	27.83	69	460	10.76
F13	27.4	65	355	8.3
F14	11	12	100	2.34
F15	24.3	24	492	11.50

### Appendix E: Yearly Peak Load and Minimum Load of the Feeders

Bay/Line	Peak Load				Minimum Load			
	Power (MW)	Current (A)			Power (MW)	Current (A)		
		R	S	T		R	S	T
F1	5.9	251	251	251	0.04	2	2	2
F2	11.4	497	497	497	0.1	4	4	4
F3	11.80	506	506	506	0.7	30	30	30
F4	12.5	528	528	528	0.4	19	19	19
F5	1.5	63	63	63	0.01	0.6	0.6	0.6
F6	8.5	360	360	360	0.2	8	8	8
F7	9.3	391	391	391	0.8	36	36	36
F8	5.2	222	222	222	0.1	8	8	8
F9	11.4	482	482	482	0.7	31	31	31

F10	9.4	396	396	396	0.9	40	40	40
F11	10.6	445	445	445	0.1	8	8	8
F12	14.3	600	600	600	1.1	47	47	47
F13	9.3	390	390	390	0.61	28	28	28
F14	2.5	107	107	107	0.02	1	1	1
F15	13.1	552	552	552	0.3	15	15	15

**Appendix F: The impedance of Distribution Line**

Conduct	Nominal Area (mm <sup>2</sup> )	Real Area	Stranding wire	Overall Diameter	Actual Diameter	GMR	Resistance (Ω/Km)	Reactance (Ω/Km)
AAC	25	24.2	7/2.1	6.3	5.56	1.88	1.181	0.37367
AAC	50	49.5	7/3.00	9	7.9377	2.88	0.5785	0.3470
AAC	95	93.5	19/2.5	12.5	10.8975	4.129	0.3085	0.32441

**Appendix H: Costs of different FACTS Controller**

Description of FACTS Controller	Cost (USD/KVAr)
DSTATCOM	\$70/KVAr
SVC	\$48/KVAr
UPQC	\$85/KVAr

Appendix I: Monthly Peak and Minimum Load Demand on the Feeder

Bay /Line	Peak Load						Minimum Load					
	Power (MW)	Current (A)			Time	Date	Power (MW)	Current (A)			Time	Date
		R	S	T				R	S	T		
<b>July, 2022</b>												
F1												
F2	10.9	458	458	458	20:00	7/29/2022	1.95	82.00	82.00	82.00	1:00	7/11/2022
F3	10.1	428	428	428	12:00	7/29/2022	1.07	45.00	45.00	45.00	1:00	7/14/2022
F4	6.5	277	277	277	13:00	7/31/2022	0.85	36.00	36.00	36.00	3:00	7/16/2022
F5	1.1	43	43	43	19:00	7/18/2022	0.10	2.00	2.00	2.00	4:00	7/13/2022
F6	8.5	360	360	360	14:00	7/27/2022	0.20	8.00	8.00	8.00	3:00	7/30/2022
F7	9.1	380	380	380	20:00	7/4/2022	1.26	53.00	53.00	53.00	1:00	7/25/2022
F8												
F9	9.1	385	385	385	11:00	7/4/2022	1.10	44.00	44.00	44.00	5:00	7/12/2022
F10	6.6	280	280	280	12:00	7/23/2022	1.42	60.00	60.00	60.00	4:00	7/4/2022
F11	8	340	340	340	14:00	7/30/2022	1.38	58.00	58.00	58.00	2:00	7/2/2022
F12	14.3	600	600	600	20:00	7/15/2022	2.09	88	88	88	1:00	7/25/2022
F13	5.9	247	247	247	11:00	7/20/2022	0.83	35	35	35	3:00	7/4/2022
F14	1.9	82	82	82	19:00	7/3/2022	0.28	12.00	12.00	12.00	9:00	7/25/2022
F15	10	420	420	420	19:00	7/5/2022	1.71	72.00	72.00	72.00	3:00	7/26/2022
<b>August, 2022</b>												
F1												
F2	11.3	497	497	497	20:00	8/2/2022	0.20	9.00	9.00	9.00	11:00	8/7/2022
F3	11.8	495	495	495	11:00	8/17/2022	1.60	68.00	68.00	68.00	2:00	8/18/2022
F4	10.5	442	442	442	21:00	8/23/2022	0.90	38.00	38.00	38.00	3:00	8/2/2022
F5	1.2	51	51	51	14:00	8/23/2022	0.10	2.00	2.00	2.00	18:00	8/1/2022
F6	6.1	258	258	258	9:00	8/19/2022	1.60	67.00	67.00	67.00	3:00	8/6/2022
F7	9.3	390	390	390	20:00	8/2/2022	1.20	50.00	50.00	50.00	3:00	8/29/2022

**Comparative Studies of Facts Devices for Reduction of Power Loss and Voltage Profile Improvement in RDS**

F8												
F9	9.3	390	390	390	14:00	8/8/2022	1.10	48.00	48.00	48.00	3:00	8/15/2022
F10	6.9	292	292	292	14:00	8/12/2022	1.40	57.00	57.00	57.00	2:00	8/18/2022
F11	8.7	366	366	366	16:00	8/20/2022	0.90	38.00	38.00	38.00	11:00	8/25/2022
F12	14.3	600	600	600	20:00	8/8/2022	2.40	100	100	100	5:00	8/8/2022
F13	6.1	258	258	258	11:00	8/2/2022	0.9	38	38	38	2:00	8/15/2022
F14	2.2	94	94	94	8:00	8/28/2022	0.30	11.00	11.00	11.00	15:00	8/28/2022
F15	11.2	470	470	470	19:00	8/28/2022	1.40	57.00	57.00	57.00	21:00	8/22/2022
<b>September, 2022</b>												
F1												
F2	11.3	473	473	473	11:00	9/3/2022	0.40	17.00	17.00	17.00	5:00	9/5/2022
F3	9.5	398	398	398	19:00	9/20/2022	1.60	65.00	65.00	65.00	3:00	9/19/2022
F4	7.2	300	300	300	13:00	9/10/2022	0.90	38.00	38.00	38.00	2:00	9/7/2022
F5	1.2	51	51	51	14:00	9/23/2022	0.10	5.00	5.00	5.00	1:00	9/7/2022/
F6	6.5	272	272	272	11:00	9/20/2022	0.40	18.00	18.00	18.00	0:00	9/27/2022
F7	6.9	291	291	291	19:00	9/19/2022	1.00	42.00	42.00	42.00	3:00	9/27/2022
F8												
F9	9.3	388	388	388	17:00	9/2/2022	1.14	48.00	48.00	48.00	3:00	9/12/2022
F10	9.1	381	381	381	10:00	9/8/2022	1.10	43.00	43.00	43.00	2:00	9/12/2022
F11	9.1	382	382	382	13:00	9/20/2022	1.40	58.00	58.00	58.00	3:00	9/12/2022
F12	14.3	600	600	600	12:00	9/10/2022	2.10	88	88	88	3:00	9/19/2022
F13	7.5	314	314	314	9:00	9/17/2022	0.8	33	33	33	2:00	9/11/2022
F14	2.6	107	107	107	22:00	9/28/2022	0.20	10.00	10.00	10.00	14:00	9/19/2022
F15	10.3	430	430	430	20:00	9/6/2022	1.20	50.00	50.00	50.00	0:00	9/25/2022
<b>October, 2022</b>												
F1												
F2	11.4	478	478	478	20:00	10/12/2022	0.10	4.00	4.00	4.00	7:00	10/2/2022
F3	12	506	506	506	19:00	10/8/2022	1.90	78.00	78.00	78.00	2:00	10/11/2022
F4	6.9	289	289	289	19:00	10/29/2022	0.90	38.00	38.00	38.00	3:00	10/22/2022
F5	1.3	54	54	54	14:00	10/4/2022	0.10	3.00	3.00	3.00	19:00	10/31/2022

**Comparative Studies of Facts Devices for Reduction of Power Loss and Voltage Profile Improvement in RDS**

F6	6.2	258	258	258	15:00	10/11/2022	0.40	18.00	18.00	18.00	3:00	10/31/2022
F7	8.3	350	350	350	20:00	10/22/2022	0.90	36.00	36.00	36.00	3:00	10/21/2022
F8												
F9	9.8	414	414	414	11:00	10/14/2022	1.40	59.00	59.00	59.00	2:00	10/10/2022
F10	9.4	396	396	396	12:00	10/25/2022	1.20	52.00	52.00	52.00	2:00	10/10/2022
F11	8.3	348	348	348	19:00	10/24/2022	1.50	61.00	61.00	61.00	2:00	10/3/2022
F12	12.2	512	512	512	19:00	10/2/2022	0.70	119	119	119	5:00	10/1/2022
F13	7.4	314	314	314	5:00	10/29/2022	1	44	44	44	2:00	10/10/2022
F14	2.3	96	96	96	9:00	10/30/2022	0.30	12.00	12.00	12.00	17:00	10/2/2022
F15	10.8	453	453	453	19:00	10/12/2022	2.80	119	119	119	3:00	10/3/2022
<b>November, 2022</b>												
F1												
F2	11	471	471	471	19:00	11/1/2022	0.80	34.00	34.00	34.00	20:00	11/4/2022
F3	10.5	444	444	444	20:00	11/2/2022	1.40	62.00	62.00	62.00	2:00	11/1/2022
F4	11	467	467	467	19:00	11/23/2022	0.80	36.00	36.00	36.00	1:00	11/21/2022
F5	1	42	42	42	10:00	11/21/2022	0.02	1.00	1.00	1.00	9:00	11/1/2022
F6	5.2	219	219	219	12:00	11/7/2022	1.90	80.00	80.00	80.00	3:00	11/11/2022
F7	7.5	317	317	317	19:00	11/9/2022	1.30	55.00	55.00	55.00	2:00	11/14/2022
F8												
F9	8.2	347	347	347	11:00	11/23/2022	1.50	65.00	65.00	65.00	0:00	11/6/2022
F10	7.4	311	311	311	19:00	11/9/2022	1.40	61.00	61.00	61.00	3:00	11/2/2022
F11	8.8	372	372	372	19:00	11/4/2022	1.60	70.00	70.00	70.00	2:00	11/14/2022
F12	11.7	495	495	495	19:00	11/16/2022	2.70	115	115	115	1:00	11/11/2022
F13	7.8	331	331	331	9:00	11/5/2022	1.4	61	61	61	0:00	11/6/2022
F14	2.4	100	100	100	7:00	11/2/2022	0.30	12.00	12.00	12.00	11:00	11/17/2022
F15	11.3	477	477	477	19:00	11/29/2022	1.20	51.00	51.00	51.00	17:00	11/17/2022
<b>December, 2022</b>												
F1												
F2	11.1	466	466	466	19:00	12/7/2022	1.40	59.00	59.00	59.00	03:00	12/16/2022
F3	9.9	418	418	418	19:00	12/7/2022	1.50	65.00	65.00	65.00	03:00	12/19/2022

**Comparative Studies of Facts Devices for Reduction of Power Loss and Voltage Profile Improvement in RDS**

F4	9.5	400	400	400	19:00	12/5/2022	0.50	19.00	19.00	19.00	04:00	12/16/2022
F5	0.95	40	40	40	11:00	12/12/2022	0.02	1.00	1.00	1.00	20:00	12/10/2022
F6	5.8	245	245	245	11:00	12/7/2022	1.50	64.00	64.00	64.00	19:00	12/27/2022
F7	8.5	359	359	359	19:00	12/12/2022	1.20	49.00	49.00	49.00	03:00	12/19/2022
F8												
F9	7.9	330	330	330	11:00	12/8/2022	1.30	55.00	55.00	55.00	02:00	12/19/2022
F10	9	377	377	377	12:00	12/14/2022	0.90	40.00	40.00	40.00	03:00	12/19/2022
F11	9	376	376	376	19:00	12/21/2022	1.20	50.00	50.00	50.00	03:00	12/19/2022
F12	11.8	497	497	497	19:00	12/27/2022	2.30	98	98	98	03:00	12/19/2022
F13	7.9	332	332	332	09:00	12/31/2022	1.2	52	52	52	02:00	12/18/2022
F14	2.1	92	92	92	21:00	12/12/2022	0.30	12.00	12.00	12.00	10:00	12/5/2022
F15	11.5	486	486	486	19:00	12/13/2022	2.02	85.00	85.00	85.00	02:00	12/5/2022