



ADDIS ABABA UNIVERSITY
ADDIS ABABA INSTITUTE OF TECHNOLOGY

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

**Performance Evaluation of Transmission Lines for Power Loss Minimization
and Voltage Profile Enhancement Using FACTS Devices
(Case Study: 400kV-230kV Transmission Lines in the Ethiopian Power
Network)**

By
Tokuma Zeleke

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

Thesis Advisor: Dr.Ing. Getachew Biru

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Addis Ababa, Ethiopia



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Performance Evaluation of Transmission Lines for Power Loss Minimization and Voltage Profile Enhancement Using FACTS Devices

DECLARATION

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

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This thesis work has been submitted for examination with my approval as a University Advisor.

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ABSTRACT

The transmission system is responsible for transporting the electric power generated at the generation station to the distribution system. When a power transmission system works with severely loaded lines, it suffers from power losses and larger voltage deviations, which can cause the system to malfunction and eventually collapse. Capacitor banks and STATCOM are used in this thesis in order to reduce line loss and enhance the voltage of the considered system. The power flow analysis using the Newton-Raphson algorithm in MATLAB software and particle swarm optimization techniques are utilized to determine the optimal devices sizing and position.

The result shows that, with proper placement of the Capacitor banks and STATCOM on the identified candidate buses (68, 65, 27, 20) with their optimal sizes, the active power losses of the system gets improved by 10.78%, 20.57%, 35.84%, 6.602% and 10.76%, 22.29%, 37.79% , 7.76% in the scenarios of base load, 25% overload, 50% overload and 75% underload respectively. In scenarios of base load, 25% overload, 50% overload and 75% underload the voltage magnitudes of weak buses are also improved by 12.5%, 19.41%, 31.15%, 3.23% and 17.5%, 22.8%, 31.4%, 9.84% after the incorporation of Capacitor banks and STATCOM respectively. The improvements made by the placements of Capacitor banks and STATCOM in the 75% underload case are not so much significant as the network is almost in a desirable operating condition under this scenario. Thus, the placement of those FACTS devices for underload (75% of base load) is not recommended.

The amount of energy cost saved after installing Capacitor bank is 1,825,856.88726 USD, 2,282,320.79712 USD, 2,518,262.57088 USD with Payback periods of 0.516 years, 0.186 years and 0.0579 years in the scenarios of base load, 25% overload and 50% overload respectively. And after installing STATCOM, the amount of energy cost saved is 15,339,987.264 USD, 31,399,157.216 USD, 33,744,416.832 USD with Payback periods of 4.344 years, 2.369 years and 0.485 years in the scenarios of base load, 25% overload and 50% overload respectively.

In general, for power loss minimization and voltage profile enhancements, STATCOM is proposed for the system due to its better performance during overload as observed from the simulation results, manages over voltage at under load case and its dynamic capability to inject reactive power based on the required reactive load.

Keywords: Transmission line Loss, STATCOM, Capacitor bank, Voltage profile, PSO

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LIST OF ABBREVIATIONS

EEP	Ethiopian Electric Power
NLDC	National load dispatch center
GERD	Grand Ethiopian renaissance dam
AC	Alternating Current
DC	Direct Current
DE	Differential Evolution
DIgSILENT	Digital Simulation and Electrical Network Calculation
FACTS	Flexible AC Transmission Systems
MVA	Mega Volt ampere
MVA _r	Mega Voltage Ampere reactive
kV	Kilo volt
MW	Mega watt
VR	Voltage regulation
SSSC	Static Synchronous Series Compensator
STATCOM	Static Compensator
SVC	Static VAR Compensator
GA	Genetic Algorithm
GTO	Gate Turn Off
HVDC	High Voltage Direct Current
IEEE	International Electrical and Electronics Engineering
IPFC	Interline Power Flow Controller
MATLAB	Matrix Laboratory
PSO	Particle Swarm Optimization
pu	per unit
UPFC	Unified Power Flow Controller
VAR	Voltage Ampere Reactive
VSC	Voltage Source Converter

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TCPST	Thyristor Controlled Phase Shifting Transformer
TCR	Thyristor Controlled Reactor
TCSC	Thyristors Controller Series Compensator
TSC	Thyristor Switched Capacitor
P_G	Generated Power
V_G	Generated line to line voltage
$\text{Cos}\theta_G$	Power factor for generator
V_R	Receiving end Voltage
V_S	Sending end Voltage
S	Apparent power
P	Active Power
Q	Reactive Power

CHAPTER 1

INTRODUCTION

1.1 Background

A sufficient supply of power is a necessary condition for economic growth to occur. For many years, Ethiopian Electric Power Corporation has strived to supply adequate and high-quality electricity to its customers.

Electricity is the lifeblood of industry and, by extension, the economy. This vital commodity is transmitted by overhead or underground power cables from the power plant to the end consumer. As a result, maintaining the integrity of these lines is critical. Aluminum, which is a good conductor of electricity, is used extensively in transmission lines. It has a resistance value, just like all other conductors. There is also a line inductance and capacitance depending on the layout of the three phases of the transmission line. All of the above have an impact on the network's efficiency as a whole [1].

The objective of a transmission network is to reliably and economically move bulk electric energy from generating power plants to electrical substations (distribution systems) positioned near demand centers through high-voltage power lines. Due to constant load expansion, electric power transmission lines have become more limited in recent years. Increases in power carrying capacity of power transmission lines are urgently needed to reduce losses and voltage insecurity, ensuring the overall reliability, power quality, and security of the power system. To supply the ever-increasing demand for electricity, utilities rely on current power generation and transmission systems rather than creating new transmission lines, which are costly and environmentally damaging. Furthermore, certain transmission lines are operating significantly below their rated thermal limits, while others are overloaded, resulting in voltage collapse and lowering system reliability and stability. This broad issue necessitates research into various approaches for minimizing transmission line losses, as well as the implementation of current solutions that would allow existing transmission lines to operate at full capacity without exposing power system security, stability, or power transfer. Because power is proportional to the product of voltage (V) and current (I), while losses are proportional to I^2 , high voltage is frequently used to transmit power with the least amount of loss.

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With the use of Flexible AC Transmission System (FACTS) devices, the loading capacity of transmission lines can be improved by minimizing real power loss in the line.

Power transfer capacity through transmission lines can be increased by using different FACTS controllers in such a way that their thermal limits are not violated, losses are minimized, power transfer is increased, and steadiness margin is increased [2].

For reactive VAR compensation and voltage support in power systems, shunt devices such as the static VAR compensator (SVC) and STATCOM have been most extensively utilized. The TCSC and SSSC are series devices that can be used to control active power flow on transmission lines. The UPFC, for example, can be utilized for voltage support and active power flow regulation with maximum flexibility and at a higher cost [3]. However, because these controllers are so expensive, the best place for them in the network must be determined [4].

Due to overloading and aging issues, Ethiopia's existing transmission networks have increased transmission line losses. Existing transmission lines will be disrupted, resulting in bus voltage insecurity and power loss. As a result, voltage regulation issues arise. In order to improve the voltage profile of the transmission network, it is important to develop appropriate controlling devices.

In large countries like Brazil, the United States, and Canada, phase-to-phase transmission voltages of up to 765 kV are employed, whereas 380 – 400 kV is more common in Europe. 765kV, 500kV, 380–400kV, 330kV, 275kV, 220–230kV, 132–133kV, and 66–69kV are the standard voltages recommended by the International Electro technical Commission (IEC) in order to reduce transmission losses, maintain economic transmission circuits, and present an environmentally acceptable transmission/distribution system (IEC, 2010).

Ethiopia's power transmission network comprises of 45kV, 66kV, 132kV, 230kV, 400kV, and 500kV (GERD, which is now under development) lines, with 33kV or 15kV sub-transmission lines used for distribution systems. The focus of this thesis is on the Ethiopian 400kV-230kV transmission lines.

The word "power line" refers to a material medium (which could be an overhead or underground line conductor) that serves as a path for directing energy transmission from one location to another. The transmission line connects the main energy converter (Generator) to the distribution network (substation). The calculation of voltage drop, line losses, and transmission efficiency are

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all significant concerns in the design and operation of transmission lines. Resistance, inductance, capacitance, and shunt conductance are four characteristics that have a significant impact on these numbers. The leakage current causes the shunt conductance, which is connected with dielectric losses. It is so modest that it can be ignored. The impact of magnetic and electric fields around the wire causes inductance and capacitance, respectively [5].

1.2 Motivation

There are numerous indicators in Ethiopia that reveal concerns with electric power transmission line performance, such as power loss, voltage profile issues, and power transfer capability. Power losses and reliability difficulties are caused by these performance issues. As a result, the analyzed case study transmission line requires upgrades in the areas mentioned above.

1.3 Statement of the Problem

In order to serve the enormous demand of consumers, the power system is a complex network of transmission lines interconnecting the generating units at various locations to the primary load sites in the overall power system. As a result, between the power stations and the load centers, a substantial network of power lines (i.e. overhead or underground conductors) is necessary. They are a collection of conductors that are run from one location to another and are supported by transmission towers. This entails making connections between a power plant and a substation that is many kilometers away.

Furthermore, the major goal of all power systems is to maintain a constant power balance between generation and consumption while keeping all bus voltages within prescribed limits, both in magnitude and angle. However, no matter how well the system is planned, grid inefficiencies or load losses will occur as a result of heat dissipation caused by current consumption in the power lines, resulting in power imbalance between generation and main load centers.

The more electricity that travels via the power lines, the more current that flows, and the power quality suffers as a result. Unusual operating issues, such as voltages below the minimum or above the maximum permitted level, are also experienced. As a result, consumers will be exposed to the dangers, poor quality, and high cost of electricity, which industry does not accept. To improve transmission network efficiency and high-quality energy supply to end-users with

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dependability and economy, it is important to monitor power losses, voltage profiles, and mitigate (minimize) losses.

Therefore, this thesis investigates the Ethiopian transmission lines of voltage level 400kV-230kV employing Capacitor banks and STATCOM to overcome the transmission line loss and voltage profile problem.

1.4 Objectives

➤ General Objective

The general objective of this thesis work is to evaluate the performance of the Ethiopian transmission lines with the voltage levels ranging from 400kV - 230kV to reduce line loss and improve voltage profile using Capacitor Banks and STATCOM.

➤ Specific Objectives

The following are the specific objectives of the thesis.

- To collect and analyze data of Ethiopian transmission line with the voltage levels ranging from 400kV - 230kV.
- To model the considered transmission lines with and without Capacitor banks and STATCOM compensators using MATLAB Software.
- To assess the current level of power losses and voltage profile of the considered transmission lines.
- To determine the optimal placement and Size of Capacitor banks and STATCOM device using PSO to reduce the transmission power losses and improve bus voltage profile for the system under the case study.
- To analyze the impact of Capacitor banks and STATCOM compensators on the performance of the considered transmission lines.
- To analyze the overall results and draw conclusions for the considered transmission line.

1.5 Methodology

The following activities are performed to carry out this thesis work.

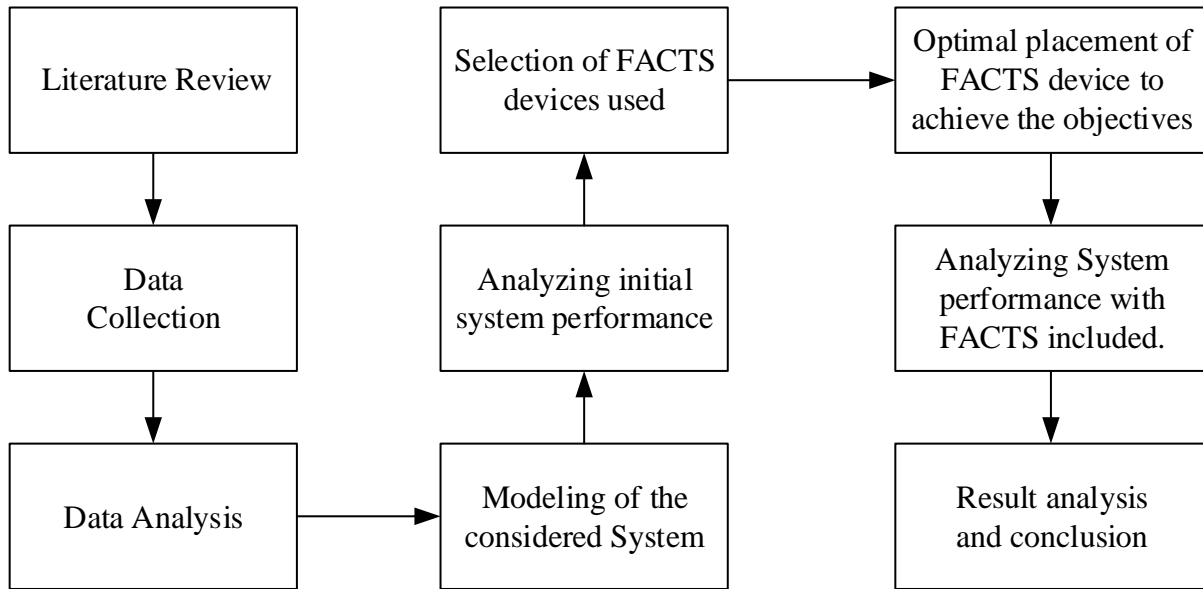


Figure 1. 1: The research methodology block diagram

- Literature review: A number of journals, article and papers on the power loss evaluation, voltage profile and other related works have been reviewed.
- Conducting data collection from National Load dispatch center.
- Analysis of the collected data.
- Modeling of the system considered with DigSILENT and the initial system performance was done with MATLAB.
- Proposing the appropriate FACTS device based on the initial system performance.
- Analyzing the system performance with the FACTS devices included.
- Result comparison of the system with and without using FACTS devices at different load level was done.
- At the last, conclusions are drawn and recommendations are made to Ethiopian Electric Power.

1.6 Scope

The scope of this thesis is to analyze, model, simulate, and evaluate the performance of a transmission line without and with Capacitor banks and STATCOM to enhance the voltage profile and decrease losses on an Ethiopian transmission line with voltage levels ranging from 400kV - 230kV.

1.7 Significance of the study

The whole electric power utility incurs significant costs as a result of power losses. As a result, assessing these losses and reducing them are critical jobs. The collapse of the voltage profile at a specific bus beyond the permitted limit will result in the system's entire collapse. As a result, this thesis has a significant impact on improving such conditions on Ethiopia's 400kV-230kV transmission line.

1.8 Organizations of the Thesis

The thesis is organized into five chapters which are briefly summarized as below.

Chapter One deals with a brief introduction of the thesis background, problem statement, objectives, scope, methodology and thesis outline.

Chapter Two discusses about the theoretical background and literature review of the study, mainly on transmission line losses, voltage drop and overview of the FACTS devices.

Chapter Three describes data collection and modelling of the Ethiopian transmission line with the voltage levels ranging from 400kV - 230kV.

Chapter Four system simulation and result discussion without and with installing both Capacitor banks and STATCOM.

Chapter Five presents the conclusions and recommendations.

CHAPTER 2

PERFORMANCE ENHANCEMENT OF TRANSMISSION LINES USING FACTS DEVICES AND LITERATURE REVIEW

2.1 Introduction

This chapter presents literature review on the related past research work with the study. It starts with a discussion of FACTS (Flexible Alternating Currents Transmission System) devices for dealing with power system issues. Section 2.2 presents analysis of transmission line losses and voltage regulation of transmission line is discussed in Section 2.3. Power loss minimization and Voltage profile improvement using FACTS devices is presented in Section 2.4. Finally, Section 2.5 presents the literature review.

2.2 Analysis of Transmission line losses

Power transmission systems have evolved significantly in recent years. The voltage deviation caused by load variation, as well as the power transfer limitations caused by reactive power imbalances, have attracted attention to the need to make better use of the existing transmission line. [6]

Transmission and distribution losses in the electric power industry include losses in transmission between sources of supply and points of distribution (substations) as well as losses in distribution to customers. Losses in generation, transmission, and distribution are included in the worldwide losses. Transmission losses occur in both the generation and transmission systems, while distribution losses only occur inside the distribution system [7]. There are two types of losses in the power system: technical and non-technical losses.

Technical Losses

Current flowing in the electrical network causes technical losses. The following types of losses are caused by it:

- Copper losses are caused by I^2R losses, which are present in all conductors due to their finite resistance. This is a real power loss that is frequently referred to as conductor loss or conductor heating loss.
- Induction and radiation losses are caused by electromagnetic fields that surround conductors.

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- Dielectric losses—losses caused by the heating of the dielectric material between conductors.

Well-known physical electricity effects such as harmonics distortion, long single-phase lines, unbalanced loading, and losses due to overloading and low voltage, as well as losses due to aging and poor equipment quality, create technical losses. They can, however, be computed using the inherent properties of resistance, reactance, capacitance, voltage, current, and power system components. They're calculated to determine which components will be added to the system to reduce losses and increase voltage levels [8].

Non-Technical Losses

Non-technical losses, on the other hand, are produced by factors outside of the power system, or by loads and conditions that the technical losses calculation unnoticed. Non-technical losses are more difficult to quantify since they are frequently unaccounted for by system operators, leaving no records [9].

Electricity theft, non-payment of bills by customers, errors in technical losses computation, and faults in accounting and record keeping that misrepresent technical facts are the most likely sources of non-technical losses [10].

Non-technical losses in the power sector, for example, are almost non-existent or negligible in industrialized countries, because the majority of the population can afford to pay prices that represent supply costs. In general, numerous operational pieces of information can be utilized to estimate technical losses; the availability and type of data define the calculation methods used and the result's veracity.

Factors affecting Power Losses

Some of the elements that determine system losses are listed below [11]:

1. **Circulating current:** Failure to maintain a flat voltage profile across networks in today's highly interconnected networks will result in the flow of circulating currents. To minimize losses, it is critical for a power system to maintain strict voltage limitations.
2. **Phase balancing:** When dealing with severely loaded lines, this is important since the goal is to balance the phase load so that the maximum deviation from the average is less than 10%.

3. **Power factor:** The current is minimal at unity power factor, and any reactive component will induce an increase in current, resulting in an increase in actual power losses. Volt ampere reactive (VAR) losses become severe for large inductive loads, necessitating demand side adjustment (i.e. by installation of shunt capacitors). Furthermore, the voltage drop owing to line resistance is greater as a result of the increased current in the system than it would be at unity power factor.
4. **Voltage regulation:** Because line losses grow with the square of load current, reducing both maximum demand and energy losses can be accomplished by maintaining and/or raising the system's normal operating voltage.

Analysis of Power Losses

When examining the pattern of generation and loads, power losses can be analyzed or estimated using numerous equations [12]:

- i. Differential Loss Method of Loss Evaluation

Differential Loss Method of Loss Evaluation

The difference between sent and received power is another way to express power loss.

$$P_{loss} = P_{sent} - P_{received} = P_S - P_R \quad (2.1)$$

Figure 2.1 depicts the relationship between the powers sent, received, and associated losses in the transmission network [14].

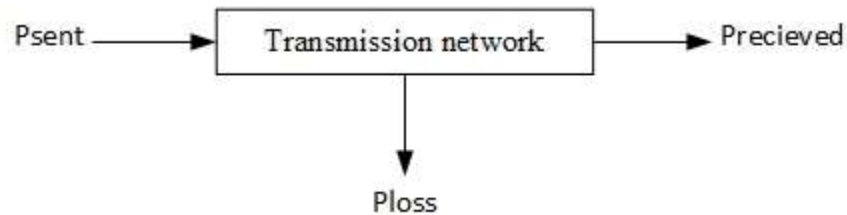


Figure 2. 1: The relationship between power sent and power received.

Technical losses can also be calculated using transmission line efficiency, where transmission line efficiency η is defined as,

$$\eta = \frac{\text{power recieved (p.u)}}{\text{Power sent}} = \frac{P_R}{P_S} \quad (2.2)$$

$$\eta = \frac{\text{power sent} - \text{power loss in the line}}{\text{Power sent}} = \frac{P_S - P_L}{P_S} \quad (2.3)$$

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$$\eta = 1 - \frac{P_L}{P_S} = 1 - \frac{\text{Power loss in the line}}{\text{Power sent}} \quad (2.4)$$

Therefore, efficiency η of a transmission line can also be defined as

$$\eta = \frac{P_R}{P_S} = \frac{P_R}{P_S + P_L} \quad (2.5)$$

Where P_S is the power sent, P_R is the load power received and P_L is the net sum of the power lost in the transmission system [15].

Transmission line losses can be simply calculated by subtracting the receiving end power from the sending end power, as shown in equation 2.7. When both the sending and receiving end powers are known, this approach is employed. Because the system will be complex, this strategy may not be appropriate to big interconnected systems.

If we have buses i and k , then the complex power leaving bus- i is given by [14],

$$S_i = P_i + jQ_i = V_i i_i^* \quad (2.6)$$

The complex power which is entering bus- k is also given by [16],

$$S_k = P_k + jQ_k = V_k i_k^* \quad (2.7)$$

Therefore, from equation 2.12 and 2.13 the real power loss due to I^2R on the transmission line between bus- i and bus- k is determined as [14],

$$P_{loss\ i-k} = P_i - P_k \quad (2.8)$$

Similarly, the reactive power loss due to I^2X on the transmission line between Bus- i and bus- k is determined as [14],

$$Q_{loss\ i-k} = Q_i - Q_k \quad (2.9)$$

2.3 Voltage regulation

When full load at a specified power factor is thrown off, voltage regulation of a transmission line is defined as the rise in voltage at the receiving end, given as a percentage of full load voltage [17]. i.e.

$$\text{Per cent regulation} = \frac{|V_{RO}| - |V_{RL}|}{|V_{RL}|} \times 100 \quad (2.10)$$

Where V_{RO} = magnitude of no load receiving-end voltage

V_{RL} = magnitude of full load receiving-end voltage, (At a specified power factor)

For short line, $|V_{RO}| = |V_S|$, $|V_{RL}| = |V_R|$

$$\text{Therefore, Percent regulation} = \frac{|V_S| - |V_R|}{|V_R|} = \frac{|I| R \cos \phi_r + |I| X \sin \phi_r}{|V_R|} \times 100 \quad (2.11)$$

2.4 Power loss minimization and Voltage profile improvement using FACTS devices

FACTS stands for Flexible Alternating Current Transmission System, which are AC transmission systems that use power electronics and other static controllers to improve controllability and power transmission capability.

The FACTS regulator is defined as a system based on power electronics and other static devices that provide control of one or more parameters of the AC transmission system. Among the adjustable parameters that can be known, are for example: voltage, current, impedance and phase angle.

FACTS devices can be divided into four main categories [18]:

1. Parallel controllers
2. Series controllers
3. Combined series – series controllers
4. Combined series – parallel controllers

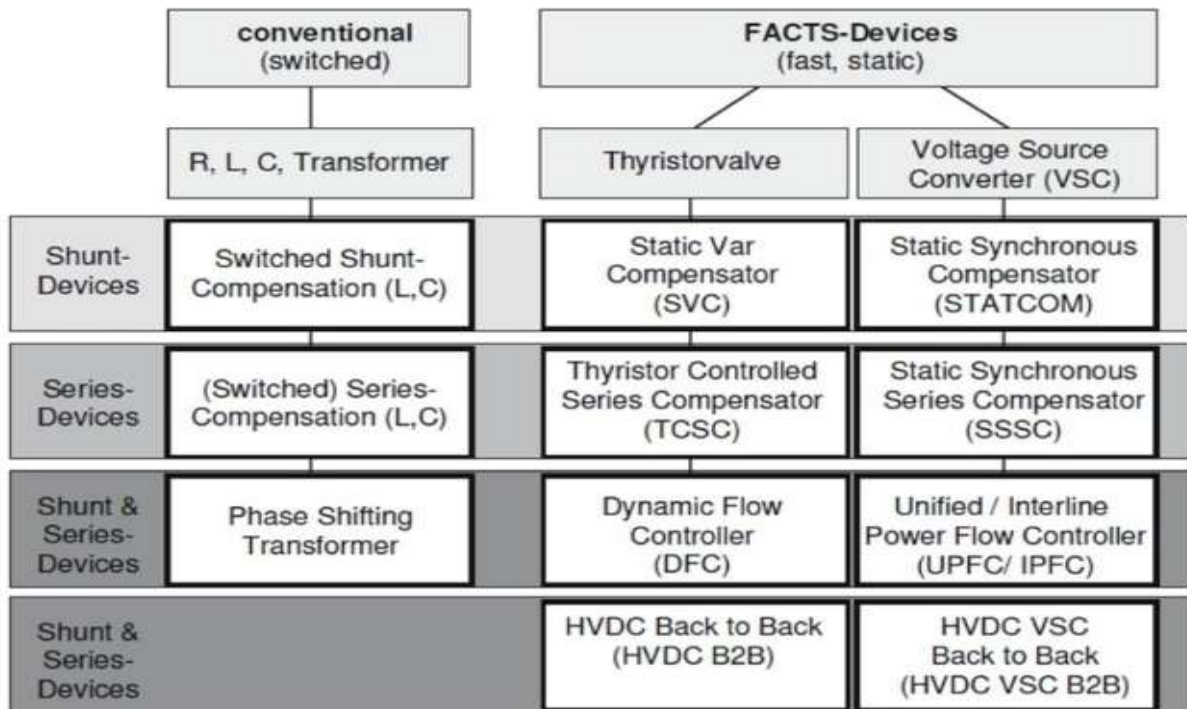


Figure 2. 2: Overview of FACTS devices

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Parallel controllers - regulate impedance (e.g., a capacitor or reactor) or power supply using power electronics with the appropriate frequency, or a combination of the two. All parallel regulators, in theory, inject current into the power system at the point of connection.

Series controllers - the impedance regulated power supply or its combination, in the case of a parallel regulator, may be changeable. All series controllers are, in theory, voltage sources connected in series with the line.

Combined series – series controllers – are available in two different versions.

The first version is made up of a series regulator that is attached to the line and is coordinated, controlling, and segregated. The second type of unified regulator is one in which the series regulator provides independent series reactive power compensation in each line as well as active power flow between lines in the one-way line connecting the regulators. Interline Power Flow Controller is a type of vision that allows for the regulation of active and reactive power flowing in lines, allowing for the most efficient use of transmission capacity. [19].

Combined series – parallel controllers can also be in two versions.

The first version is a hybrid of series and parallel regulators that are regulated separately. The Unified Power Flow Controller (unified power flow controller) is the second variant, which uses a combination of series and parallel controllers connected to the direct line. The second version has the advantage of allowing active power exchange between the series and shunt regulators due to series compensation and current injections into the system.

Parallel Controllers

Static Synchronous Compensator (STATCOM) - A static synchronous generator that functions as a parallel-connected static var compensator, allowing the capacitive and inductive currents to be regulated independently of the systems alternating voltage. It provides for quick and accurate responses to voltage increases and decreases in the system. Its function is comparable to that of a rotary synchronous compensator; its advantages include improved response speed, control accuracy, and symmetric range Q, as well as the fact that it does not add to the short-circuit current in the Energy system (ES) [20].

Static Synchronous Generator (SSG) - A static synchronous compensator and an energy source combined. This permits the power system unit and the relevant unit to regulate the

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exchange of reactive and active power. A static synchronous generator's power source can act similarly to a battery, superconducting magnet, or capacitor [20].

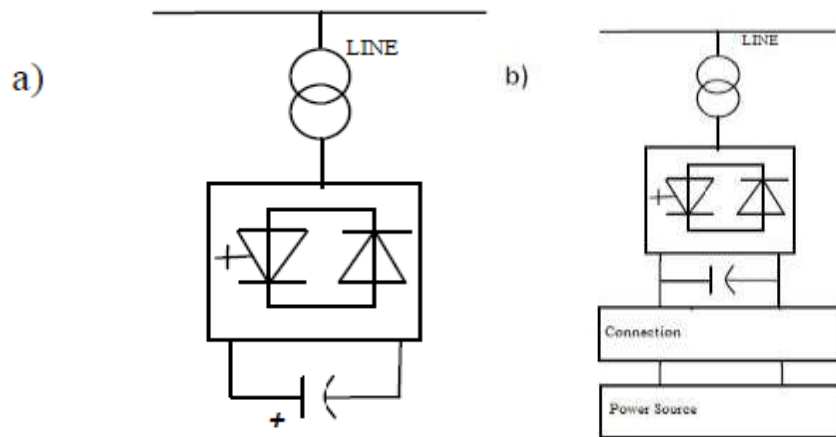


Figure 2. 3: Static synchronous compensator a) without power source, b) with power source [21].

Static Var Compensator (SVC) – Reactive Power Static Compensator – The function of a parallel connected static device or source of reactive power is to regulate specific parameters in the system (usually it is voltage at the node in system). It is a generic term for thyristor control, switched inductor, capacitor, or a combination of these components. Static var compensators come in a variety of designs, but the majority of them include the following components [20].

Thyristor Controlled Reactor (TCR) Through the control of current through the inductor, reactive power can be altered continually. Switching thyristors create deformation of the current flowing through the device TCR, resulting in increased harmonics in this device. The way thyristors are coupled (triangle, star), their number (e.g. 6-pulse, 12-pulse TCR), and the mode of operation all influence the multiples of the fundamental harmonic. For its eradication, high harmonic filters are used in parallel with the TCR device.

Thyristor Switched Reactors (TSR) In this situation, switching reactors can vary the reactive power. TSR is normally made up of many parallel-connected reactors that are connected or disconnected from the system depending on their needs.

Thyristor Switched Capacitor (TSC) - Switching capacitors can modify the reactive power. TSCs are typically made up of numerous capacitors connected in parallel that are connected or disconnected from the system depending on the requirements. The device connects the reactors in series to restrict switching transients, dampen surges, and avoid resonances with the network's

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inductive reactance. It is feasible to lessen the negative transients induced by switching by using TSC correctly [22].

Mechanical Switched Reactor a Mechanical Switched Capacitor (MSR a MSC)-When speed is not the main focus, mechanically switched capacitors (MSC) are a simple and low speed solution that provides grid stabilization and voltage control under heavy load conditions, while mechanically switched reactors (MSR) provide stabilization under low load conditions.

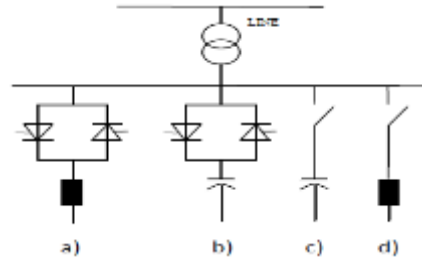


Figure 2. 4: Static compensator of reactive power (a) reactor controlled by thyristor and reactor switched by thyristor, (b) condensator switched by thyristor, (c) mechanical switched condensator, (d) mechanical switched reactor [23].

Thyristor Controlled Braking Resistor (TCBR) - Switched resistor thyristor (usually linear). It permits the energy system to be stabilized and minimizes the generator's acceleration power during malfunctions. The optimal position for TCBR is near the generator, which necessitates acceleration during transient unstable situations.

Series Controllers

Static Synchronous Series Compensator (SSSC) - The output voltage of a static synchronous generator operating as a series compensator can be controlled independently of the system's current. It enables for power flow regulation in both directions as well as the absorption of oscillations. It's similar to a regulated series capacitor, but it's a lot more efficient and precise [33].

One of the most FACTS controllers is the SSSC controller, which works in tandem with the STATCOM controller.

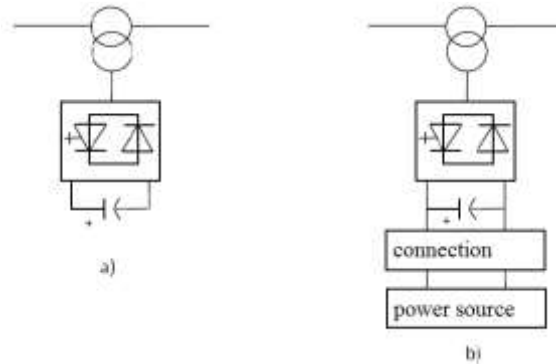


Figure 2. 5: Static synchronous series compensator a) without power source, b) with additional power source [18].

Interline Power Flow Controller (IPFC) - A two-way exchange system consisting of two or more static synchronous series compensators connected by a one-way line. Compensators are controlled to maintain the needed reactive power flow across the lines while regulating the flow of active power [18].

Thyristor Switched Series Capacitor (TSSC) - A compensator made up of thyristor-controlled reactors (TCR) connected in series with the condensation. It allows for discrete series impedance adjustment in a line. TSSC configurations frequently incorporate additional capacitors to which parallel thyristors are coupled in an antiparallel configuration. In this approach, the degree of compensation is controlled discretely by increasing or decreasing the number of capacitors linked to the system [18].

Thyristor Controlled Series Reactor (TCSR) A compensator made up of parallel reactors controlled by a thyristor (TCR). It gives you complete control over the series line impedance.

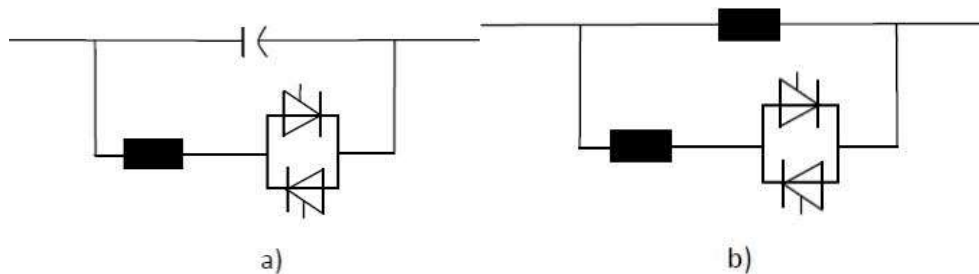


Figure 2. 6: a) Thyristor controlled series capacitor and thyristor switched series capacitor b) thyristor controlled series reactor and thyristor switched series reactor [18].

Combined Series-Parallel Controllers

Unified Power Flow Controller (UPFC) - A one-way wire connects a static synchronous compensator (STATCOM) with a series synchronous static compensator (SSSC) enabling bidirectional transfer between active power compensators. Voltage control, impedance control, and phase angle control are all available in real time and in any combination. It allows for separate regulation of the active and reactive power flows in the line.

The basic functions of UPFC [18]:

- a) Voltage regulation,
- b) Series capacitive compensation
- c) The regulation of the phase angle (in both directions) without changing the voltage.

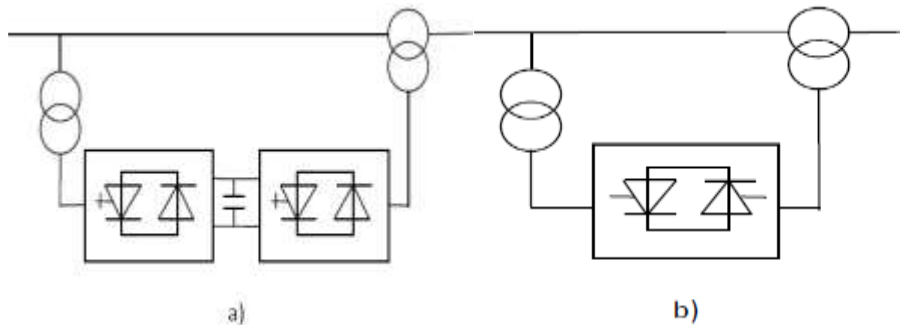


Figure 2. 7: a) Unified power flow controller, b) thyristor controlled transformer with angle Regulation [18].

Table 2. 1: Application areas of FACTS devices [18]

Type of FACTS regulator	Application area
STATCOM without additional energy source	voltage control, reactive power compensation, damping oscillations, voltage stability
STATCOM with the additional energy source	voltage control, reactive power compensation, damping oscillations, static and dynamic stability, voltage stability
SVC, TCR, TSC, TSR	voltage control, reactive power compensation, damping oscillations, static and dynamic stability, voltage stability
SSSC without additional source of energy	current control, damping oscillations, static and dynamic stability, voltage stability, short circuit current limitation
SSSC with additional source	current control, damping oscillations, static and dynamic

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of energy	stability, voltage stability
TCSC, TSSC	current control, damping oscillations, static and dynamic stability, voltage stability, short circuit current limitation
TCSR, TSSR, TCPST	current control, damping oscillations, static and dynamic stability, voltage stability, short circuit current limitation active power regulation, damping oscillations, static and dynamic stability, voltage stability
UPFC	control of active and reactive power, voltage control, reactive power compensation, damping oscillations, static and dynamic stability, voltage stability, short circuit current limitation
TCVL	voltage limits during transient and dynamic storylines
TCVR	reactive power compensation, voltage regulation, damping oscillations, static and dynamic stability, voltage stability
IPFC	reactive power compensation, voltage regulation, damping oscillations, static and dynamic stability, voltage stability

The following FACTS devices specifically can be applied for power loss minimization and voltage profile improvement.

Table 2. 2: FACTS used for power loss minimization and Voltage profile improvement [18]

Formulation	Problem	Corrective action	Conventional solution	FACTS used
Voltage profile improvement	Voltage drop at higher load	Reactive power supply	Under excitation of generator, Parallel capacitors, series capacitors	SVC, TCSC, STATCOM
	High voltage at low load	Disconnecting reactive power supply	Turn off the line or parallel capacitor	SVC, TCSC, STATCOM

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		Absorption of reactive power	Turn off the parallel connection of capacitors or inductors	SVC, STATCOM
Power loss minimization	Overload of lines or transformers	Overload reduction	Connection of line or transformer	TCSC, UPFC
			Connection of series reactor	SVC, TCSC
	Turn of the line	Limitation of the line overload	Connection of the series reactor	UPFC, TCSC

Static Var Compensator (SVC)

SVC is a FACTS device with a parallel connection that includes a capacitor battery and a reactor controlled statically by thyristor switches. The voltage at the inclusion node is controlled using this device [21].

The static reactive power compensator is based on the principle of the electric network's "internal control" mode, which refers to the regulation of SVC passive elements that do not have their own EMF (capacitor batteries, reactors). There are several SVC methods depending on how the cumulative electromagnetic field of energy elements is managed [21]:

SVC – direct compensation, Because of the stepped switching on the capacitor bank, the equivalent resistance of the compensator changes discretely in this system.

SVC – indirect compensation, This technique, which is represented in Figure 2.10, Combined SVC, is based on a smooth regulation of current through the controlled reactor (CR) and is carried out for both principles.

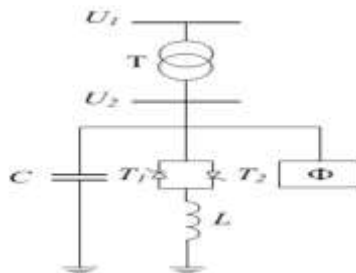


Figure 2. 8: Scheme of SVC of indirect compensation [21].

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The use of an SVC based on a controlled reactor allows for a more flexible solution to the problem of reactive power compensation and lowers power losses in the electrical network. In different modes of operation, the SVC's speed operation offers continuous generation or consumption of reactive power required to maintain a constant voltage on the network. Power fluctuations are also dampened by the compensator.

At the moment, the indirect and combined compensation method is the most popular. In contrast to the parallel connected capacitive battery, the SVC's equivalent resistance and, as a result, reactive power at its output, are continuously regulated. This is due to the fact that the resistance of TRC, which is part of the static compensator, may be adjusted constantly by altering the angle of the thyristor switch in series with the reactor.

2.5 Literature Review

Bindeshwar Singh, N.K.Sharma, and A.N.Tiwari [24] studied the FACTS controller model to increase the loadability of power system networks. By strategically placing and coordinating multiple FACTS controllers in large-scale power system networks, major improvements in operating parameters such as active power loss, voltage profile, congestion management, power system quality, efficiency of power system operations, and power system loadability can be achieved.

Saravanan [25] suggested using Particle Swarm Optimization to determine the best placement, settings, type, and quantity of FACTS devices, including UPFC, in order to reduce installation costs and increase transmission network loadability for single and multi-type FACTS devices. The best placement, the thermal limit for the lines, and the voltage limit for the buses are all used as restrictions in this process. IEEE 6 and IEEE 30 bus test systems have been used to verify this. After a certain number of devices have been installed, it has been discovered that system loadability cannot be improved any further. UPFC provides maximum system loadability in IEEE test systems, but the cost of installation is significant when compared to all other scenarios. Singh [26] proposed the best UPFC locations to improve system loadability. It has been put through its paces on the IEEE 14 bus system. For finding the best location for UPFC, a sensitivity-based approach has been developed. A nonlinear objective function and a set of nonlinear equality and inequality constraints are present in the optimal power flow problem. OPF solutions were obtained using sequential quadratic programming (SQP).

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With respect to line thermal limits and bus voltage magnitude limits, Shaheen [27] proposed using evolutionary optimization techniques to determine the best location and parameter settings for multiple UPFC devices in order to maximize loadability and reduce installation costs in power systems. This approach has been successfully tested on the IEEE 6 and IEEE 14 bus test power systems. Because the system loadability can be increased significantly by a specific load factor by installing UPFC, the results obtained by GA and PSO have a stable convergence characteristic and good computational efficiency.

G. Tulasiram Das, S. Tara Kalyani [28] indicated The Unified Power Flow Controller (UPFC) is the most versatile and complex power electronic equipment for controlling and optimizing power flow in electrical power transmission networks that has emerged. As of this study, actual and reactive power flow through a transmission line is controlled by installing UPFC at the sending end. Real and reactive power over the transmission line cannot be managed without the addition of a UPFC device. The UPFC is emulated using a control system that allows it to track changes in reference values such as AC voltage, DC voltage, and angle order of the series voltage source converter. The firing pulses for both converters are generated using a generalized pulse width modulation technique in this control system. It is feasible to manage the active power flowing through the line by installing the UPFC. MATLAB and PSCAD software were used to do the simulations.

Farhangfar [29] demonstrated a UPFC injection model and examined its impact on power flow and loss reduction in a power system network. The main transmission line is an ideal place for UPFC for loss reduction. Two ways can be used to accomplish this. The first way involves increasing transmission power in low-impedance wires. This can be accomplished by applying a series voltage that is in phase with the voltage on the sending end bus. Because of the higher transmission power, the size of the UPFC grows with this manner, making it more expensive. In lines with high impedance, the second method is to lower the transmission power. As a result, the line should have an inverse series voltage with respect to the voltage of the sending end bus. It is more cost-effective to install a UPFC device in high-voltage lines to reduce power system losses.

As an optimization problem, Kothari [30] devised the voltage phasor approach and loss minimization, which included UPFC. When a UPFC is implemented, Particle Swarm

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Optimization is used to reduce real power loss. IEEE 14 and IEEE 57 bus test systems are used to test it. The algorithm is simple to construct and capable of determining the global best solution for loss minimization. When it comes to huge power systems, PSO outperforms exhaustive and other methods by providing better results with less processing work.

Rashed [31] devised a Differential Evolutionary (DE) algorithm for determining the appropriate position and parameter settings for the Unified Power Flow Controller (UPFC) in order to reduce active and reactive power losses in the power system network. The IEEE 14-bus and IEEE 30-bus systems were utilized as case studies for the simulations, which were done in MATLAB. The DE approach was compared to Particle Swarm Optimization for comparison purposes. When compared to particle swarm optimization, the results show that DE is a simple to use, reliable, and powerful optimization technique (PSO). The active and reactive power losses in the transmission system network can be greatly reduced by installing UPFC in the ideal location identified by DE.

As of N.Poornachandrarao, P.Pavan Kumar [32], the unified power flow controller manages transmitted power by simultaneously managing essential system parameters such as transmission voltage, impedance, and phase angle. The impacts of UPFC are studied using an IEEE 14 bus system in this research. The nodal voltages and power flow between the nodes were determined by load flow experiments for a specific system. The output is evaluated using the MATLAB application, both with and without UPFC installed. When a UPFC device is placed, the power flow across the lines improves to a pre-specified value. After the UPFC was installed, the real power losses between the lines were reduced. As a result, it can be inferred that the voltage profile and power flow across the lines improves following the insertion of the UPFC device. This application can also be used to obtain UPFC control settings for various pre-specified power flows.

Aditya Tiwari, K.K.Swarnkar, S.Wadhvani and A.K.Wadhvani [33] Uses a genetic algorithm, a multi-objective optimal power flow for optimal FACTS device allocation. According to their studies FACTS devices can help to reduce power system losses, lower generation costs, improve system stability, and increase power transmission capabilities. The major goal is to develop a GA-based technique for determining the number and placement of FACTS devices.

CHAPTER 3

MODELING AND ANALYSIS OF THE ETHIOPIAN 400kV-230kV TRANSMISSION LINE NETWORK

3.1 Introduction

This thesis focuses basically on the specific objectives presented in Section 1.3. It starts with necessary data collection from the EEP office of NLDC and performs Newton-Raphson power flow analysis on the chosen case study to analyze the current state of the power system. Depending on the power flow result, the optimal placement of the Capacitor and STATCOM device is identified. Section 3.2 presents data collection while Section 3.3 discusses modeling of 400kV-230kV Ethiopian transmission line network. Power loss analysis of 400kV-230kV transmission line without STATCOM and Capacitor Bank is presented in Section 3.4. Identification of weak buses for placement of STATCOM and Capacitor Bank is carried out in Section 3.5. Finally, Section 3.6 discusses particle swarm optimization method.

3.2 Data Collection

For this thesis work the necessary data were collected from EEP specific office of NLDC. The collected data includes Generator data, Transmission line data, Transformer data and Load data of the specific transmission line of the case study.

Generation Data

Generators are modeled as voltage-controlled sources that control the magnitude of the voltage and the amount of active power injected into the busbar. PV bus refers to the generator's busbar. At least one of the generators in the network must be set up as a reference machine, which controls the voltage magnitude and angle. The reference machine's busbar is configured as a slack (SL) bus. Among various power generating stations, the Gilgel Gibe III bus is selected as the slack bus. It is also necessary to specify the active and reactive power maximum and lowest limits in order to analyze the loading and operating limit violations.

Table 3. 1: Generation data

<i>No</i>	<i>Generation Name</i>	<i>P_G(MW)</i>	<i>Q_G(MVA_r)</i>	<i>Q_{min}(MVA_r)</i>	<i>Q_{max}(MVA_r)</i>
1	Gilgel Gibe III	955.9	164.7	-862	755.8
2	Gilgel Gibe II	278.4	-143.2	-311.4	246.8
3	Tana Beles	461.3	-94.8	-130.4	77.2

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4	Fincha	153	65	-98.7139	87.722
5	Amerti Neshe	89.674	-17.1218	-17.1218	33.8782
6	Gilgel Gibe I	129.2332	66.1467	-117.603	97.4525
7	Tekeze	176.1252	-6.6285	-244.29	407.31
8	Ashegoda	8.3305	19.6678	0	58.4
9	Melka Wakena	39.8231	31.875	-145.118	119.1918
10	Adama Wind	114.888	17	-17	66.534

Transmission Line Data

Transmission lines are the long conductors with special design (bundled) to carry bulk amount of generated power at very high voltage from one station to another as per variation of the voltage level.

Table 3. 2: Transmission line parameters in (pu)

From Bus	To Bus	r (pu)	x (pu)	$\frac{B}{2}$ (pu)
1	2	0.000606	0.00993	0.480435
3	4	0.000656	0.007453	0.06119
3	5	0.004336	0.049246	0.454305
3	29	0.002839	0.037756	0.522095
3	24	0.000431	0.005737	0.07934
10	6	0.00082	0.012093	0.3786
10	12	0.000958	0.012159	0.565695
6	7	0.002531	0.037495	0.5938
7	8	0.00282	0.041775	0.645
9	5	0.000392	0.006787	0.092015
9	2	0.003438	0.05143	0.83835
11	12	0.029325	0.084425	0.127612
12	13	0.024457	0.072578	0.116545
12	14	0.012781	0.066429	0.06003
15	14	0.017209	0.089447	0.08083
15	16	0.014652	0.076154	0.068815
16	17	0.001673	0.005116	0.007735
18	17	0.005897	0.018027	0.02725
17	19	0.014058	0.042977	0.06496
16	19	0.010041	0.053852	0.04852
19	20	0.020486	0.106479	0.09622
20	21	0.003382	0.010038	0.01612
21	22	0.0017	0.0049	0.007455
20	22	0.0019	0.0054	0.008135

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20	23	0.003382	0.010038	0.01612
19	24	0.021099	0.102687	0.0943
21	25	0.0032	0.009	0.01445
20	26	0.002361	0.0066	0.010598
26	27	0.001564	0.00438	0.007033
27	28	0.030445	0.087649	0.132485
27	29	0.002321	0.011775	0.01114
29	24	0.010779	0.056025	0.050625
28	30	0.019119	0.055043	0.083199
30	31	0.008435	0.024285	0.036708
32	24	0.010779	0.056025	0.050625
24	33	0.014081	0.039358	0.063202
33	34	0.008307	0.023219	0.037285
34	35	0.104962	0.197555	0.019135
35	36	0.018245	0.055777	0.08431
36	37	0.029974	0.086293	0.130435
38	39	0.034129	0.095395	0.153187
39	40	0.034343	0.095995	0.154151
40	41	0.012825	0.038059	0.061115
42	41	0.020153	0.059806	0.096038
42	43	0.021228	0.062997	0.10116
44	43	0.0041	0.0117	0.0177
44	45	0.0265	0.0762	0.11524
45	46	0.008876	0.025592	0.038664
43	46	0.020982	0.060405	0.091305
12	47	0.027501	0.084074	0.12708
47	48	0.020626	0.063056	0.09531
48	45	0.020626	0.063056	0.09531
45	49	0.008876	0.025592	0.038664
49	50	0.034276	0.104784	0.158385
50	51	0.011089	0.033901	0.05124
49	52	0.025733	0.072	0.115614
52	53	0.036152	0.110521	0.167056
54	55	0.022453	0.100028	0.096199
55	56	0.035593	0.158565	0.152496
54	57	0.075556	0.211189	0.339131
57	56	0.003791	0.010689	0.016835
57	58	0.028047	0.080746	0.12205
57	59	0.043807	0.126117	0.19063
54	60	0.029689	0.127801	0.12083
60	61	0.000906	0.0039	0.003687

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61	62	0.050313	0.144849	0.218945
62	63	0.063526	0.177565	0.285137
64	54	0.0022	0.0065	0.009785
54	65	0.011017	0.044456	0.042032
65	66	0.001619	0.007688	0.007395
66	67	0.0017	0.0048	0.00771
65	68	0.001619	0.007688	0.007395
21	66	0.0045	0.0126	0.02023
68	27	0.002314	0.011264	0.010345

Bus Data

Active and reactive power load data of 230kV and 400kV voltage levels of the case studies are collected and presented in Table 3.3 below.

Table 3. 3: Bus data

<i>Bus No</i>	P_L (MW)	Q_L (MVar)
1	0	0
2	79	35.6
3	0	0
4	0	0
5	0	0
6	0	0
7	0	0
8	0	0
9	0	0
10	20	6.3
11	63	29.16
12	110.72	53.46
13	33.68	16.17
14	2.4989	1.2096
15	19.6732	9.5216
16	9.284	3.452
17	0	0
18	3.435	1.6618
19	9.058	4.13702
20	102.9644	51.2936
21	0	0
22	11.7052	5.6576
23	1.3222	0.6422
24	4.8088	1.4143
25	8.38	4.06

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26	10.8524	4.5064
27	120.5025	56.574
28	20.3304	9.8399
29	17.5767	8.5122
30	12.6958	6.1448
31	13.2296	6.4032
32	2.0672	1.005
33	27.493	13.3064
34	2.1012	1.0506
35	3.8139	1.8459
36	14.2218	6.203
37	4.4444	2.1512
38	2.3596	1.1421
39	11.6976	5.6614
40	3.7716	1.7915
41	7.5432	3.583
42	4.523	1.364
43	134.04	44.46
44	0	0
45	16.9918	8.2242
46	8.248	3.2456
47	4.6258	0.5002
48	4.238	0.2231
49	10.24	4.7144
50	5.7776	2.7963
51	2.2305	1.0818
52	0	0
53	20.855	9.931
54	0	0
55	14.3413	6.3233
56	43.5966	14.47
57	21	13
58	0.4341	-0.8888
59	0	0
60	0	0
61	23.368	7.784
62	7.45	3.6035
63	1.0336	0.5002
64	0	0
65	176.1537	85.2837
66	93.347	45.259
67	16.1638	7.8232

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68

242.4168

99.0045

Two Winding Transformer Data

Transformers are used at the ends of the transmission lines to operate the lines at a high voltage and low current. The Ethiopian power system grid has both three winding and two winding transformers. The transmission line considered in this case study consists 32 two winding and 26 three winding transformers. The data of these two winding and three winding transformers which are used for this study are collected from NLDC and presented in Tables 3.4 and 3.5 below respectively.

Table 3. 4: Two Winding Transformer Data

<i>No</i>	<i>Node 1</i>	<i>Node 2</i>	<i>Network Level</i>	<i>Un1 (KV)</i>	<i>Un2 (KV)</i>	<i>Sn (MVA)</i>
1	Shehedi 230	Shehedi 15	230	230	15	25
2	Mota 230	Mota 33	230	230	33	20
3	Bedele 230	Bedele 132	230	230	132	40
4	Ginchi 230	Ginchi 15	230	230	15	25
5	Gefersa 230	Gefersa 132	230	230	132	32.5
6	Agaro 230	Agaro15	230	230	15	20
7	Jimma 230	Jimma 132	230	230	132	25
8	G/Gibe PP+SS 230	G/Gibe PP+SS 132	230	230	132	73
9	Hosaina 230	Hosaina 132	230	230	132	63
10	Sebeta 230	Sebeta 132	230	230	132	50
11	Sebeta II 230	Sebeta II 33	230	230	33	25
12	Torhayloch 230	Torhayloch 15	230	230	15	25
13	Shegole 230	Shegole 230	230	230	132	63
14	Wolkayite 230	Wolkayite 33	230	230	33	63
15	Axum 230	Axum 132	230	230	132	25
16	Tekeze 230	Tekeze 15	230	230	15	90
17	Mekele 230	Mekele 132	230	230	132	66
18	Dichito 230	Dichito 33	230	230	33	25
19	Semera 230	Semera 33	230	230	33	25
20	Kaliti 230	Kaliti 132	230	230	132	31.5
21	Sino steel 230	Sino steel 33	230	230	33	25
22	L/Tafo 230	L/Tafo 132	230	230	132	31.5
23	Gelan 230	Gelan 132	230	230	132	50
24	M/W/Yugo 230	M/W/Yugo 132	230	230	132	12.5
25	Awash Town 230	Awash Town 132	230	230	132	25
26	Adigala 230	Adigala 33	230	230	33	25

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27	Hurso 230	Hurso 132	230	230	132	25
28	Gilgel Gibe II-400Kv	Gilgel Gibe I-230Kv	400	400	230	250
29	Sebeta II-400Kv	Sebeta II-230kV	400	400	230	250
30	B/Dar-400Kv	B/Dar-230kV	400	400	230	250
31	D/Markos-400kV	D/Markos-230kV	400	400	230	250
32	Gelan-400kV	Gelan-230kV	400	400	230	250

Three Winding Transformer Data

The three winding transformers are also widely used in power systems. The VA ratings of all the three windings of the transformer are usually unequal. The primary winding has the highest voltage rating, the secondary has the intermediate voltage rating and the tertiary has the lowest voltage rating.

Table 3. 5: Three Winding Transformer Data

No	Node1	Node 2	Node3	Un1 (kV)	Un2 (kV)	Un3 (kV)	Sn12 (MVA)	Sn23 (MVA)	Sn31 (MVA)
1	Gonder II 230	Gonder II 66	Gonder II 15	230	66	15	63	63	63
2	Gonder II 230	Gonder II 66	Gonder II 15	230	66	15	40	20	20
3	B/DarII 230	B/DarII 132	B/DarII 15	230	132	15	63	21	21
4	B/DarII 230	B/DarII 66	B/DarII 15	230	66	15	63	63	63
5	D/Markos 230	D/Markos 66	D/Markos 15	230	66	15	63	63	63
6	Fincha PP+SS 230	Fincha PP+SS 66	Fincha PP+SS 15	230	66	15	40.5	20	20
7	Fincha II 230	Fincha II 33	Fincha II 15	230	33	15	20	10	10
8	Ghedo 230	Ghedo 132	Ghedo 15	230	132	15	63	63	63
9	Chancho 230	Chancho 132	Chancho 33	230	132	33	125	37.5	37.5
10	Wolkite 230	Wolkite 66	Wolkite 33	230	66	33	40	40	40
11	Sekoru 230	Sekoru 132	Sekoru 33	230	132	33	40	40	40
12	Alaba	Alaba 132	Alaba 15	230	132	15	40	20	23

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13	230 Metu	Metu 66	Metu 15	230	66	15	40	40	40
14	230 Gambella	Gambella 66	Gambella 33	230	66	33	40	40	40
15	230 Humera	Humera 33	Humera 15	230	33	15	25	12.5	12.5
16	230 E/Sillassie	E/Sillassie 66	E/Sillassie 15	230	66	15	40	40	40
17	230 Mekele	Mekele 132	Mekele 15	230	132	15	125	125	125
18	230 Alamata	Alamata 132	Alamata 15	230	132	15	40	23	23
19	230 N/Mewucha	N/Mewucha 33	N/Mewucha 15	230	33	15	30	10	10
20	230 Gashena	Gashena 33	Gashena 15	230	33	15	30	10	10
21	230 Mehoni	Mehoni 33	Mehoni 15	230	33	15	40	23	23
22	230 Combolcha II	Combolcha II 132	Combolcha II 33	230	132	33	63	63	23
23	230 D/Dawa	D/Dawa 132	D/Dawa 15	230	132	15	63	18.9	18.9
24	230 Gode	Gode 132	Gode 33	230	132	33	50.4	18.4	18.4
25	230 Ramo	Ramo 132	Ramo 33	230	132	33	50.4	18.4	18.4
26	230 Cotebe New	Cotebe New 132	Cotebe New 33	230	132	33	125	125	37.5

3.3 Modeling of 400kV-230kV Ethiopian transmission line network

The starting point of any power-flow problem is the development of a single-line diagram of the power system, from which computer solutions can be obtained. Currently, the 400kV network consists of only a few transmission lines and substations. In the south of Addis Ababa, an interconnection between Gilgel Gibe II, Wolytasodo, Gilgel Gibe III power plants, and Sebeta II to Gelan substation, and in the north of Addis Ababa, an interconnection between Beles power plant, Bahir Dar, Sululta, Debremarkos, and Gerbaguracha substation.

The 230kV network includes:

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- A complete ring around Addis Ababa, including; Sululta, Gefersa, Sebeta kaliti and Cotobie new to Lege Tafo.
- Interconnections between Addis Ababa and power plants to the south east including Koka and Melka Wakena.
- Interconnection between Koka and D/Dawa in the east, with interconnected to Djibouti.
- North-western corridor, including interconnection with Fincha, D /Markos, Tis-Abbay and Beles power plants and interconnected to Sudan through Metema.
- Northern corridor including Combolcha, Alamata, Mekele and Tekeze power plant.
- A 230kV transmission line between Bahir Dar and Alamata interconnects the north western and northern routes.

The network single line diagram is drawn using DIgSILENT power factory software as shown in the figure below. The DIgSILENT power factory software is used in this thesis for only drawing purpose because it has a good feature to show all of the power system components. The power flow analysis is done by using MATLAB software.

PowerFactory is a computer-aided engineering application for the analysis of transmission, distribution, and industrial electrical power systems, produced by DIgSILENT. It is an advanced integrated and interactive software program dedicated to electrical power system and control analysis, with the primary goals of planning and operation optimization. The acronym "DIgSILENT" stands for "DIgital SIMuLation of Electrical NeTworks." The world's first power system analysis program with an integrated graphical single-line interface was DIgSILENT Version 7. Drawing functions, editing capabilities, and all important static and dynamic calculation tools were all integrated in that interactive single-line diagram.

PowerFactory was created by competent engineers and programmers with extensive experience in the disciplines of electrical power system analysis and development. PowerFactory's correctness and validity have been proven in a wide number of implementations by organizations involved in the planning and operation of power systems all over the world [35].

The single line diagram of this case study network was modeled on the DIgSILENT Power factory for this study. Due to the bulk coverage of system networks considered under this case study, the single line diagrams of the system are drawn on the software's different grids as shown in the following figures.

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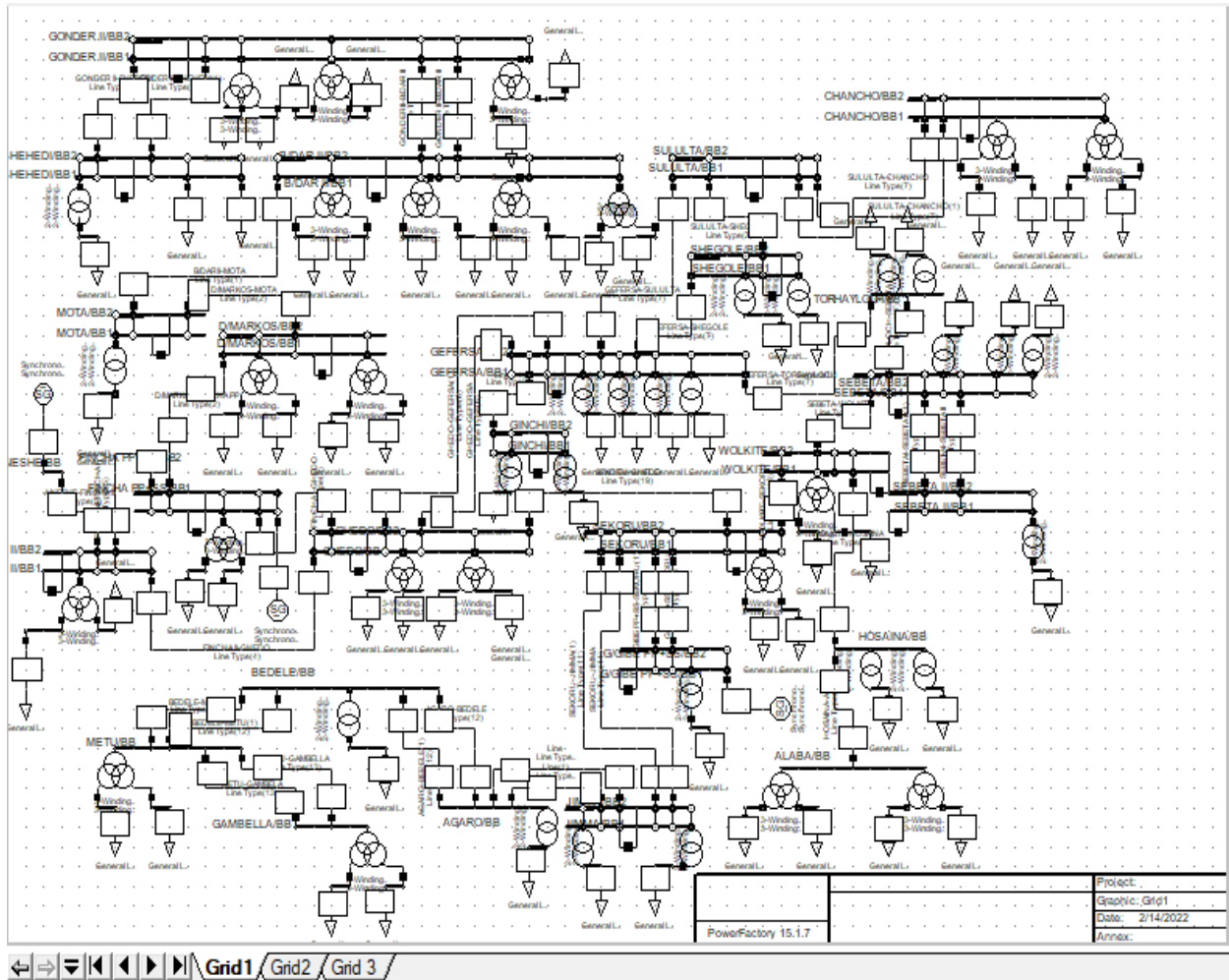


Figure 3.1: Single Line diagram of the system on Grid 1.

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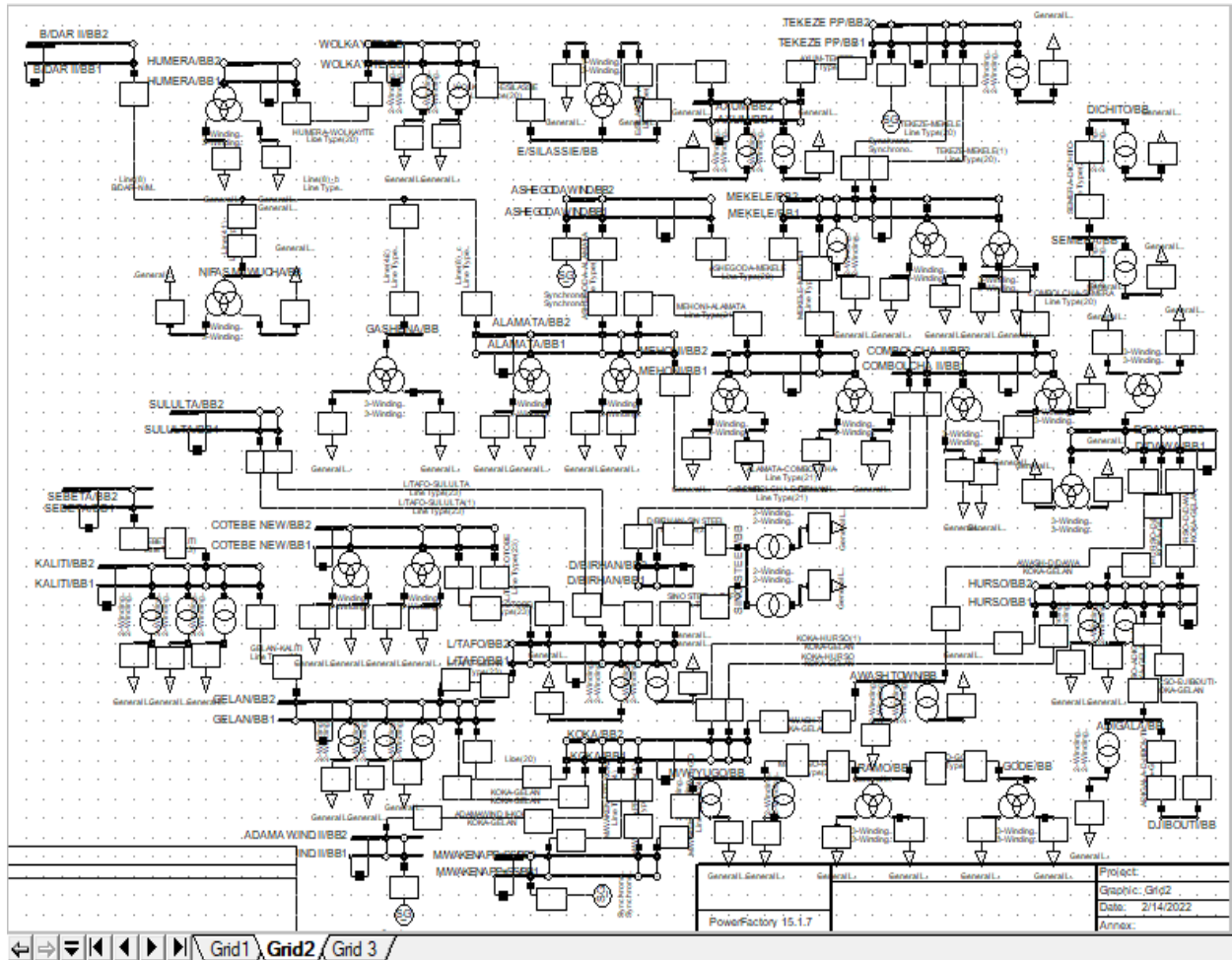


Figure 3. 2: Single Line diagram of the system on Grid 2.

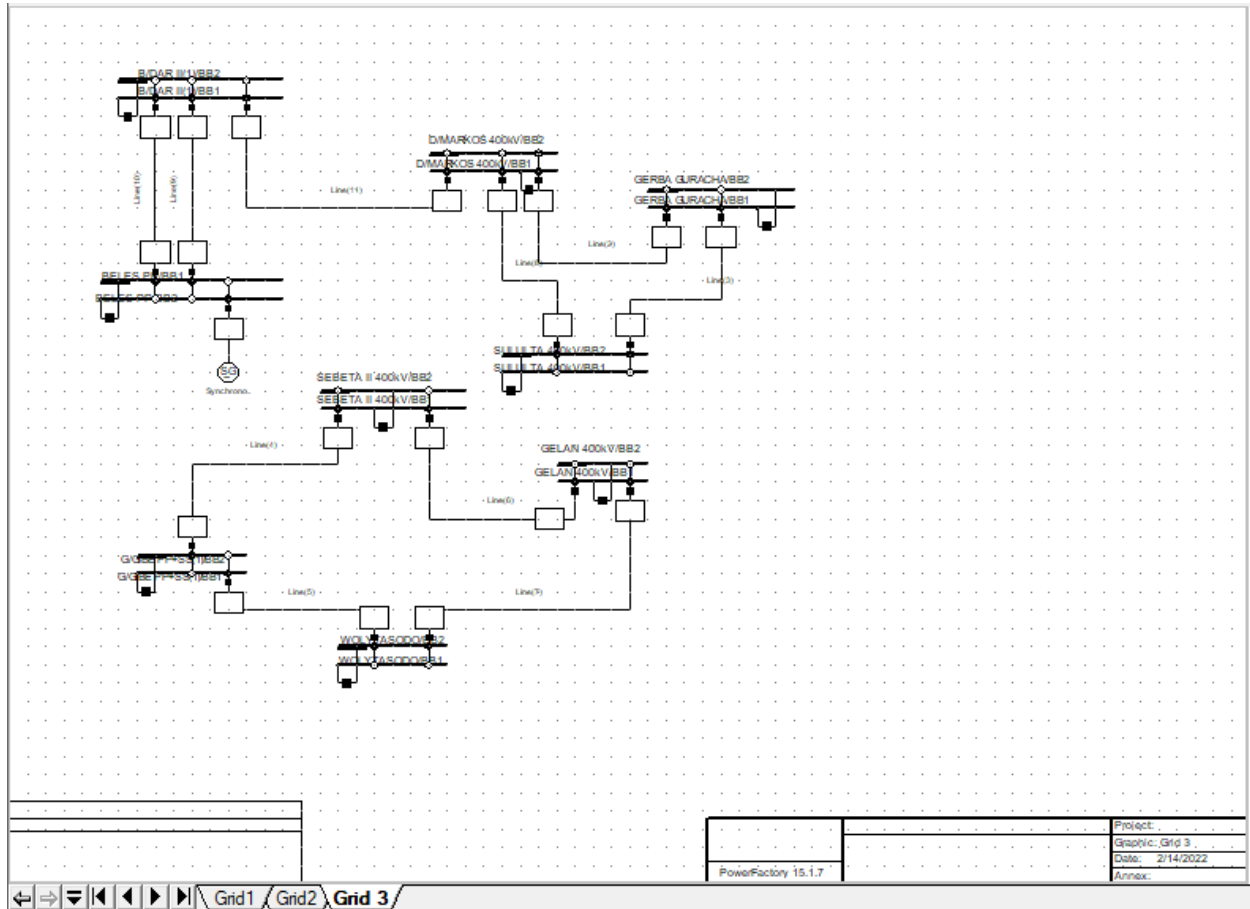


Figure 3. 3: Single Line diagram of the system on Grid 3.

The grids listed in the figures above (Grid 1, Grid 2 and Grid 3) are an interconnected grids and they are on the same system.

3.4 Power Flow Analysis of 400kV-230kV Transmission line without STATCOM and Capacitor Bank.

Load flow studies, also known as power flow studies, are an important component of power system analysis. They are required for existing system planning, economic scheduling, and control, as well as future growth planning. The task entails calculating the magnitudes and phase angles of voltages at each bus, as well as the active and reactive power flow in each line [36].

When the injecting complex power is defined, power system load flow calculations can be thought of as the problem of calculating the node voltage phasor for each node. If the complex power can be represented by equations of complex voltages, the node voltage phasors can be

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solved using a nonlinear equation solving approach like the Newton Raphson method. The foundation for solving performance equations in computer aided electrical power system analyses, such as load flow analysis, is a mathematical analysis relating the solution of arithmetic simultaneous equations [37].

Forming the Y-bus admittance with the transmission line and transformer input data is the first step in performing load flow analysis. The following is the nodal equation for a power system grid using Y bus:

$$I = Y_{bus} * V \quad (3.1)$$

The nodal equation can be inscribed in a comprehensive form for an n bus system

$$I_i = \sum_{j=1}^n Y_{ij} V_j \quad \text{For } i=1,2,\dots,n \quad (3.2)$$

The complex power delivered to bus i is

$$P_i + jQ_i = V_i I_i^* \quad (3.3)$$

$$I_i = \frac{P_i - jQ_i}{V_i^*} \quad (3.4)$$

Substituting for I_i in terms of P_i and Q_i , the equation gives

$$\frac{P_i - jQ_i}{V_i^*} = V_i \sum_{j=1}^n y_{ij} - \sum_{j=1}^n y_{ij} V_j \quad j \neq i \quad (3.5)$$

This is equation (3.5) uses iterative techniques to solve load flow problems.

Newton-Raphson Method

The technique was termed after Isaac Newton and Joseph Raphson. It is an iterative technique that uses Taylor's series expansion to convert a collection of non-linear simultaneous equations to a set of linear simultaneous equations, with the terms constrained to the initial approximation. The Newton-Raphson approach is the most iterative technique used for load flow because its convergence features are comparatively more powerful than other alternate methods, and the consistency of the Newton-Raphson approach is relatively good because it can solve cases that cause divergence with other common methods [38].

If the assumed value is close to the solution, the result is achieved quickly; but, if the supposed value is far from the solution, the strategy may take longer to converge [39].

The admittance matrix is used to write equations for currents entering a power system.

Equation (3.2) is expressed in a polar form, in which j includes bus i

$$I_i = \sum_{j=1}^n |Y_{ij}| |V_j| \angle \theta_{ij} + \delta_j \quad (3.6)$$

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The real and reactive power at bus i is

$$P_i - jQ_i = V_i^* I_i \quad (3.7)$$

Substituting for I_i in Equation (3.6) from Equation (3.7)

$$P_i - jQ_i = |V_i| \left\langle -\delta_i \sum_{j=1}^n |Y_{ij}| |V_j| \right\rangle < \delta_{ij} + \delta_j \quad (3.8)$$

The real and imaginary parts are divided,

$$P_i = \sum_{j=1}^n |V_i| |V_j| |Y_{ij}| \cos(\theta_{ij} - \delta_i + \delta_j) \quad (3.9)$$

$$Q_i = \sum_{j=1}^n |V_i| |V_j| |Y_{ij}| \sin(\theta_{ij} - \delta_i + \delta_j) \quad (3.10)$$

The above Equation (3.9) and (3.10) establish a set of non-linear algebraic equations in terms of $|V|$ in per unit and δ in radians. Equation (3.9) and 3.10) are prolonged in Taylor's series about the initial estimation and ignoring all higher order terms, the following set of linear equations are obtained.

$$\begin{bmatrix} \Delta P_2^{(k)} \\ \vdots \\ \Delta P_n^{(k)} \\ \Delta Q_2^{(k)} \\ \vdots \\ \Delta Q_n^{(k)} \end{bmatrix} = \begin{bmatrix} \frac{\Delta P_2^{(k)}}{\partial \delta_2} & \cdots & \frac{\Delta P_2^{(k)}}{\partial \delta_n} & \frac{\Delta P_2^{(k)}}{\partial |V_2|} & \cdots & \frac{\Delta P_2^{(k)}}{\partial |V_n|} \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ \frac{\Delta P_n^{(k)}}{\partial \delta_2} & \cdots & \frac{\Delta P_n^{(k)}}{\partial \delta_n} & \frac{\Delta P_n^{(k)}}{\partial |V_2|} & \cdots & \frac{\Delta P_n^{(k)}}{\partial |V_n|} \\ \frac{\Delta Q_2^{(k)}}{\partial \delta_2} & \cdots & \frac{\Delta Q_2^{(k)}}{\partial \delta_n} & \frac{\Delta Q_2^{(k)}}{\partial |V_2|} & \cdots & \frac{\Delta Q_2^{(k)}}{\partial |V_n|} \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ \frac{\Delta Q_n^{(k)}}{\partial \delta_2} & \cdots & \frac{\Delta Q_n^{(k)}}{\partial \delta_n} & \frac{\Delta Q_n^{(k)}}{\partial |V_2|} & \cdots & \frac{\Delta Q_n^{(k)}}{\partial |V_n|} \end{bmatrix} \begin{bmatrix} \Delta \delta_2^{(k)} \\ \vdots \\ \Delta \delta_n^{(k)} \\ \Delta \left| \frac{V_2}{V} \right| \\ \vdots \\ \Delta \left| \frac{V_n}{V} \right| \end{bmatrix} \quad (3.11)$$

Because the slack bus variable voltage magnitude and angle are already known, they are not included in the preceding equation. After partial derivatives of Equations (3.9) and (3.10) are expressed, the element of the Jacobian matrix is obtained, which establishes a linearized relationship between tiny changes in voltage magnitude and voltage angle. The following is a matrix representation of the equation:

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_1 & J_3 \\ J_2 & J_4 \end{bmatrix} \begin{bmatrix} \Delta \delta \\ \Delta \left| \frac{V}{V} \right| \end{bmatrix} \quad (3.12)$$

Where J_1, J_2, J_3, J_4 are the elements of the Jacobian matrix and $J_1 = \frac{\partial P}{\partial \delta}, J_2 = \frac{\partial P}{\partial V}, J_3 = \frac{\partial Q}{\partial \delta},$

$$J_4 = \frac{\partial Q}{\partial V}.$$

The difference between the schedule and calculated values known as power residuals for the terms $\Delta P_i^{(k)}$ and $\Delta Q_i^{(k)}$ is represented as:

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$$\Delta P_i^{(k)} = P_i^{sch} - P_i^{(k)}; i=2, \dots, n-1 \quad (3.13)$$

$$\Delta Q_i^{(k)} = Q_i^{sch} - Q_i^{(k)}; i=n+1, \dots, n-1-m \quad (3.14)$$

The new estimates for bus voltage are

$$\delta^{(k+1)} = \delta_i^{(k)} + \Delta \delta_i^{(k)} \quad (3.15)$$

$$|V^{(k+1)}| = |V_i^{(k)}| + \Delta |V_i^{(k)}| \quad (3.16)$$

Iterative Algorithm

The iterative algorithm for the solution of the load flow problem by the NR method is as follows:

1. With voltage and angle (usually $\delta=0$ at slack bus, assume $|V|$, δ at all PQ buses and δ at all PV buses. In the absence of any other information flat voltage start is recommended.
2. Compute ΔP_i (for PV and PQ buses) and ΔQ_i (for all PQ buses) from Eqs. (3.13 and 3.14). If all the values are less than the prescribed tolerance, stop the iterations, calculate P_1 and Q_1 and print the entire solution including line flows.
3. If the convergence criterion is not satisfied, evaluate elements of the Jacobian using Eq. (3.12).
4. Solve Eq. (3.11) for corrections of voltage angles and magnitudes.
5. Update voltage angles and magnitudes by adding the corresponding changes to the previous values and return to step 2.

Note: 1. In step 2, if there are limits on the controllable Q sources at PV buses, Q is computed each time and if it violates the limits, it is made equal to the limiting value and the corresponding PV bus is made a PQ bus in that iteration. If in the subsequent computation, Q does come within the prescribed limits, the bus is switched back to a PV bus.

2. If there are limits on the voltage of a PQ bus and if any of these limits is violated, the corresponding PQ bus is made a PV bus in that iteration with voltage fixed at the limiting value.

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The flowchart of the Newton-Raphson load flow method is shown in Figure 3.4

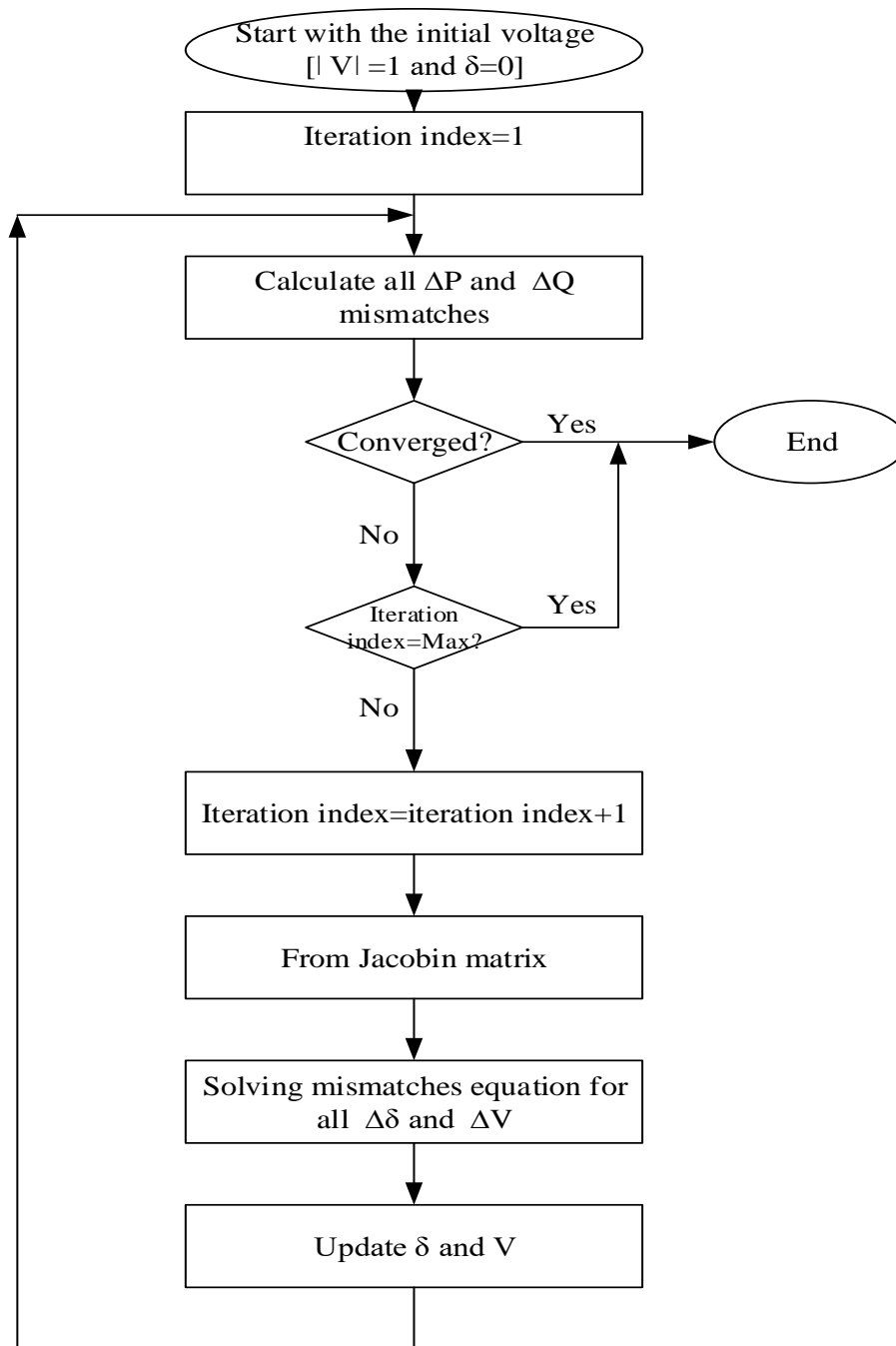


Figure 3. 4: Flowchart of the Newton Raphson load flow method

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A single-phase model is utilized to solve a power flow problem since the system is believed to be operating under balanced conditions. Each bus is related with four different quantities. Voltage magnitude $|V|$, phase angle δ , real power P , and reactive power Q are the four variables. The system buses are divided into three categories.

Slack bus One bus, referred to as the slack or swing bus, is used as a reference for determining the magnitude and phase angle of the voltage. This bus compensates for the mismatch between scheduled loads and generated power induced by network losses.

Load buses The active and reactive powers are given on these buses. The magnitude of the bus voltages as well as their phase angle are unknown. P-Q buses are the name of these buses.

P-V buses These buses are the generator buses. They are also known as voltage-controlled buses. The real power and voltage magnitude are specified on these buses. It is necessary to establish the phase angles of the voltages as well as the reactive power. There are additional constraints on the amount of reactive power that can be used. These buses are called regulated buses. [40]

3.5 Identification of weak buses for placement of STATCOM and Capacitor Bank

Voltage regulation, stability enhancement, and increased power transmission capabilities all require reactive power compensation [41, 42]. Variable shunt reactive compensation has been achieved using both the STATCOM and the Capacitor [43]. They provide variable shunt compensation that is quickly adjustable and automatic at the appropriate buses in the power system [44]. Furthermore, these devices can be more readily integrated into the network than generating units, with no risk of growing faults.

Capacitors improve bus voltage profiles, boost system stability margin, and dampen power system oscillations [41, 44, 45, 46]. A Capacitor is used in conjunction with the STATCOM's coupling transformer. STATCOM primarily serves the same purpose as a Capacitor, but it is more reliable since, unlike a Capacitor, its operation is unaffected by the voltage of the bus on which it is mounted.

Capacitor Bank Power Flow Model

The social behavior-based PSO is used to estimate the required degree of shunt capacitive compensation in order to optimize the voltage profile of the system. When a capacitor is inserted

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on a bus, the injected reactive power value of that bus is changed to match the size of the capacitor installed. The capacitor bank, which was just installed, can now give reactive power to the bus to which it is attached, as well as to nearby buses if necessary. The additional current required to meet the reactive power requirement for the loads on these buses does not need to travel from the source (slack) bus, resulting in lower line losses and voltage drop. The capacitors are then allocated optimally to establish the proper size of the capacitor bank to be installed.

Optimum Allocation of Capacitor Bank

The value of a capacitor is determined using the methodology described in Figure 3.5, which is based on the cost of active power losses and the cost of installing a capacitor bank in the sub-transmission network. The procedure begins with a standard load flow method. Following the load flow procedure, the capacitor size (Q_{Var}) is randomly initialized between zero and two times the total reactive load of the system Q_{load} , i.e. the minimum value is defined as zero and the highest value is defined as two times the total reactive load of the system Q_{load} .

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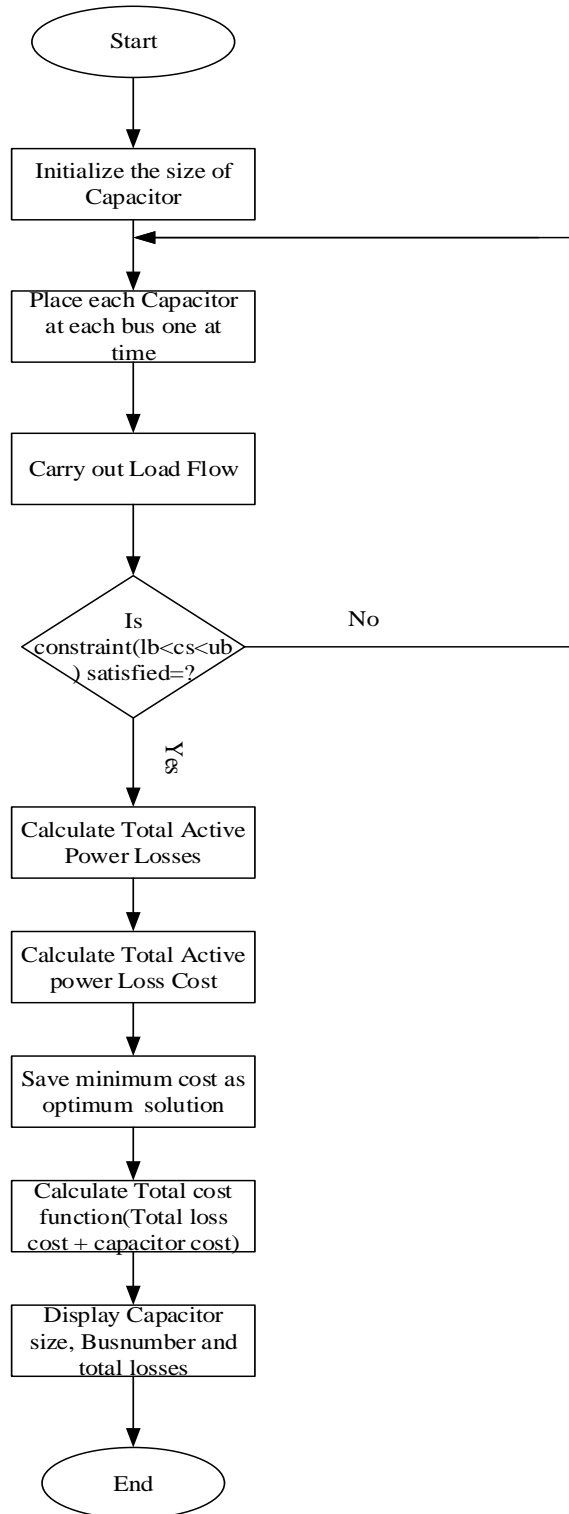


Figure 3. 5: Optimal capacitor Bank placement algorithm

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The voltage of the bus is kept as constraint to be satisfied. Constraint defined for voltage regulation limit is considered from IEEE standard i.e.

$$0.95 < V_{bus} < 1.05 \quad (3.17)$$

The objective of this research is to reduce total cost by reducing power losses and capacitor installation costs while also improving the voltage profile of the system. The cost is divided into two parts.

- Power loss Cost
- Capacitor Cost

Cost of Power Losses

Line current I and branch resistance R are used to determine the branch's power loss, which is $P=I^2 R$. When all of the line losses are added together, the overall power loss is calculated.

$$P_{loss} = \sum_{i=1}^n P_{loss_i} \quad (3.18)$$

Where n is the number of lines. The annual capital cost associated with this loss is given by

$$P_{cost} = P_{loss} * Unit\ energy\ cost * 8760 \quad (3.19)$$

Where P_{loss} is in kW,

Unit Energy Cost is the rate charged by the utility company per kWh of energy and the number 8760 is the number of hours in a year.

The cost analysis is based on Ethiopian Electric Utility's ETB/kWh energy rates under the new power tariff. The average of all tariff class energy unit costs (ETB/kWh) yields 2.48 ETB/kWh as the cost of energy. The entire amount of annual financial loss due to power loss in each scenario is assessed using the 2.48 ETB/kWh.

Cost of Capacitors

The cost of a capacitor is determined by the size of the capacitor bank that will be placed. Though the cost of a capacitor per unit size varies by size, the cost of a capacitor per unit size in smaller capacitor banks is higher than the cost of a capacitor per unit size in larger capacitor banks [46].

The cost of installing a capacitor bank in a transmission line network is calculated as follows:

$$C_{cost} = k_{Cap} * Q_{VAR} \quad (3.20)$$

Where k_{Cap} is the unit cost of capacitor per kVAr and Q_{VAR} is the size of the capacitor installed at a bus.

Objective Function

The optimization process seeks to discover a set of capacitor (or STATCOM) values that minimize the value of the objective function cost (total cost), which is made up of the loss, capacitor, and voltage deviation costs, all combined in a weighted expression as:

$$F = w_1 * V_{cost} + w_2 * C_{cost} + w_3 * P_{cost} \quad (3.21)$$

Where V_{cost} is usually quantified in terms of the voltage deviation from the required value of 1 pu, and the weights w_1 , w_2 , and w_3 are specified based on the priority the user give to each cost component.

STATCOM Power Flow Model

Unlike Capacitor Banks, the STATCOM may be represented as a variable voltage source, making it a better tool for improving the voltage profile of the system. The STATCOM model thus created is more flexible than the standard one in which the STATCOM is represented as a synchronous condenser, which is usually the model of synchronous generator with zero active power generation in most circumstances. The equivalent circuit, shown in Figure 3.6, can be used to create the proposed STATCOM model for inclusion in the power flow algorithm.

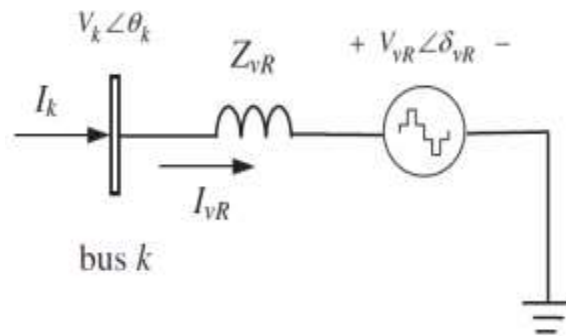


Figure 3. 6: Equivalent circuits of STATCOM

The voltage source representation is given by Equation (3.22) as,

$$E_{vR} = V_{vR}(\cos \delta_{vR} + j \sin \delta_{vR}) \quad (3.22)$$

The power flow equation for STATCOM can be constructed as follows from the preceding equation:

$$S_{vR} = V_{vR} I_{vR}^* = V_{vR} Y_{vR} (V_{vR}^* - V_k^*) \quad (3.23)$$

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The real and reactive power flow expressions for STATCOM can be obtained using Equation (3.23), and then incorporated into Newton-Raphson load flow analysis formulae. As a result, the following can be deduced for a STATCOM linked at bus k as shown in Figure 3.6:

$$P_{vR} = V_{vR}^2 G_{vR} + V_{vR} V_k (G_{vR} \cos(\delta_{vR} - \delta_k) + B_{vR} \sin(\delta_{vR} - \delta_k)) \quad (3.24)$$

$$Q_{vR} = -V_{vR}^2 B_{vR} + V_{vR} V_k (G_{vR} \sin(\delta_{vR} - \delta_k) + B_{vR} \cos(\delta_{vR} - \delta_k)) \quad (3.25)$$

$$P_k = V_{vR}^2 G_{vR} + V_k V_{vR} (G_{vR} \cos(\delta_k - \delta_{vR}) + B_{vR} \sin(\delta_k - \delta_{vR})) \quad (3.26)$$

$$Q_k = -V_{vR}^2 B_{vR} + V_k V_{vR} (G_{vR} \sin(\delta_k - \delta_{vR}) + B_{vR} \cos(\delta_k - \delta_{vR})) \quad (3.27)$$

Where $Z_{vR} = G_{vR} + jB_{vR}$

The new linearized Newton-Raphson equation with the STATCOM included is then given as:

$$\begin{bmatrix} \Delta P_k \\ \Delta Q_k \\ \Delta P_{vR} \\ \Delta Q_{vR} \end{bmatrix} = \begin{bmatrix} \frac{\partial P_k}{\partial \theta_K} & \frac{\partial P_k}{\partial V_K} V_k & \frac{\partial P_k}{\partial \delta_{vR}} & \frac{\partial P_k}{\partial V_{vR}} V_{vR} \\ \frac{\partial Q_k}{\partial \theta_K} & \frac{\partial Q_k}{\partial V_K} V_k & \frac{\partial Q_k}{\partial \delta_{vR}} & \frac{\partial Q_k}{\partial V_{vR}} V_{vR} \\ \frac{\partial P_{vR}}{\partial \theta_K} & \frac{\partial P_{vR}}{\partial V_K} V_k & \frac{\partial P_{vR}}{\partial \delta_{vR}} & \frac{\partial P_{vR}}{\partial V_{vR}} V_{vR} \\ \frac{\partial Q_{vR}}{\partial \theta_K} & \frac{\partial Q_{vR}}{\partial V_K} V_k & \frac{\partial Q_{vR}}{\partial \delta_{vR}} & \frac{\partial Q_{vR}}{\partial V_{vR}} V_{vR} \end{bmatrix} \begin{bmatrix} \Delta \theta \\ \frac{\Delta V_k}{V_k} \\ \Delta \delta_{vR} \\ \frac{\Delta V_{vR}}{V_{vR}} \end{bmatrix} \quad (3.28)$$

Candidate Buses Identification for Capacitor Bank (STATCOM)

To get the potential node, the capacitor was placed by turning off the reactive power at each node or load one at a time. After adjusting reactive power at each bus, load flows were conducted once more. Using this load flow, we will calculate the new real power loss and voltage fluctuation.

Power loss reduction index and voltage profile improvement index for each bus will be calculated by using equation (3.29) and (3.30). From this value the potential buses for capacitor placement will be identified.

Power Loss reduction Index (P_{LI}) of the i^{th} bus can be calculated as follows. [47]

$$P_{LI}(i) = \frac{\text{Loss reduction}[i] - \text{Min.reduction}}{\text{Max.reduction} - \text{Min.reduction}} \quad (3.29)$$

$$P_{ired} = \text{Loss reduction}[i] = P_{uncomp} - P(i) \quad (3.30)$$

Where: P_{ired} is power loss reduction

P_{uncomp} is the uncompensated active power loss.

$P(i)$ is the active power loss obtained by making the reactive power at bus i zero

$P_{LI}(i)$ is normalized loss reduction weight due to compensation at bus i

$\text{Loss reduction}[i]$ is the total power loss reduction resulting from compensating bus i

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Min. reduction is the minimum loss reduction of all individual bus compensation

Max. reduction is the maximum loss reduction of all individual bus compensation.

The voltage improvement index is calculated in the same manner.

$$V_{II} = \frac{\text{Voltage drop reduction [i]} - \text{Min.voltage drop reduction}}{\text{Max.voltage drop reduction} - \text{Min.voltage drop reduction}} \quad (3.31)$$

Where:

V_{II} is normalized voltage profile improvement weight measured due to compensation at bus i

Voltage drop reduction [i] is the total voltage drop reduction due to compensation at bus i

Min.voltage drop reduction is the minimum voltage drop reduction of all individual bus compensation.

Max.voltage drop reduction is the maximum voltage drop reduction of all individual bus compensation.

The algorithm for candidate bus identification is explained below.

1. Read transmission line system data
2. Run the load flow and calculate the uncompensated active power loss and voltage deviation.
3. By compensating the reactive power injection (Q_c) at each node and run the load flow, to calculate the active power loss and voltage deviation in each case.
4. Calculate the power loss reduction and voltage deviation reduction, power loss index (P_{LI}) and voltage improvement index (V_{PI})
5. Select the candidate node whose P_{LI} and V_{PI} in the top.
6. Stop

The above algorithm identifies the candidate buses. Then, to locate and size the capacitors on the candidate buses, in MATLAB, the PSO optimizers have been employed.

The following MATLAB code implements the above algorithm

```
function cand_buses = Sensitivity(busdata,linedata,num)
nbus = length(busdata(:,1));
%tempBus = busdatas(nbus);
P_loss = zeros(nbus,1);
Q_loss = zeros(nbus,1);
v_dev = zeros(nbus,1);
```

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```
for count=1:nbus+1
    tempBus = busdata;
    if count~=nbus+1
        diff = tempBus(count,6)-tempBus(count,8);
        if diff>0
            tempBus(count,8) =+ diff;
        end
    end
    [busD_new,V,Ploss,Qloss,Lpij,maxerror] =
lf_newton3 (tempBus,linedata);

    if count~=nbus+1
        P_loss(count) = Ploss;
        Q_loss(count) = Qloss;
        v_dev(count) = 1-min(V);
    elseif count==nbus+1
        PlossN = Ploss;
        QlossN = Qloss;
        v_devN = 1-min(V);
    end
end

P_reduct = PlossN - P_loss;
Q_reduct = QlossN - Q_loss;
V_imprv = v_devN-v_dev;

minP_loss = min(P_reduct);
maxP_loss = max(P_reduct);
minV_imprv = min(V_imprv);
maxV_imprv = max(V_imprv);

loss_diff = maxP_loss-minP_loss;
imprv_diff = maxV_imprv - minV_imprv;

PLI = (P_reduct - minP_loss)/loss_diff;
VLI = (V_imprv - minV_imprv)/imprv_diff;

LI = PLI + VLI;

[sortedPLI, I] = sort(PLI, 'descend');
cand_buses = I(1:num);
```

3.5 Particle Swarm Optimization Method

Particle swarm optimization is a population-based algorithm. It is similar to the genetic algorithm in this regard. The algorithm was inspired by flocks of birds or insects swarming. Each particle is drawn to the best place it has discovered so far, as well as the best location any other member of the swarm has discovered. Following a series of phases, the population may consolidate around a single area, a few locations, or continue to move. Particles are a group of individuals that travel in stages throughout a location. The method assesses the goal function at each particle at each step. Following this evaluation, the program determines each particle's new velocity. The algorithm is reevaluated once the particles move.

Using a Particle Swarm Optimization Algorithm, the particle swarm function tries to optimize the cost.

Particle Swarm Optimization Algorithm

The first step in the particle swarm algorithm is to create the initial particles and assign them initial velocities. [49]

By assessing the objective function at each particle site, it determines the ideal (lowest) function value and the optimum position.

It calculates new velocities based on the current velocity, the best individual particle locations, and the best neighboring particle positions.

It then iteratively updates particle positions, velocities, and neighbors (the new location is the previous one plus the velocity, modified to keep particles within boundaries).

Iterations continue until the algorithm hits a threshold for halting.

Here are the details of the steps.

Initialization

Particle swarm creates particles at random and uniformly within limitations by default. Particle swarm creates particles with a random uniform distribution from -1000 to 1000 if there is an unlimited component. If you just have one bound, particle swarm shifts the creation to include the bound as an endpoint and a 2000-width creation interval. Position $x(i)$ of particle I is a row vector with $nvars$ elements. The First Swarm Span option allows one to control the initial swarm's span.

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Similarly, particle swarm generates homogeneous beginning particle velocities v in the range $[-r, r]$, where r is the initial ranges vector. Component i 's range is $ub(i) - lb(i)$, however for unbounded or semi-unbounded components, the Initial Swarm Span option is used.

The objective functions (power loss and voltage deviation) are evaluated at all particles via particle swarm. It keeps track of each particle's current position $p(i)$. $p(i)$ will be the location of the best objective function that particle i has identified in following iterations. And b is the best overall particles: $b = \min(\text{fun}(p(i)))$. d is the location such that $b = \text{fun}(d)$. The neighborhood size N is set to $\text{minNeighborhoodSize} = \max(1, \text{floor}(\text{Swarm Size} * \text{Min Neighbors Fraction}))$ by particle swarm.

Particle swarm sets the inertia to $W = \max(\text{Inertia Range})$, or $W = \min$ if Inertia Range is negative (Inertia Range).

Particle swarm initializes the stall counter $c = 0$.

Set the variables $y1 = \text{Self Adjustment Weight}$ and $y2 = \text{Social Adjustment Weight}$ for simplicity of notation, where Self Adjustment Weight and Social Adjustment Weight are choices.

Iteration algorithm

The algorithm updates the swarm as follows. For particle i , which is at position $x(i)$:

1. Choose a random subset S of N particles other than i .
2. Find $f_{\text{best}}(S)$, the best objective function among the neighbors, and $g(S)$, the position of the neighbor with the best objective function.
3. For $u1$ and $u2$ uniformly (0,1) distributed random vectors of length n_{vars} , update the velocity
$$v = W * v + y1 * u1 * (p - x) + y2 * u2 * (g - x).$$

This update uses a weighted sum of:

- The previous velocity v
 - The difference between the current position and the best position the particle has seen $p - x$
 - The difference between the current position and the best position in the current neighborhood $g - x$
4. Update the position $x = x + v$.
 5. Enforce the bounds. If any component of x is outside a bound, set it equal to that bound.
 6. Evaluate the objective function $f = \text{fun}(x)$.
 7. If $f < \text{fun}(p)$, then set $p = x$. This step ensures p has the best position the particle has seen.

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8. If $f < b$, then set $b = f$ and $d = x$. This step ensures b has the best objective function in the swarm, and d has the best location.
 9. If, in the previous step, the best function value was lowered, then set $\text{flag} = \text{true}$. Otherwise, $\text{flag} = \text{false}$. The value of flag is used in the next step.
 10. Update the neighborhood. If $\text{flag} = \text{true}$:
 - Set $c = \max(0, c-1)$.
 - Set N to $\text{minNeighborhoodSize}$.
 - If $c < 2$, then set $W = 2 * W$.
 - If $c > 5$, then set $W = W/2$.
 - Ensure that W is in the bounds of the Inertia Range option.
- If $\text{flag} = \text{false}$:
- Set $c = c+1$.
 - Set $N = \min(N + \text{min Neighborhood Size}, \text{Swarm Size})$.

Stopping Criteria

Particle swarm iterates until it reaches a stopping criterion.

Stopping Option	Stopping Test	Exit Flag
MaxStallIterations and Function Tolerance	Relative change in the best objective function value g over the last MaxStallIterationsiterations is less than FunctionrTolerance.	1
MaxIterations	Number of iterations reaches MaxIterations.	0
OutputFcn or PlotFcn	OutputFcn or PlotFcn can halt the iterations.	-1
ObjectiveLimit	Best objective function value g is less than or equal to ObjectiveLimit.	-3
MaxStallTime	Best objective function value g did not change in the last MaxStallTimesseconds.	-4
MaxTime	Function run time exceedsMaxTime seconds.	-5

If particle swarm stops with exit flag 1, it optionally calls a hybrid function after it exits.

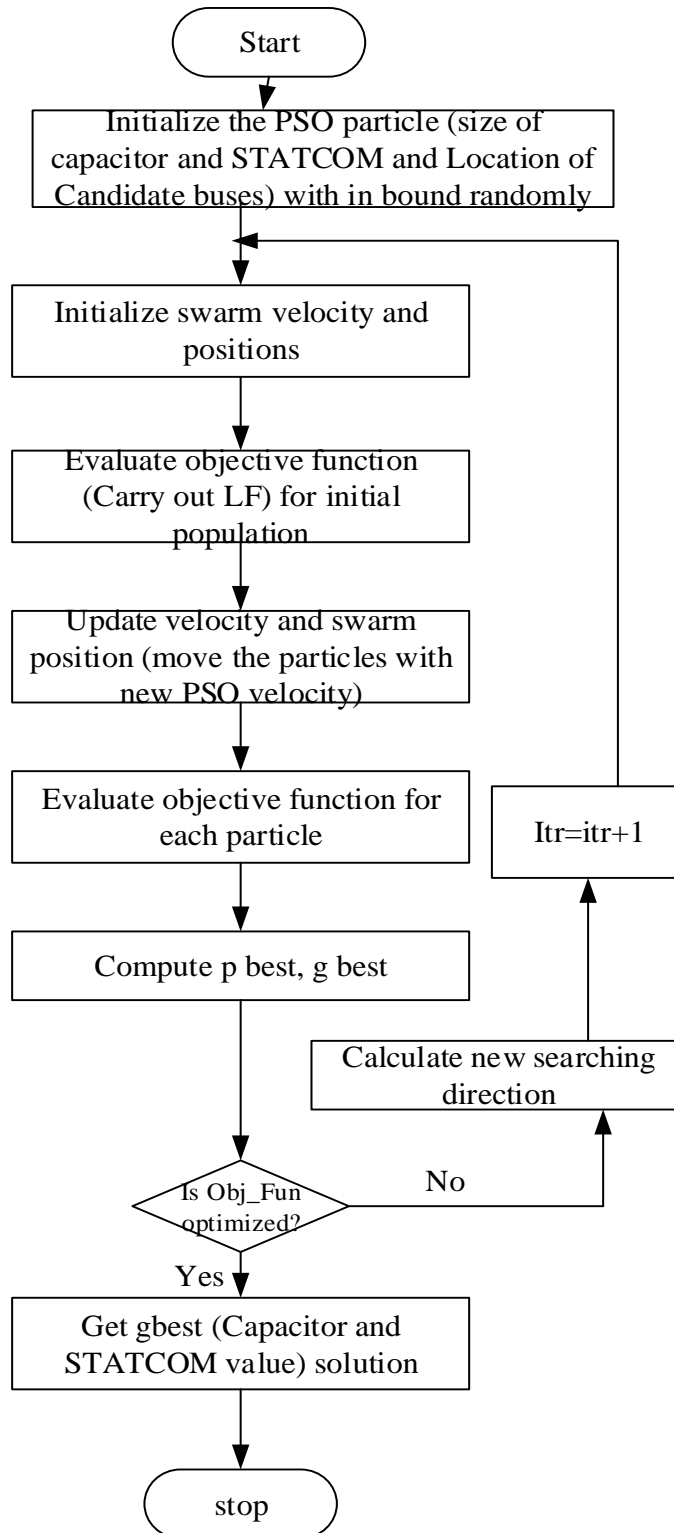


Figure 3. 7: Particle Swarm optimization flow chart

CHAPTER 4

SIMULATION STUDIES AND ANALYSIS OF RESULTS

4.1 Introduction

The transmission line system, which comprises bulk power transfer, is the only subject of load flow studies. The networks power flow study comprises two cases with four alternative scenarios. The power system network is simulated under varied load demand without and with optimal placement of capacitor bank as well as STATCOM. The bus voltage profile and overall system losses are analyzed both before and after placement of capacitor bank as well as STATCOM. Section 4.2 discusses the optimal placement of capacitor bank while Section 4.3 presents optimal placement of STATCOM using PSO technique. Cost benefit analysis of placement of capacitor bank and STATCOM is presented in Section 4.4.

4.2 Simulation Studies

Case 1: Optimal placement of Capacitor bank

The Bus voltage magnitudes and power flows over transmission lines are determined using the Newton-Raphson load flow analysis method. The analysis is carried out by increasing the load demand from the base load to 25% and 50% increments of the base load and at 75% under load of the base load. MATLAB is used to do the load flow analysis.

The PSO optimization algorithm is used to install the optimal amount of Capacitor at the candidate buses, reducing total line loss and improving the overall voltage profile. To achieve this an objective function is coded that first performs load flow by injecting reactive power into each of the candidate buses and computes the respective bus voltages and line losses. The PSO algorithm then modifies the values of the injected reactive power values according to swarm intelligence and collects the results after which it chooses the Capacitor values with the best (minimum) objective function value (in this case low line loss and low voltage deviation from nominal value).

4.2.1 Comparison of Voltage Profile and Power Loss when Capacitor bank is used.

Scenario One: The Newton-Raphson Power flow simulation at Base Load before and after Capacitor is added.

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The simulation is run at base load demand, and the results are displayed below for the power system network. PSO converged after 43 iterations under base load demand conditions.

The optimization results gives the following Capacitor sizes to be installed at the candidate buses.

Table 4. 1: Installed Capacitor values at the candidate buses for 0% overload

Candidate bus	68	65	20	27
Installed Capacitor (MVar)	99.0045	85.2837	51.2936	56.5740

In MATLAB and Excel, Figures 4.1 and 4.2 show the voltage profile improvement of the system and power loss minimization in the scenario of 0% overload without utilizing Capacitor and with Capacitor Bank at the candidate buses of 68, 65, 20, and 27 respectively.

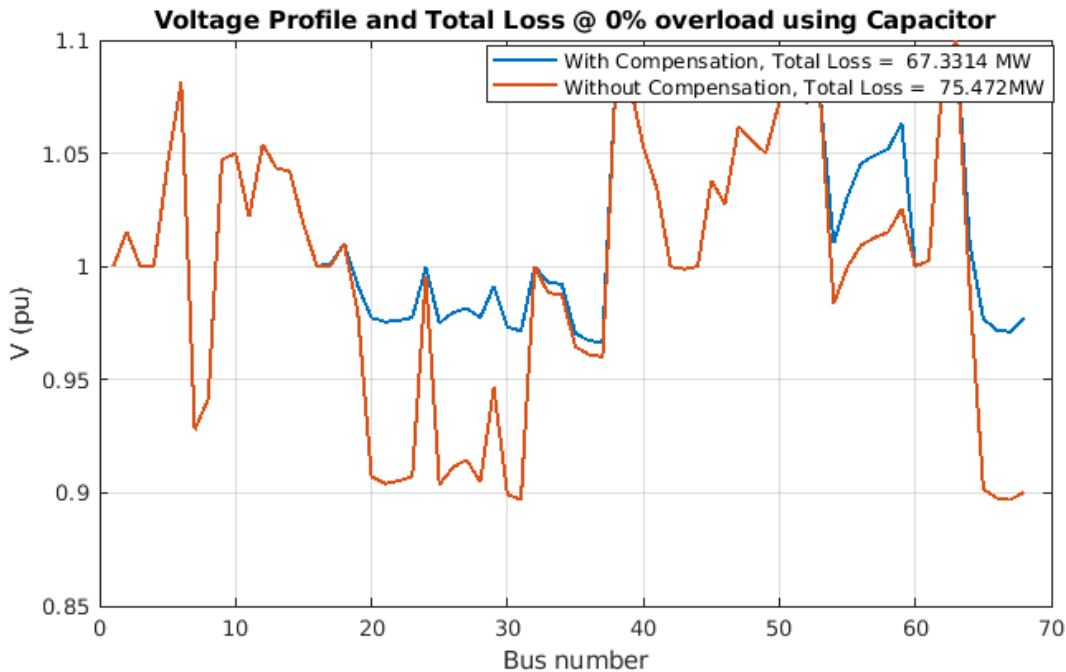


Figure 4. 1: Voltage profile plot for 0% overload before and after Capacitor installed

As shown from the figure, the voltage profile has improved significantly from 0.904 pu to 1.0339 pu which is about 12.5% and the total line losses for the two cases are 75.472MW+365.6667MVar for the uncompensated and 67.3314 MW+330.8598MVar for the

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compensated system. The real power loss has been reduced by 10.78% after the system compensation.

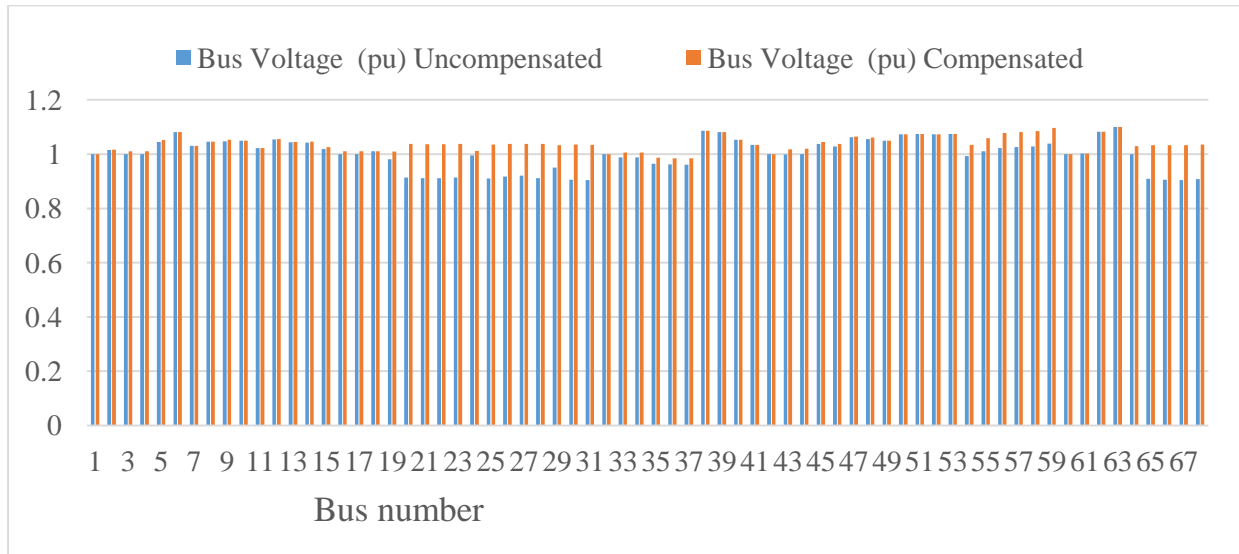


Figure 4. 2 : Voltage profile at 0% overload before and after Capacitor installed.

According to the simulation findings given in Figures 4.1 and 4.2, after installing the Capacitor bank at the sensitivity-based candidate buses, all of the identified buses with the weakest voltage magnitudes compared to the standards gets improved. After compensation the network system comes to the desirable operation.

Scenario two: The Newton Raphson Power flow simulation at 25% overload when Capacitor is added.

The simulation was performed at a 25% overload demand, and the results for the power system network are displayed below. The optimization converged after 22 PSO iterations when the overload condition was set at 25%.

As a result of the optimization, the following Capacitor Values should be put on the identified candidate buses.

Table 4. 2: Installed Capacitor values at the candidate buses for 25% overload

Candidate bus	68	65	27	20
Installed Capacitor Bank (MVar)	123.7556	106.6046	70.7175	64.1170

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The voltage profile improvement and power loss minimizations in the case of a 25% overload employing Capacitor are shown in Figures 4.3 and 4.4 below for the candidate buses 68, 65, 27, and 20.

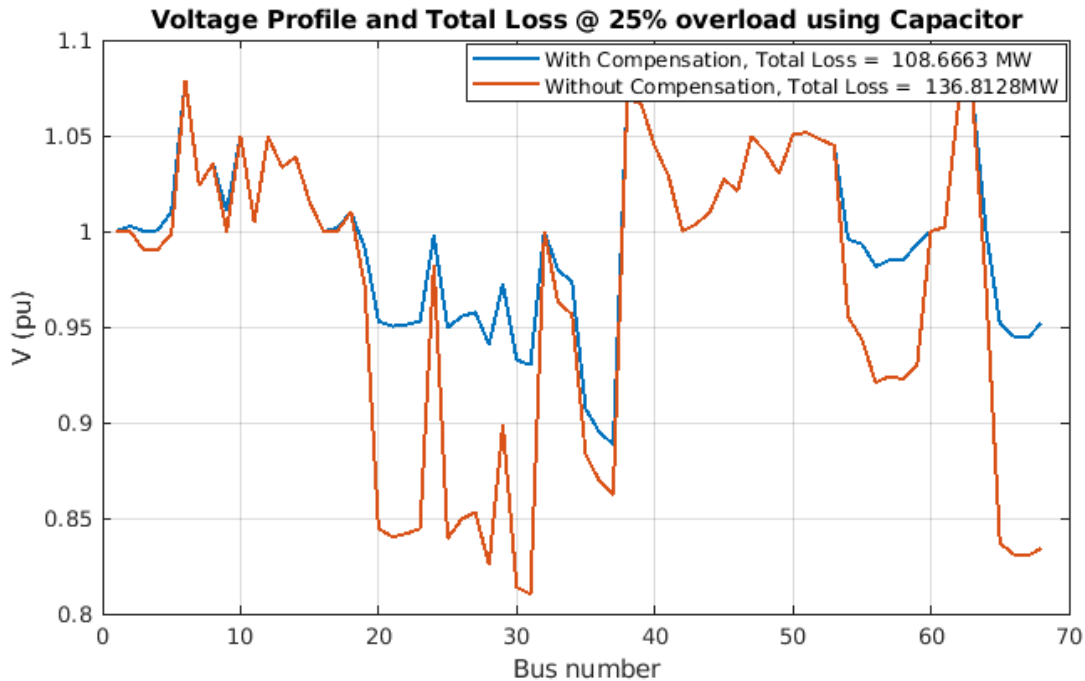


Figure 4. 3: Voltage profile plot for 25% overload with and without Capacitor

The voltage profile has greatly improved from 0.8266 pu to 1.0258 pu which is 19.41% improvement as indicated in the figure and the total line losses of the system are 136.8128 MW +860.6226 MVar for the uncompensated system and 108.6663 MW +696.6259 MVar for the compensated system. The active power loss is reduced from 136.8128 MW to 108.6663 MW when the load variation is set to 25% overload, a reduction of 20.57%.

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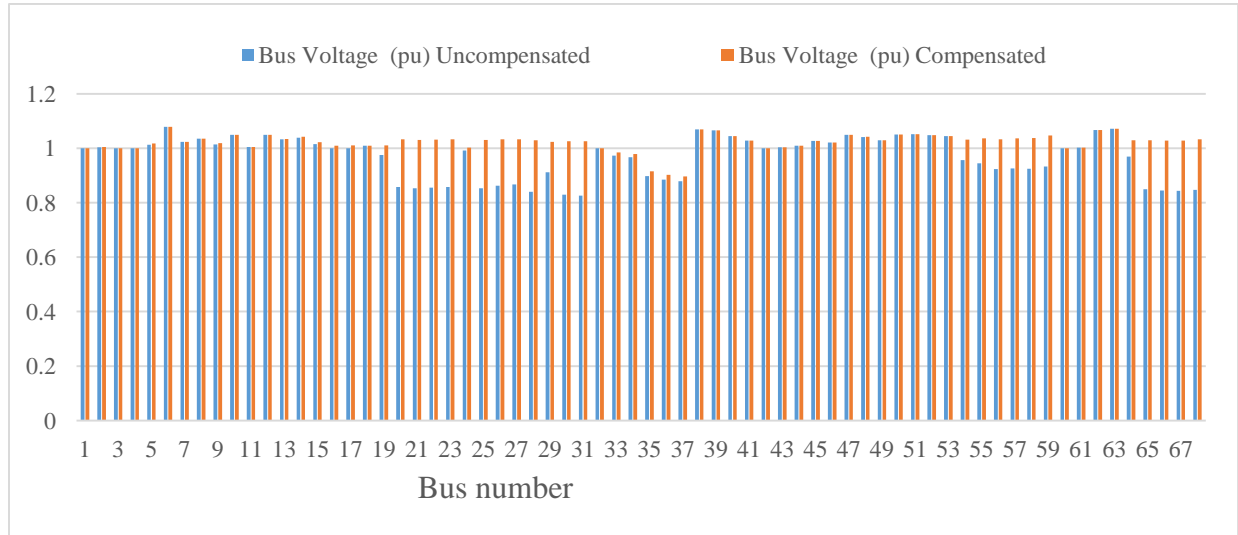


Figure 4. 4: Voltage profile at 25% overload before and after Capacitor installed.

In this situation as well, after installing the Capacitor at the PSO identified candidate buses, all of the identified buses with the poorest reactive and active power loss sensitivity values compared to the standards improve. All of the identified buses with the weakest voltage profiles compared to the standards gets improved and the network system comes to the desired operation.

Scenario Three: The Newton-Raphson Power flow simulation at 50% overload when Capacitor is added.

The simulation is run at 50% overload demand, and the results are displayed below for the power system network. The optimization converged after 30 PSO rounds under the 50% overload condition.

The following Capacitor values should be put at the candidate buses based on the optimization results.

Table 4. 3: Installed Capacitor values at the candidate buses for 50% overload

Candidate bus	68	65	27	20
Installed Capacitor Bank (MVar)	136.3990	117.6915	78.0721	70.7852

In the case of a 50 percent overload, Figures 4.5 and 4.6 show the voltage profile improvement of the system and power loss minimizations in the transmission network employing Capacitor at the candidate buses of 68, 65, 27, and 20.

Performance Evaluation of Transmission Lines for Power Loss Minimization and Voltage Profile Enhancement Using FACTS Devices

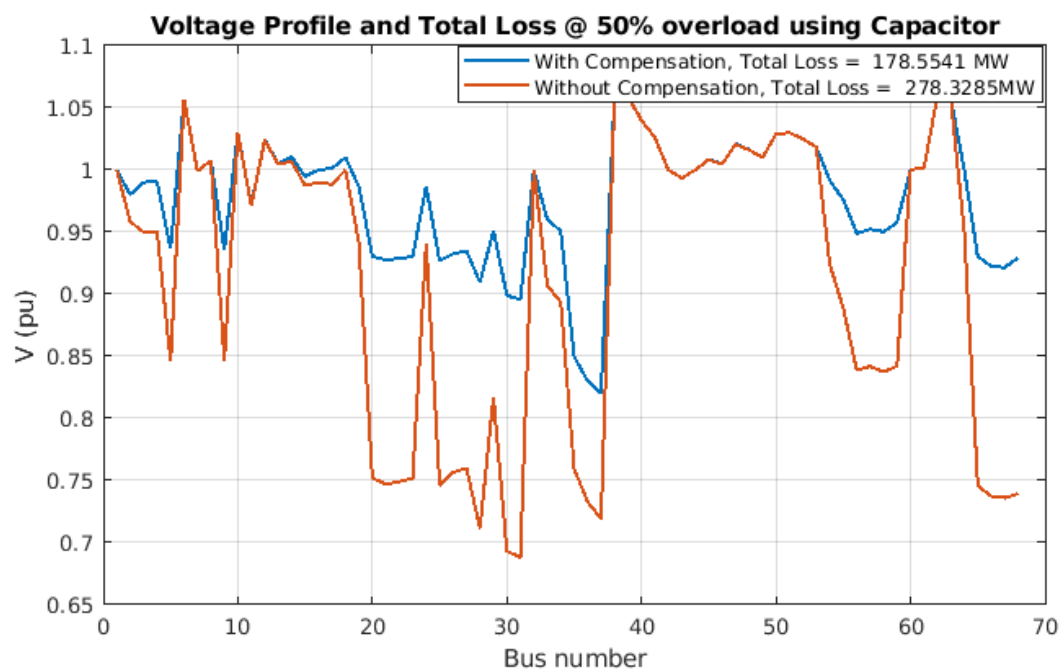


Figure 4. 5: Voltage profile at 50% overload before and after Capacitor installed.

The voltage profile has improved dramatically from 0.7066 pu to 1.0264 pu which is about 31.15%, as indicated in the figure, with total line losses of 278.3285 MW + 2.0405e+03 MVAR for the uncompensated system and 178.5541 MW + 1.3164e+03MVAR for the compensated system. The active power loss is reduced from 278.3285 MW to 178.5541 MW when the load variation is taken at 50% overload, which is a 35.84 % loss reduction.

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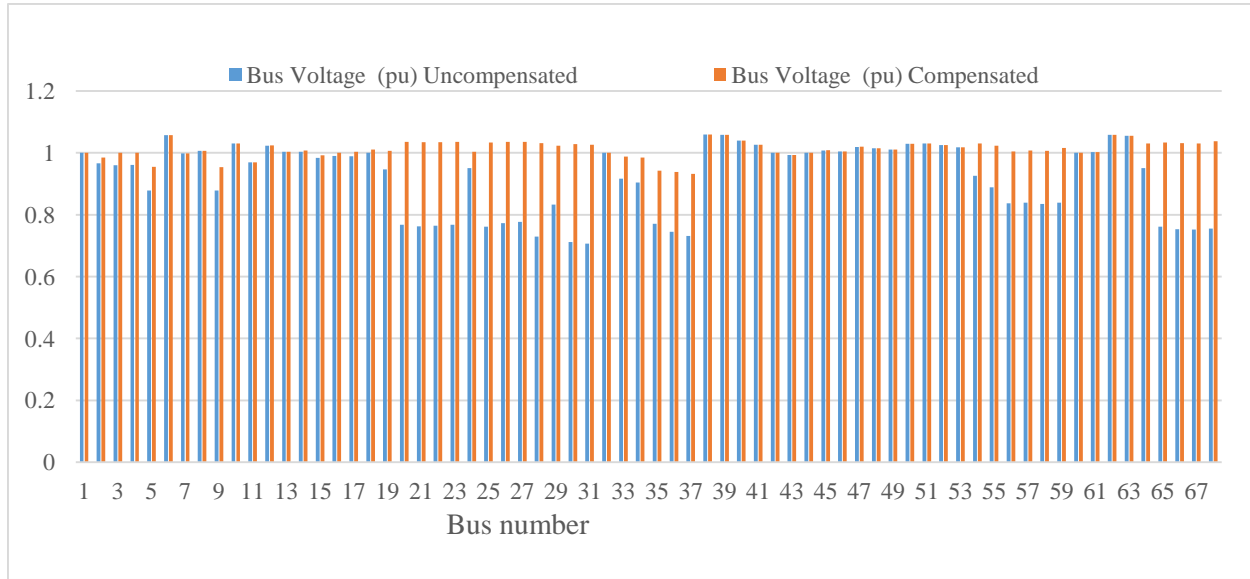


Figure 4. 6: Voltage profile at 50% overload before and after Capacitor installed.

The majority of the bus voltage magnitudes are below the allowed voltage deviation limit in this circumstance. After installing the Capacitor at the PSO selected candidate buses, all of the identified buses with the weakest voltage profiles compared to the standards gets improved and the network system comes to the favored operation.

We can see that as the load demand of the consumer's increases, the bus voltage magnitude of the system decreases, according to the Newton Raphson power flow simulation results in all of the above scenarios. As a result, we can deduce that an increase in load demand induces a decrease in voltage profile.

Scenario Four: The Newton-Raphson Power flow simulation at 75% Underload when Capacitor is used.

The simulation is run at 75% underload demand, and the results are displayed below for the power system network. The optimization converged after 41 PSO iterations under the 75% underload condition.

The following Capacitor values should be put at the candidate buses based on the optimization results.

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Table 4. 4: Installed Capacitor values at the candidate buses for 75% underload

Candidate bus	68	65	27	20
Installed Capacitor Bank (MVar)	66.8797	18.9299	38.4700	0

In the case of a 75% underload, Figures 4.7 and 4.8 show the voltage profile improvement of the system and power loss minimizations in the transmission network using Capacitor at the candidate buses of 68, 65, 27, and 20.

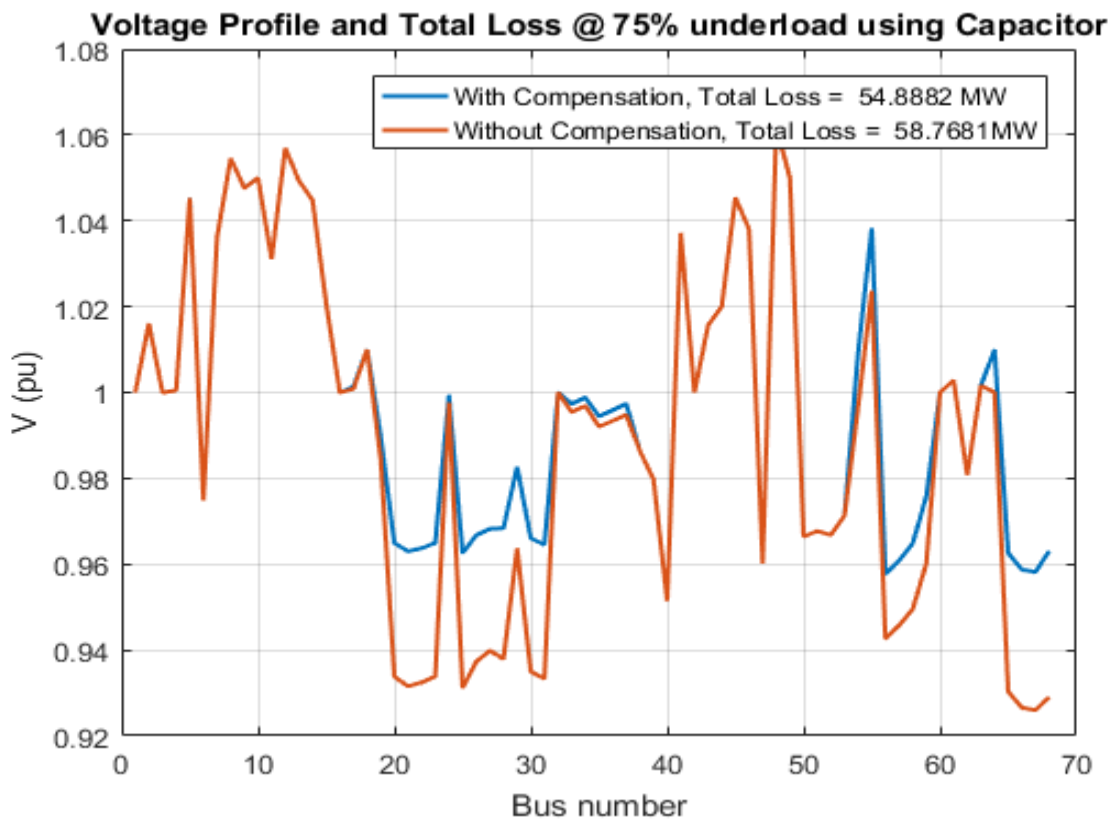


Figure 4. 7: Voltage profile at 75% underload before and after Capacitor installed.

The voltage profile has improved from 0.9333 pu to 0.9645 pu which is about 3.23% as indicated in the figure and the total line losses of the system are 58.7681 MW + 353.6489 MVar for the uncompensated system and 54.8882 MW + 337.8549 MVar for the compensated system. The active power loss is reduced from 58.7681 MW to 54.8882 MW when the load variation is taken at 75% underload, which is a 6.602 % loss reduction.

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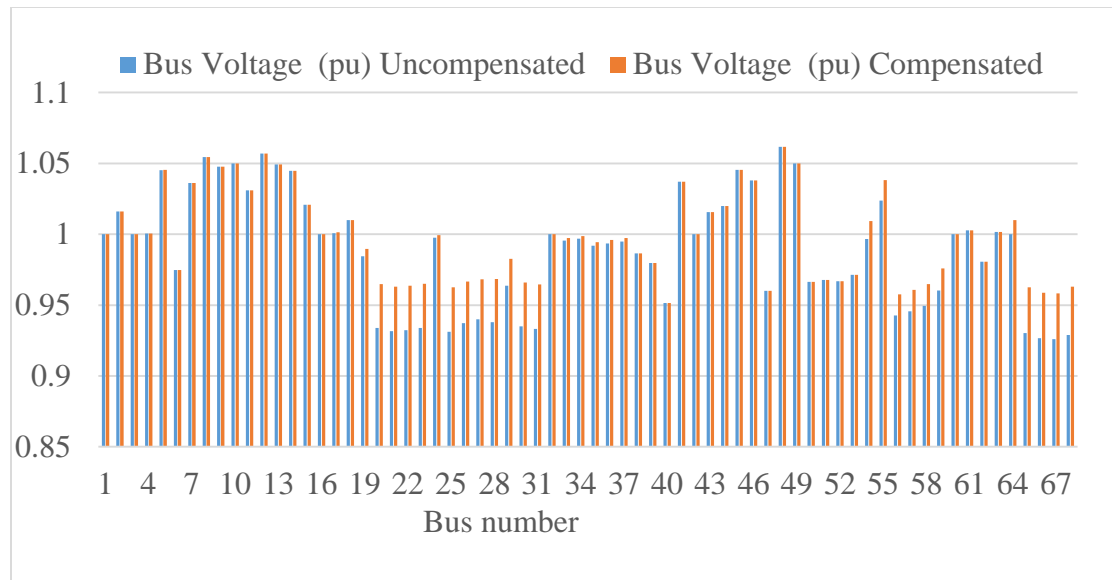


Figure 4. 8: Voltage profile at 75% underload before and after Capacitor installed.

As we can observe from these results, the network is already in a desirable operating condition except few buses for the 75% underload case. After installing the Capacitor banks at the PSO selected candidate buses, all of the identified buses with the weakest voltage profile values gets improved relative to the standards.

Table 4. 5: Summary for the Active Power losses and Voltage profile improvements for the considered system at different conditions while using Capacitor banks.

System condition	Active power loss(MW)		Active Power loss Improvement in Percentage	Voltage Profile Improvement in Percentage
	Pre Capacitor	Post Capacitor		
At Base load	75.472	67.3314	10.78	12.5
At 25% Overload	136.8128	108.6663	20.57	19.41
At 50% Overload	278.3285	178.5541	35.84	31.15
At 75% Underload	58.7681	54.8882	6.602	3.23

Case 2: Optimal placement of STATCOM

The Newton-Raphson load flow analysis method is used to determine the magnitudes of bus voltages and power flows via transmission lines. The analysis is conducted by raising the load demand from the base load to increments of 25% and 50% of the base load and at 75% under load to the base load. The load flow analysis is done in MATLAB.

The PSO optimization algorithm is used to install the optimal amount of STATCOM at the candidate buses, reducing total line loss and improving the overall voltage profile.

To do so, an objective function is written that executes load flow by injecting reactive power into each of the candidate buses and then computes the bus voltages and line losses. The PSO algorithm then uses swarm intelligence to modify the values of the injected reactive power values and gathers the results before selecting the STATCOM values with the best (minimum) objective function value (in this case low line loss and low voltage deviation from nominal value).

4.2.2 Comparison of Voltage profile and Power loss when STATCOM is used.

Scenario One: The Newton Raphson-Power flow simulation at Base Load before and after STATCOM is added.

The simulation is run at base load demand, and the results are displayed below for the power system network. The Newton-Raphson power flow analysis was converged after 21 PSO iterations under base load demand conditions.

As a result of the optimization, the following STATCOM should be deployed on the candidate buses.

Table 4. 6: Installed STATCOM values at the candidate buses for 0% overload

Candidate bus	68	65	20	27
Installed STATCOM (MVar)	54.1767	213.2092	128.2340	7.2159

In MATLAB and Excel, Figures 4.9 and 4.10 show the voltage profile improvement and power loss minimizations in the scenario of 0% overload using STATCOM at the candidate buses of 68, 65, 27, and 20 correspondingly.

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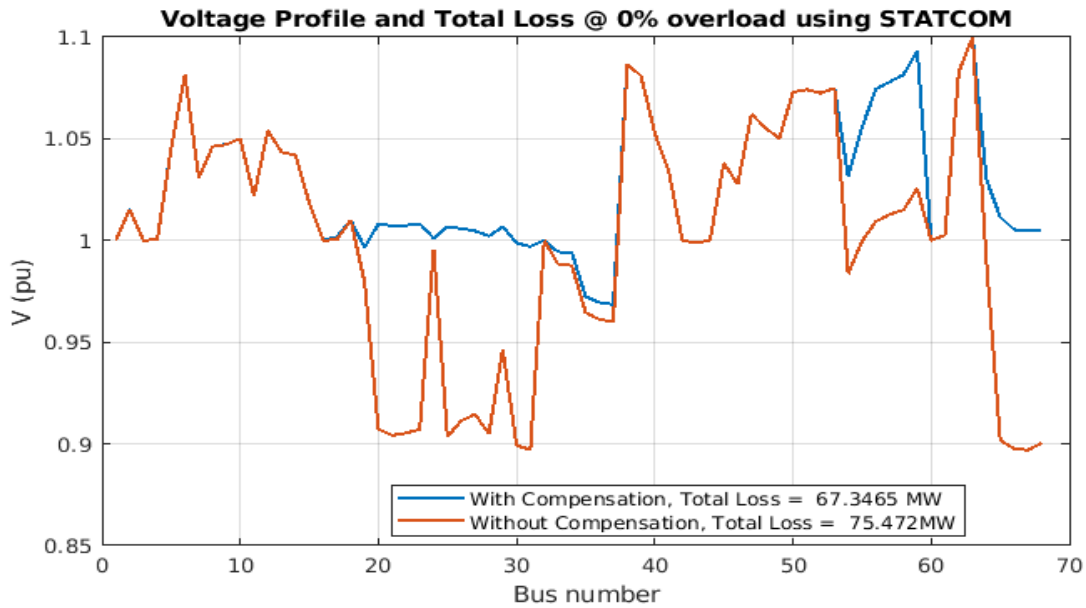


Figure 4. 9: Voltage profile plot for 0% overload before and after STATCOM is used.

The voltage profile has improved greatly from 0.904 pu to 1.0991 pu which is about 17.75% as indicated in the figure and the total line losses of the system are 75.472 MW + 365.6667 MVar for the uncompensated system and 67.3465 MW + 324.0218 MVar for the compensated system. After system compensation, the active power loss was reduced by 10.76%.

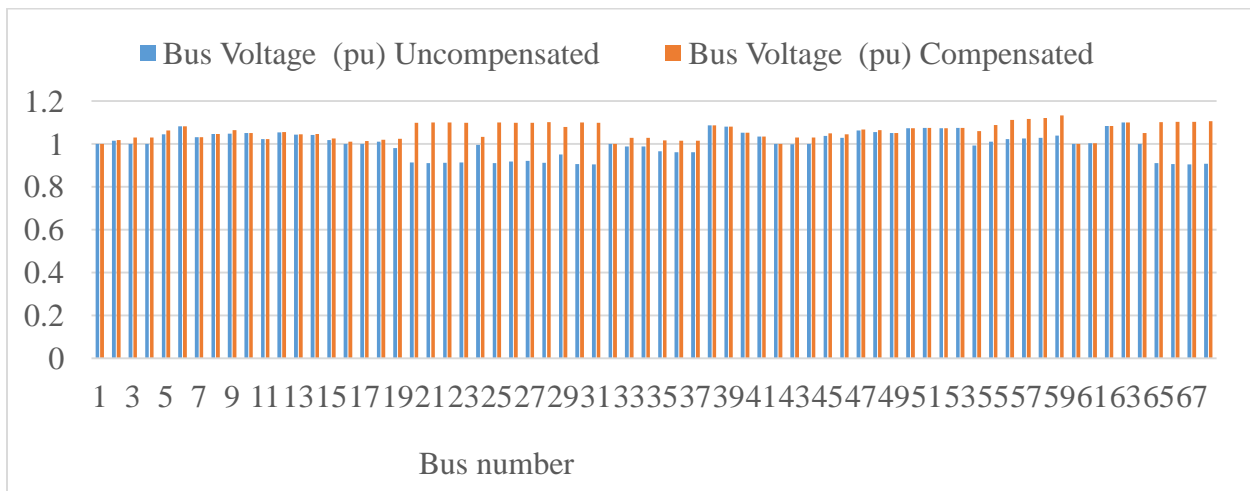


Figure 4. 10: Voltage profile at 0% overload before and after STATCOM installed.

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According to the simulation findings presented in Figures 4.9 and 4.10, after installing the STATCOM at the PSO determined candidate buses, all of the recognized buses with the lowest voltage magnitudes compared to the standards gets improved.

Scenario two: The Newton Raphson Power flow simulation at 25% overload before and after STATCOM is added.

The simulation is run with a 25% overload demand, and the results are displayed below for the power system network. After 21 PSO iterations under the 25% overload condition, the optimization converged.

The optimization results gives the following STATCOM sizes to be installed at the candidate buses.

Table 4. 7: Installed STATCOM values at the candidate buses for 25% overload

Candidate bus	68	65	27	20
Installed STATCOM (MVA _r)	309.3891	229.8969	124.9792	160.2925

In MATLAB and Excel, Figures 4.11 and 4.12 show the voltage profile improvement and power loss minimization in the case of a 25% overload using STATCOM at the candidate buses of 68, 65, 27, and 20.

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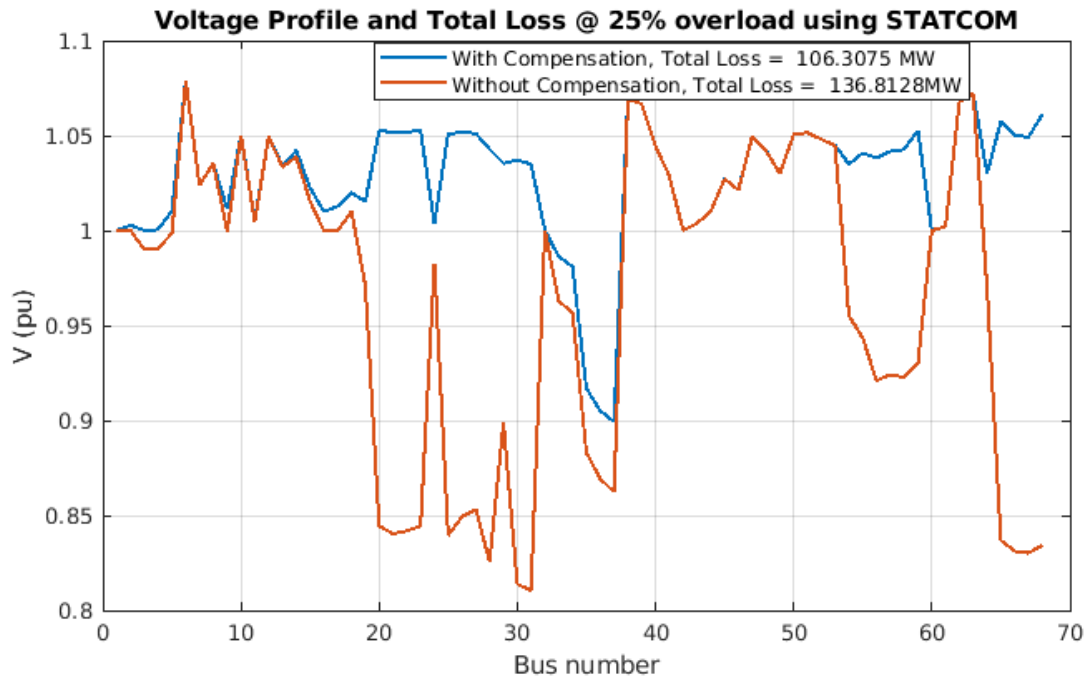


Figure 4. 11: Voltage profile at 25% overload before and after STATCOM installed.

The voltage profile has greatly improved from 0.8266 pu to 1.0712 pu which is about 22.8% as indicated in the figure and the total line losses of the system are 136.8128 MW + 860.6226 MVar for the uncompensated system and 106.3075 MW + 693.8340 MVar for the compensated system. The active power loss is reduced from 136.8128 MW to 106.3075 MW when the load variation is set to 25% overload, which is a reduction of 22.29%.

Performance Evaluation of Transmission Lines for Power Loss Minimization and Voltage Profile Enhancement Using FACTS Devices

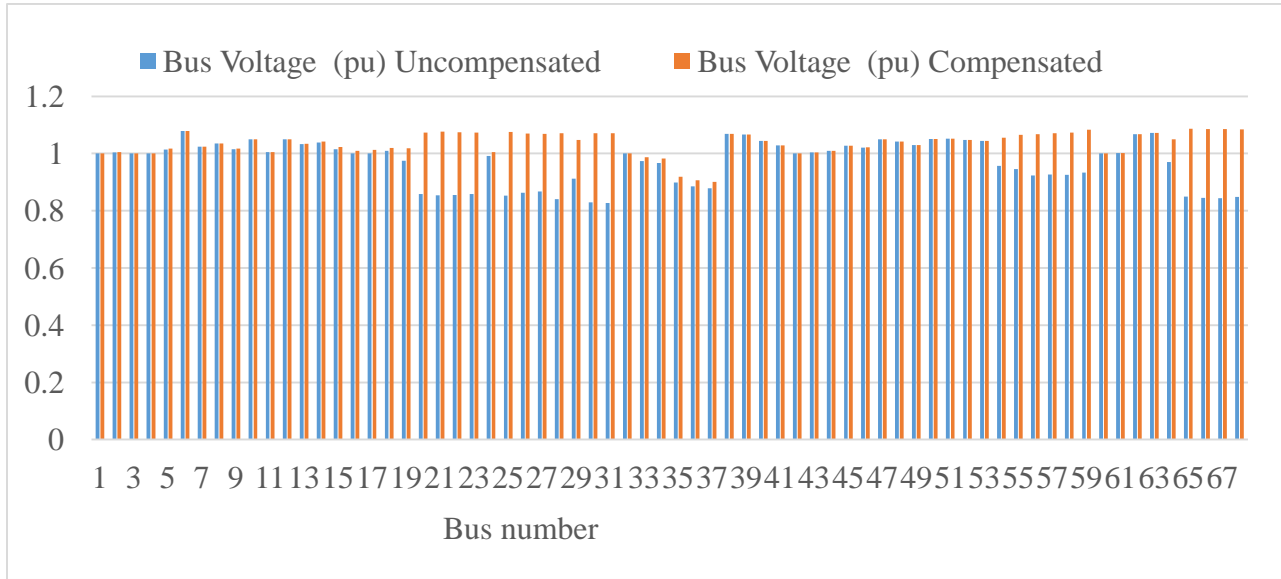


Figure 4. 12: Voltage profile at 25% overload before and after STATCOM installed.

In this case, after installing the STATCOM at the PSO determined candidate buses, all of the recognized buses with the weakest voltage magnitudes compared to the standards improve.

Scenario three: The Newton-Raphson Power flow simulation at 50% overload before and after STATCOM is added.

The simulation is run at 50% overload demand, and the results are displayed below for the power system network. The optimization converged after 21 PSO iterations.

According to the optimization results, the following STATCOM sizes should be put on the candidate buses.

Table 4. 8: Installed STATCOM values at the candidate buses for 50% overload

Candidate bus	68	65	27	20
Installed STATCOM (MVar)	329.7672	268.2009	131.3461	156.8312

Figure 4.13 shows how STATCOM improved the system's voltage profile and reduced power loss in the case of a 50 percent overload on the candidate buses 68, 65, 27, and 20.

During the 50 percent overload condition, and the simulation result, which illustrates the voltage profile improvement of the transmission network at 50 percent overload, is shown in figures 4.13 and 4.14 in MATLAB and Excel, respectively.

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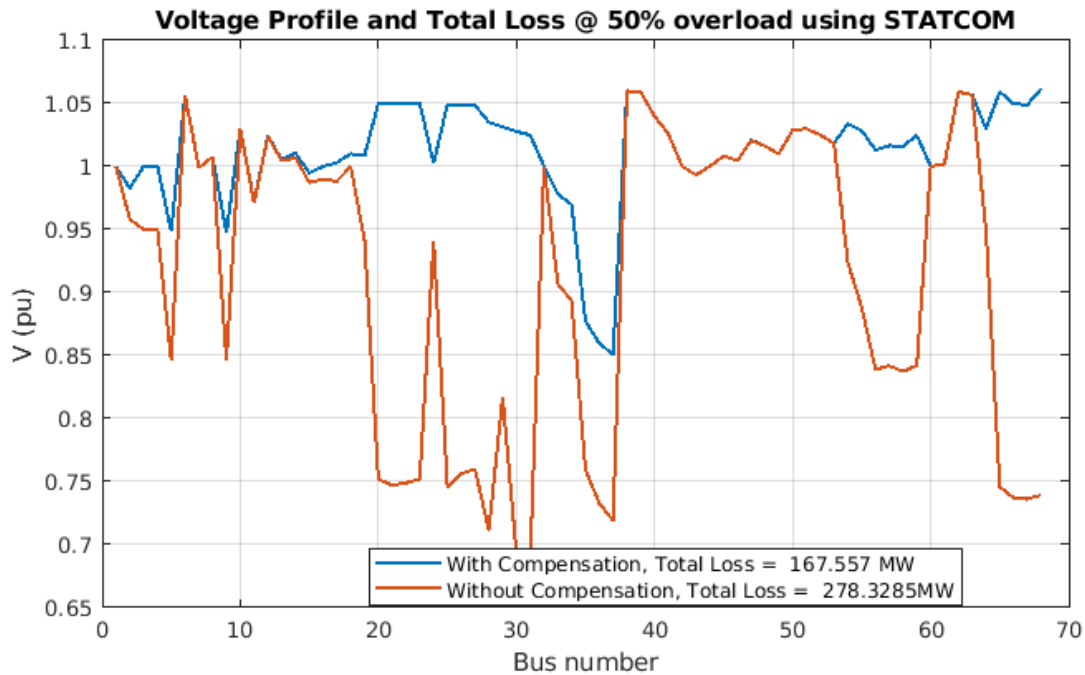


Figure 4. 13: Voltage profile at 50% overload before and after STATCOM is installed.

The voltage profile has get improved from 0.6883 pu to 1.0034 pu which is about 31.4% and the total line losses for the two cases are 278.3285 MW+ 2.0405e+03 MVA_r for the uncompensated system and 167.557 MW+ 1.2356e+03 MVA_r for the compensated system, as shown in the figure. After system compensation, the active power loss has been reduced by 39.79% in this circumstance.

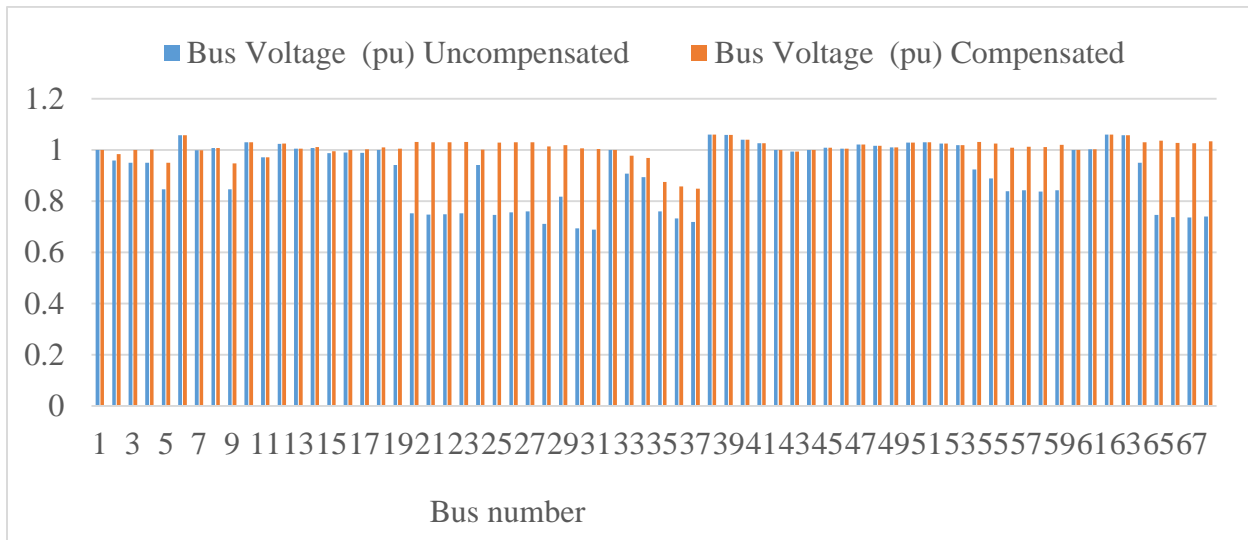


Figure 4. 14: Voltage profile at 50% overload before and after STATCOM installed.

Performance Evaluation of Transmission Lines for Power Loss Minimization and Voltage Profile Enhancement Using FACTS Devices

Under this scenario also, all the identified buses those with smallest voltage magnitudes comparing with the standards gets improved after installing the STATCOM at the PSO identified candidate buses.

Scenario Four: The Newton-Raphson Power flow simulation at 75% Underload when STATCOM is used.

The simulation is run at 75% underload demand, and the results are displayed below for the power system network. The optimization converged after 21 PSO iterations under the 75% underload condition.

The following STATCOM values should be put at the candidate buses based on the optimization results.

Table 4. 9: Installed STATCOM values at the candidate buses for 75% underload

Candidate bus	68	65	27	20
Installed STATCOM (MVar)	131.3455	132.6865	96.1755	52.6265

In the case of a 75% underload, Figures 4.15 and 4.16 show the voltage profile improvement of the system and power loss minimizations in the transmission network using STATCOM at the candidate buses of 68, 65, 27, and 20.

Performance Evaluation of Transmission Lines for Power Loss Minimization and Voltage Profile Enhancement Using FACTS Devices

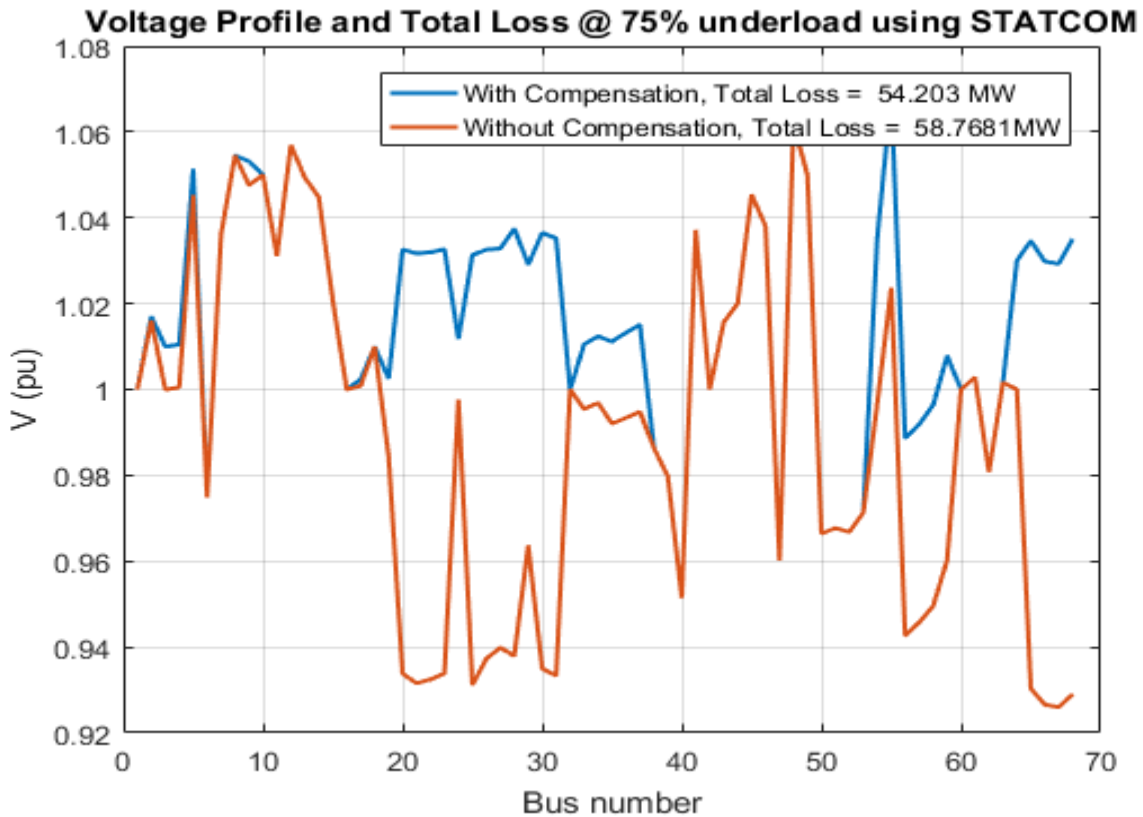


Figure 4. 15: Voltage profile at 75% underload before and after STATCOM installed.

The voltage profile has improved from 0.9333 pu to 1.0352 pu which is about 9.84%, as indicated in the figure, with total line losses of 58.7681 MW + 353.6489 MVar for the uncompensated system and 54.203 MW + 334.9128 MVar for the compensated system. The active power loss is reduced from 58.7681 MW to 54.203 MW when the load variation is taken at 75% underload, which is a 7.76 % loss reduction.

Performance Evaluation of Transmission Lines for Power Loss Minimization and Voltage Profile Enhancement Using FACTS Devices

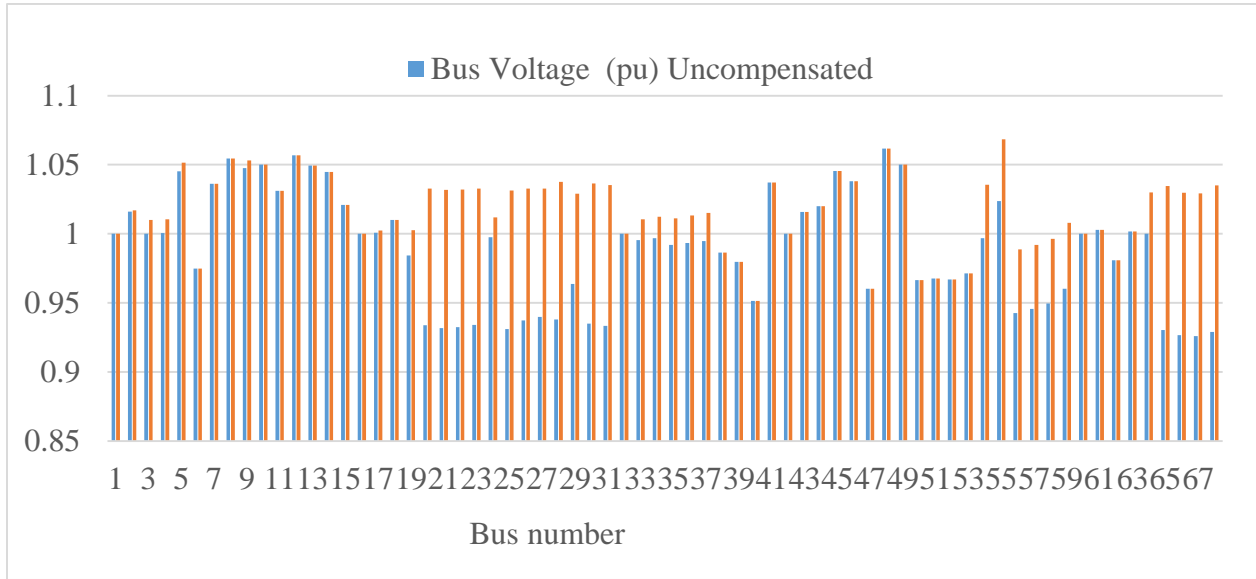


Figure 4. 16: Voltage profile at 75% underload before and after STATCOM installed.

As we can observe from these results, the network is already in a desirable operating condition except few buses for the 75% underload case. After installing the STATCOM at the PSO selected candidate buses, all of the identified buses with the weakest voltage profile and reactive and active power loss sensitivity values improved relative to the standards.

Table 4. 10: The Active Power losses and Voltage Profile improvement for the considered system at different conditions while using STATCOM.

System condition	Active power loss(MW)		Active Power loss Improvement in Percentage	Voltage Profile Improvement in Percentage
	Pre STATCOM	Post STATCOM		
At Base load	75.472	67.3465	10.76	17.75
At 25% Overload	136.8128	106.3075	22.29	22.8
At 50% Overload	278.3285	167.557	39.79	31.4
At 75% Underload	58.768	54.203	7.76	9.84

Performance Evaluation of Transmission Lines for Power Loss Minimization and Voltage Profile Enhancement Using FACTS Devices

Table 4. 11: Result Comparison of Case 1 and Case 2

System condition	Active Power loss Improvement in Percentage while using Capacitor Bank	Voltage Profile Improvement in Percentage while using Capacitor Bank	Active Power loss Improvement in Percentage while using STATCOM	Voltage Profile Improvement in Percentage while using STATCOM
At Base load	10.78	12.5	10.76	17.75
At 25% Overload	20.57	19.41	22.29	22.8
At 50% Overload	35.84	31.15	39.79	31.4
At 75% Underload	6.602	3.23	7.76	9.84

Discussion

It can be seen that the voltage profile improvement and line loss reduction obtained in both scenarios of capacitor bank and STATCOM deployment are nearly identical. The STATCOM location, on the other hand, provides slightly better outcomes for overloaded systems (at 25% and 50% overload), despite the fact that the cost of such devices is higher than capacitors of equal size, resulting in a longer payback period. In addition to improved performance, STATCOM devices are controlled, allowing just the appropriate amount of reactive to be injected into the relevant bus, reducing the risk of over-voltage generated by fixed size capacitors in under-load situations.

The improvements made by the placements of Capacitor banks and STATCOM in the 75% underload case are not so much significant as the network is in a desirable operating condition under this scenario. Although the improvement using STATCOM is shown to be better than using Capacitors. Thus, the placement of those FACTS devices for underload (75% of base load) is not recommended.

4.3 Cost benefit analysis of placement of Capacitor bank and STATCOM

The cost analysis is based on Ethiopian Electric Utility's ETB/kWh energy rates under the new power tariff. The average of all tariff class energy unit costs (ETB/kWh) yields 2.48 ETB/kWh as the cost of energy. The entire amount of annual financial loss due to power loss in each scenario is assessed using the 2.48 ETB/kWh.

According to the exchange rate of Commercial Bank of Ethiopia on January 10, 2022 GC, One USD≈50 ETB

CASE 1: Cost Analysis Before and after installing Capacitor Banks

Scenario 1: At Base Load (0% Overload)

The power loss improvement due to the capacitor usage is

$$75.472\text{MW} - 67.3314\text{ MW} = 8.1406\text{ MW}$$

The total energy saved after capacitor is installed in one year is

$$8.1406\text{ MW} * 8760\text{ hr} = 71,311.656\text{MWhr}$$

The saving in terms of Ethiopian birr is

$$71311.656\text{MWhr} * 2.48 \frac{\text{ETB}}{\text{kWh}} * 1000 \frac{\text{K}}{1\text{M}} = 176,852,906.88\text{ ETB}$$

Cost Analysis for Capacitor Banks

Cost analysis of the selected size of capacitors for base load have been calculated. From Table 4.1 and Appendix J, the cost of the selected size of Capacitor is calculated as follows:

Table 4. 12: Cost of the Capacitor sizes identified during scenario 1.

Candidate buses on which Capacitors are located	Size of Capacitors in kVAr	Cost of Capacitors in USD
68	99,004.5	552,445.11
65	85,283.7	475,883.046
20	51,293.6	286,218.288
27	56,574.0	315,682.92
Total Capacitor cost		1,630,229.364
Installation Cost (10%)		163,022.936
Maintenance Cost (2%)		32,604.58728
Total Cost		1,825,856.88728

Performance Evaluation of Transmission Lines for Power Loss Minimization and Voltage Profile Enhancement Using FACTS Devices

Total Cost in ETB	91,292,844.364
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Payback Period

The Payback Period is the number of months of benefits required for the project to breakeven point. The payback time can be estimated by the following equation.

$$\text{Payback Period} = \frac{\text{Net investment cost}}{\text{Net annual saving}}$$

The payback period for this scenario becomes $\frac{91,292,844.364}{176,852,906.88} = 0.516 \text{ year}$

Scenario 2: At 25% Overload

The power loss improvement after the capacitor bank is installed is

$$136.812 \text{ MW} - 108.6663 \text{ MW} = 28.1457 \text{ MW}$$

The total energy saved under this scenario in one year is

$$28.1457 \text{ MW} * 8760 \text{ hr} = 246,556.332 \text{ MWhr}$$

Therefore, the saving in terms of Ethiopian birr become

$$246,556.332 \text{ MW h} * 2.48 \frac{\text{ETB}}{\text{kWh}} * 1000 \frac{\text{K}}{1\text{M}} = 611,459,703.36 \text{ ETB}$$

Cost Analysis for Capacitor Banks

Cost analysis of the selected size of capacitors for 25% overload have been calculated. From Table 4.2 and Appendix J, the cost of the selected size of Capacitor is calculated as follows:

Table 4. 13: Cost of the Capacitor sizes identified during Scenario 2

Candidate buses on which Capacitors are installed	Size of Capacitors in kVAr	Cost of Capacitors in USD
68	123,755.6	690,556.248
65	106,604.6	594,853.668
20	70,717.5	394,603.65
27	64,117.0	357,772.86
Total Capacitor Cost		2,037,786.426
Installation Cost (10%)		203,778.6426
Maintenance Cost (2%)		40,755.72852
Total Cost		2,282,320.79712

Performance Evaluation of Transmission Lines for Power Loss Minimization and Voltage Profile Enhancement Using FACTS Devices

Total Cost in ETB	114,116,039.856
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Payback Period

The Payback Period is the number of months of benefits required for the project to breakeven point. The payback time can be estimated by the following equation.

$$\text{Payback Period} = \frac{\text{Net investment cost}}{\text{Net annual saving}}$$

The payback period for this scenario becomes $\frac{114,116,039.856}{611,459,703.36} = 0.186 \text{ year}$

Scenario 3: At 50% Over load

The power loss improvement obtained after installing the capacitor bank is
278.3285 MW -178.5541 MW =99.7744 MW

The total energy saved under this scenario in one year is

$$99.7744 \text{ MW} * 8760 \text{ hr} = 874,023.744 \text{ MWhr}$$

Therefore, the saving in terms of Ethiopian birr becomes

$$874,023.744 \text{ MWh} * 2.48 \frac{\text{ETB}}{\text{kWh}} * 1000 \frac{\text{K}}{1\text{M}} = 2,174,571,075.072 \text{ ETB}$$

Cost Analysis for Capacitor Banks

Cost analysis of the selected size of Capacitors for 50% overload have been calculated. From Table 4.3 and Appendix J, the cost of the selected size of capacitor is calculated as follows:

Table 4. 14: Cost of the Capacitor sizes identified during Scenario 3.

Candidate buses on which Capacitors are installed	Size of Capacitors in kVAr	Cost of Capacitors in USD
68	136,399.0	761,106.42
65	117,691.5	656,718.57
20	78,072.1	435,642.318
27	70,785.2	394,981.416
Total cap cost		2,248,448.724
Installation cost (10%)		224,844.8724
Maintenance cost (2%)		44,968.97448
Total cost		2,518,262.57088

Performance Evaluation of Transmission Lines for Power Loss Minimization and Voltage Profile Enhancement Using FACTS Devices

Total cost in ETB	125,913,128.544
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Payback Period

The Payback Period is the number of months of benefits required for the project to breakeven point. The payback time can be estimated by the following equation.

$$\text{Payback Period} = \frac{\text{Net investment cost}}{\text{Net annual saving}}$$

The payback period for this scenario becomes $\frac{125,913,128.544}{2,174,571,075.072} = 0.0579 \text{ year}$

CASE 2: Cost Analysis Before and after installing STATCOM

Scenario 1: At Base Load

The power loss improvement obtained after installing STATCOM is

$$75.472 \text{ MW} - 67.3465 \text{ MW} = 8.1255 \text{ MW}$$

The total energy saved under this scenario in one year is

$$8.1255 \text{ MW} * 8760 \text{ hr} = 71,179.38 \text{ MW hr}$$

The cost saving in terms of Ethiopian birr is

$$71,179.38 \text{ MW h} * 2.48 \frac{\text{ETB}}{\text{kWh}} * 1000 \frac{\text{K}}{1\text{M}} = 176,524,862.4 \text{ ETB}$$

Cost Analysis for STATCOM device

Cost analysis of the selected size of STATCOM for base load have been calculated. From Table 4.5 and Appendix I, the cost of the selected size of STATCOM is calculated as follows:

Table 4. 15: Cost of the STATCOM identified during Scenario 1.

Candidate buses on which STATCOM is installed	Size of STATCOM in kVAr	Cost of STATCOM in USD
68	54,176.7	1,842,007.8
65	213,209.2	7,249,112.8
20	128,234.0	4,359,956.0
27	7,215.9	245,340.6
Total STATCOM cost		13,369,641.72
Installation Cost (10%)		1,369,641.72
Maintenance Cost (2%)		273,928.344

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Total Cost	15,339,987.264
Total Cost in ETB	766,999,363.2

Payback Period

The Payback Period is the number of months of benefits required for the project to breakeven point. The payback time can be estimated by the following equation.

$$\text{Payback Period} = \frac{\text{Net investment cost}}{\text{Net annual saving}}$$

The payback period for this scenario becomes $\frac{766,999,363.2}{176,524,862.4} = 4.344 \text{ year}$

Scenario 2: At 25% Over Load

The power loss improvement obtained after using STATCOM is
 $136.812 \text{ MW} - 106.3075 \text{ MW} = 30.5045 \text{ MW}$

The amount of energy saved under this scenario in one year is
 $30.5045 \text{ MW} * 8760 \text{ hr} = 267,219.42 \text{ MW hr}$

The cost saving in terms of Ethiopian birr is

$$267,219.42 \text{ MW h} * 2.48 \frac{\text{ETB}}{\text{kWh}} * 1000 \frac{\text{K}}{1\text{M}} = 662,704,161.6 \text{ ETB}$$

Cost Analysis for STATCOM device

Cost analysis of the selected size of STATCOM for 25% overload have been calculated. From Table 4.6 and Appendix I, the cost of the selected size of STATCOM is calculated as follows:

Table 4. 16: Cost of the STATCOM identified during Scenario 2.

Candidate buses on which STATCOM is installed	Size of STATCOM in kVAr	Cost of STATCOM in USD
68	309,389.1	10,519,229.4
65	229,896.9	7,816,494.6
20	124,979.9	4,249,292.8
27	160,292.5	5,449,945.0
Total STATCOM Cost		28,034,961.8
Installation Cost (10%)		2,803,496.18
Maintenance Cost (2%)		560,699.236

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Total Cost	31,399,157.216
Total Cost in ETB	1,569,957,860.8

Payback Period

The Payback Period is the number of months of benefits required for the project to breakeven point. The payback time can be estimated by the following equation.

$$\text{Payback Period} = \frac{\text{Net investment cost}}{\text{Net annual saving}}$$

The payback period for this scenario becomes $\frac{1,569,957,860.8}{662,704,161.6} = 2.369 \text{ year}$

Scenario 3: At 50% Over Load

The power loss improvement obtained after using STATCOM is
 $278.3285 \text{ MW} - 167.557 \text{ MW} = 110.7715 \text{ MW}$

The amount of energy saved under this scenario in one year is

$$110.7715 \text{ MW} * 8760 \text{ hr} = 970,358.34 \text{ MW hr}$$

The cost saving in terms of Ethiopian birr is

$$970,358.34 \text{ MW h} * 2.48 \frac{\text{ETB}}{\text{kWh}} * 1000 \frac{\text{K}}{1\text{M}} = 2,406,488,683.2 \text{ ETB}$$

Cost Analysis for STATCOM device

Cost analysis of the selected size of STATCOM for 50% overload have been calculated. From Table 4.7 and Appendix I, the cost of the selected size of STATCOM is calculated as follows:

Table 4. 17: Cost of the STATCOM identified during Scenario 3.

Candidate buses on which STATCOM is installed	Size of STATCOM in kVAr	Cost of STATCOM in USD
68	329,767.2	11,212,084.8
65	286,200.9	9,118,830.6
20	131,346.1	4,465,767.4
27	156,831.2	5,332,260.8
Total STATCOM Cost		30,128,943.6
Installation Cost (10%)		3,012,894.36
Maintenance Cost (2%)		602,578.872

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Total Cost	33,744,416.832
Total Cost in ETB	1,168,220,841.6

Payback Period

The Payback Period is the number of months of benefits required for the project to breakeven point. The payback time can be estimated by the following equation.

$$\text{Payback Period} = \frac{\text{Net investment cost}}{\text{Net annual saving}}$$

The payback period for this scenario becomes $\frac{1,168,220,841.6}{2,406,488,683.2} = 0.485 \text{ year}$

The STATCOM location, provides slightly better outcomes for overloaded systems (at 25% and 50% overload), despite the fact that the cost of such devices is higher than capacitors of equal size, resulting in a longer payback period. Overall, if initial and maintenance costs are ignored, STATCOM devices give higher performance in terms of improving system behavior. The reason for the payback period gets smaller with increasing overload is that, for higher overload cases the capital cost saved is much higher for relatively similar amount of installed FACTS device. This in turn reduces the payback period which is the ratio of those two variables.

Table 4. 18: Comparison of Case 1 and Case 2 in terms of Payback Period

System condition	Payback period (in years)	
	When Capacitor is used	When STATCOM is used
At Base load	0.516	4.344
At 25% overload	0.186	2.369
At 50% overload	0.0579	0.485

CHAPTER 5

CONCLUSION, RECOMMENDATION AND FUTURE WORK

5.1 Conclusion

In recent years, there has been an increase in interest from electric power generation and transmission in FACTS devices, which can provide tremendous technological advantages when used correctly. In this research, two basic types of FACTS devices with different total loads were studied in order to assess their improvement of the performance of a system. The major issues investigated in this thesis, are the location and sizing of Capacitor banks and STATCOM to reduce the total power loss, and boost the voltage profile of the system.

The PSO algorithm is implemented to find the optimal locations and size for Capacitor Banks and STATCOM device in the network considered under the case study.

In case 1, the addition of Capacitor banks in the optimum location of the system at buses 68, 65, 27, 20 reduces the active power loss of the system by 10.78% , 20.57%, 35.84% and 6.602% in the scenarios of base load, 25% overload, 50% overload and 75% underload, respectively.

In case 2 again, the STATCOM device is installed on the candidate buses 68, 65, 27, 20 of system which results an improvement in the active power loss reduction by 10.76%, 22.29% ,37.79% and 7.76% in the scenarios of base load, 25% overload, 50% overload and 75% underload, respectively.

There is also significant improvements in the bus voltage profile in both cases under different scenarios. Thus, in scenarios of base load, 25% overload, 50% overload and 75% underload the voltage magnitudes of weak buses are improved by 12.5%, 19.41%, 31.15%, 3.23% and 17.5%, 22.8%, 31.4%, 9.84% after the incorporation of Capacitor banks and STATCOM respectively.

The weak bus voltages gets improved and accordingly meets with IEEE specified ranges. The overall simulation results showed that the proposed technique is comparatively efficient in terms of reducing the active and reactive power losses, and boost-up voltage profile in the system.

5.2 Recommendation

In this thesis, it is observed that PSO-based capacitor placement on the case study system results in loss reductions of 10.78 percent, 20.57 percent, 35.84 percent and 6.602 percent in the scenarios of base load, 25% overload, 50% overload and 75% underload respectively.

As well as voltage profile gets improved by 12.5%, 19.41%, 31.15% and 3.23% in the scenarios of base load, 25% overload, 50% overload and 75% underload respectively. The energy cost savings of 1,825,856.88728 USD, 2,282,320.79712 USD and 2,518,262.5788 USD are obtained with payback periods of 0.516 years, 0.186 years and 0.0579 years for the above scenarios of base load, 25% overload and 50% overload respectively.

Again, the PSO-based STATCOM device on the case study system results in loss reductions of 10.76 %, 22.29%, 37.79%, 7.76 % and the voltage profile improvement of 17.5%, 22.8%, 31.4%, and 9.84% in the scenarios of base load, 25% overload, 50% overload and 75% underload respectively. The energy cost savings of 15,339,987.264 USD, 31,399,157.216 USD, and 33,744,416.832 USD are obtained with payback periods of 4.344 years, 2.369 years, and 0.485 years for the above scenarios of base load, 25% overload and 50% overload respectively.

Based on the simulation results, however, STATCOM has higher maintenance and investment costs than Capacitor Banks which it leads to have somewhat longer payback periods, STATCOM is proposed for the system due to the following reasons.

- It has better performance, especially in overload cases.
- No over voltage happens at under load and
- Due to its dynamic capability

The implementation of this study especially the use of STATCOM device is recommended to Ethiopian Electric Power.

5.3 Suggestions for the future work

This thesis work covers only 400kV and 230kV Ethiopian high voltage transmission lines. The future work may include 45kV, 66kV, 132kV and 500kV transmission lines to analyze transmission line losses and voltage profile improvement.

This thesis carried out extensive analysis of the considered system without considering any fault conditions. Assessment and improvement of the system loss and voltage profile under different fault conditions may also be considered as a future research work.

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APPENDICES

Appendix A: MATLAB Code for Main Optimization program

```
% clear all

% close all
accuracy = 0.0001; max_iter = 500;
global f slack_bus pv_bus load_bus basemva
f          = 50;
basemva    = 100;
%%
    slack_bus = 0;
    pv_bus    = 1;
    load_bus  = 2;
%     busdata  = xlsread('400_230kV_data.xlsx',2);
%     linedata = xlsread('400_230kV_data.xlsx',3);

%     busdata  = xlsread('400_230kV_data_2.xlsx',1);
%     linedata = xlsread('400_230kV_data_2.xlsx',2);

    busdata  = xlsread('400_230kV_data_5.xlsx',1);
    linedata = xlsread('400_230kV_data_5.xlsx',2);
%% For Book data
    % code 0 = load bus (PQ-bus, prev-1), code 1 = slack
bus(prev-3),
    % code 2 = voltage controlled bus (PV-bus, prev-2)
%     slack_bus = 1;
%     pv_bus    = 2;
%     load_bus  = 0;
%     data_Converter;
%%
    overload = 0;
    if overload
        percent_overload = 0;
        busdata(:,5) = (1+percent_overload/100)*busdata(:,5);
        busdata(:,6) = (1+percent_overload/100)*busdata(:,6);
        busdata(:,10) = (1+percent_overload/100)*busdata(:,10);
    else
        percent_overload = 0;
    end
    [busD_init,V_init,Ploss_init,Qloss_init,Lpij_new,maxerror] =
lf_newton3_noUPFC(busdata,linedata);
%%
% [busD_cand,V,cand_buses] = Sensitivity_test(busdata,linedata);
% cand_buses = [cand_buses];
no_cand_buses = 4;
```

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```
cand_buses = Sensitivity(busdata,linedata,no_cand_buses);
nvars = length(cand_buses);
stat = 0; % Use 0 for dynamic
optimization and 1 for static optimization
if stat==0
    cond = 'STATCOM';
    lb = zeros(nvars,1);
    ub = 2.5*busdata(cand_buses,6);
elseif stat==1
    cond = 'Capacitor';
    lb = zeros(nvars,1);
    ub = 1.0*busdata(cand_buses,6);
end

func =
@(x) objectiveWithParams(x,busdata,linedata,cand_buses,stat);

options = optimoptions('particleswarm');
options.Display = 'iter';
x = particleswarm(func,nvars,lb,ub,options)
%% PSO Optimization result
[busD_new,V_new,Ploss_new,Qloss_new,Lpij_new,maxerror] =
lf_newton3_PSO(x,busdata,linedata,cand_buses);
%% Performance Plot
% Using line plot
% figure
% bar(busdata(:,1),V_new);
% hold on
% bar(busdata(:,1),V_init);
% grid on
% legend(['With Compensation, Total Loss = ',
num2str(Ploss_new),' MW'],['Without Compensation, Total Loss =
', num2str(Ploss_init),'MW']);
% title(['Voltage Profile and Total Loss @ ',
num2str(percent_overload), '% overload using ', cond]);

% Using line plot
figure
plot(busdata(:,1),V_new,'Linewidth',1.5)
hold on
plot(busdata(:,1),V_init,'Linewidth',1.5)
grid on
legend(['With Compensation, Total Loss = ',
num2str(Ploss_new),' MW'],['Without Compensation, Total Loss =
', num2str(Ploss_init),'MW']);
```

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```
title(['Voltage Profile and Total Loss @ ',  
num2str(percent_overload), '% overload using ', cond]);  
xlabel('Bus number')  
ylabel('V (pu)')  
%% Cost Calculation  
E_loss = (Ploss_init-Ploss_new)*1000*8760;           % Energy loss  
per year  
E_cost = E_loss*2.48;                               % Annual cost of  
lost energy  
PbP    = costOf(x)*50/E_cost;                       % Perback_period
```

Appendix B: MATLAB Code for Newton-Raphson load flow

```
% Program for Bus Power Injections, Line & Power flows (p.u)...
```

```
function [Si,Pg,Qg,Ploss,Lpij,Qloss,yload] =  
loadflow_noUPFC(V,del,Y,busD,lineD)  
global basemva  
nb = length(busD(:,1));  
Vm = pol2rect(V,del);           % Converting polar to  
rectangular..  
fb = lineD(:,1);               % From bus number...  
tb = lineD(:,2);               % To bus number...  
nl = length(fb);               % No. of Branches..  
Pl = busD(:,5);                 % PLi..  
Ql = busD(:,6);                 % QLi..  
Qs = busD(:,11);  
  
Iij = zeros(nb,nb);  
Sij = zeros(nb,nb);  
Si   = zeros(nb,1);  
  
yload = zeros(nb,1);  
% Bus Current Injections..  
I = Y*Vm;  
% Im = abs(I);  
% Ia = angle(I);  
  
%Line Current Flows..  
for m = 1:nl  
    p = fb(m); q = tb(m);  
    Iij(p,q) = -(Vm(p) - Vm(q))*Y(p,q); % Y(m,n) = -y(m,n)..  
    Iij(q,p) = -Iij(p,q);  
end  
% %Iij = sparse(Iij);           % Commented out..
```

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```
% Iijm = abs(Iij);
% Iija = angle(Iij);

% Line Power Flows..
for m = 1:nb
    for n = 1:nb
        if m ~= n
            Sij(m,n) = Vm(m)*conj(Iij(m,n))*basemva;
        end
    end
end
end
% %Sij = sparse(Sij);      % Commented out..
% Pij = real(Sij);
% Qij = imag(Sij);

% Line Losses..
Lij = zeros(nl,1);
for m = 1:nl
    p = fb(m); q = tb(m);
    Lij(m) = Sij(p,q) + Sij(q,p);
end
Lpij = real(Lij);
Lqij = imag(Lij);

% Bus Power Injections..
for i = 1:nb
    for k = 1:nb
        Si(i) = Si(i) + conj(Vm(i))*Vm(k)*Y(i,k)*basemva;
    end
    % Compute the load equivalent admittances including the UPFC
    effect
    yload(i) = (Pl(i) - li*Ql(i)+li*Qs(i))/(V(i)^2);
end
Pi = real(Si);
Qi = -imag(Si);
Pg = Pi+Pl;
Qg = Qi+Ql;

Ploss = sum(Lpij);
Qloss = sum(Lqij);
```

Appendix C: MATLAB Code for PSO Objective function

```
function F =
objectiveWithParams(x,busdata,linedata,cand_buses,stat)
```

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```
    if stat==1
        cc = 1;
        [busD_new,V,Ploss,Lpij,maxerror] =
lf_newton3_PSO_Static(x,busdata,linedata,cand_buses);
    else
        cc = 0;
        [busD_new,V,Ploss,Lpij,maxerror] =
lf_newton3_PSO_Dynamic(x,busdata,linedata,cand_buses);
    end
    V_cost = sum(1-V(cand_buses));
    P_cost = Ploss;
    M_cost = costOf(x);

    weight = 0.5;

    F = weight*V_cost + (1-weight)*P_cost + cc*M_cost*1e-6;

end
```

Appendix D: MATLAB Code for load flow Newton-Raphson with capacitor included.

```
function [busD_new,V,Ploss,Lpij,maxerror] =
lf_newton3_PSO_Static(x,busdata,linedata,cand_buses)
global slack_bus pv_bus load_bus basemva

Ybus = ybusppg(linedata);

bus = busdata(:,1);           % Bus Number..
type = busdata(:,2);         % Type of Bus 0-Slack, 1-PV,
2-PQ..
V = busdata(:,3);            % Specified Voltage..
del = busdata(:,4)*pi/180;   % Voltage Angle..
Pl = busdata(:,5)/basemva;   % PLi..
Ql = busdata(:,6)/basemva;   % QLi..
Pg = busdata(:,7)/basemva;   % PGi..
Qg = busdata(:,8)/basemva;   % QGi..
Qmin = busdata(:,9)/basemva; % Minimum Reactive Power
Limit..
Qmax = busdata(:,10)/basemva; % Maximum Reactive Power
Limit..
Qsh = busdata(:,11)/basemva; % Injected shunt reactive
power
```

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```

%cand_len = length(cand_buses);
%type(cand_buses) = pv_bus*ones(cand_len,1);
%V(cand_buses) = 1.0;

Qsh(cand_buses) = Qsh(cand_buses)+x'/basemva;

P    = Pg - Pl;           % Pi = PGi - PLi..
Q    = Qg - Ql + Qsh;    % Qi = QGi - QLi..
Psp = P;                 % P Specified..
Qsp = Q;                 % Q Specified..

nbus = length(bus);
pv    = find(type == slack_bus | type == pv_bus); % PV Buses..
pq    = find(type == load_bus); % PQ Buses..
npv   = length(pv); % No. of PV
buses..
npq   = length(pq); % No. of PQ
buses..

Tol   = 1;
Iter  = 1;
converge = 1;
accuracy = 0.001;
maxiter = 1000;
while (Tol > 1e-3)&&(Iter<=maxiter) % Iteration starting..
    G = real(Ybus); % Conductance matrix..
    B = imag(Ybus); % Susceptance matrix..

    P = zeros(nbus,1);
    Q = zeros(nbus,1);
    % Calculate P and Q
    for i = 1:nbus
        for j = 1:nbus
            P(i) = P(i) + V(i)*V(j)*(G(i,j)*cos(del(i)-del(j)) +
B(i,j)*sin(del(i)-del(j)));
            Q(i) = Q(i) + V(i)*V(j)*(G(i,j)*sin(del(i)-del(j)) -
B(i,j)*cos(del(i)-del(j)));
        end
    end

    % Checking Q-limit violations..
    if Iter <= 7 && Iter > 2 % Only checked up to 7th
iterations..
        for n = 2:nbus

```

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```
        if type(n) == pv_bus
            QG = Q(n)+Ql(n);
            if QG < Qmin(n)
                V(n) = V(n) + 0.01;
            elseif QG > Qmax(n)
                V(n) = V(n) - 0.01;
            end
        end
    end
end

% Calculate change from specified value
dPa = Psp-P;
dQa = Qsp-Q;
k = 1;
dQ = zeros(npq,1);
for i = 1:nbus
    if type(i) == load_bus
        dQ(k,1) = dQa(i);
        k = k+1;
    end
end
dP = dPa(2:nbus);
M = [dP; dQ];           % Mismatch Vector

% Jacobian
% J1 - Derivative of Real Power Injections with Angles..
J1 = zeros(nbus-1,nbus-1);
for i = 1:(nbus-1)
    m = i+1;
    for k = 1:(nbus-1)
        n = k+1;
        if n == m
            for n = 1:nbus
                J1(i,k) = J1(i,k) + V(m)* V(n)* (-
G(m,n)*sin(del(m)-del(n)) + B(m,n)*cos(del(m)-del(n)));
            end
            J1(i,k) = J1(i,k) - V(m)^2*B(m,m);
        else
            J1(i,k) = V(m)* V(n)* (G(m,n)*sin(del(m)-del(n))
- B(m,n)*cos(del(m)-del(n)));
        end
    end
end

% J2 - Derivative of Real Power Injections with V..
```

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```
J2 = zeros(nbus-1,npq);
for i = 1:(nbus-1)
    m = i+1;
    for k = 1:npq
        n = pq(k);
        if n == m
            for n = 1:nbus
                J2(i,k) = J2(i,k) + V(n) * (G(m,n) * cos(del(m) -
del(n)) + B(m,n) * sin(del(m) - del(n)));
            end
            J2(i,k) = J2(i,k) + V(m) * G(m,m);
        else
            J2(i,k) = V(m) * (G(m,n) * cos(del(m) - del(n)) +
B(m,n) * sin(del(m) - del(n)));
        end
    end
end

% J3 - Derivative of Reactive Power Injections with Angles..
J3 = zeros(npq,nbus-1);
for i = 1:npq
    m = pq(i);
    for k = 1:(nbus-1)
        n = k+1;
        if n == m
            for n = 1:nbus
                J3(i,k) = J3(i,k) + V(m) *
V(n) * (G(m,n) * cos(del(m) - del(n)) + B(m,n) * sin(del(m) - del(n)));
            end
            J3(i,k) = J3(i,k) - V(m)^2 * G(m,m);
        else
            J3(i,k) = V(m) * V(n) * (-G(m,n) * cos(del(m) - del(n))
- B(m,n) * sin(del(m) - del(n)));
        end
    end
end

% J4 - Derivative of Reactive Power Injections with V..
J4 = zeros(npq,npq);
for i = 1:npq
    m = pq(i);
    for k = 1:npq
        n = pq(k);
        if n == m
            for n = 1:nbus
```

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```

        J4(i,k) = J4(i,k) + V(n) * (G(m,n) * sin(del(m) -
del(n)) - B(m,n) * cos(del(m) - del(n)));
    end
    J4(i,k) = J4(i,k) - V(m) * B(m,m);
else
    J4(i,k) = V(m) * (G(m,n) * sin(del(m) - del(n)) -
B(m,n) * cos(del(m) - del(n)));
end
end
end
end
%%
J = [J1 J2; J3 J4]; % Jacobian Matrix..
X = J\M; % Correction Vector

% [X,flag,relres] = lsqr(J,M,1e-3,400);
dTh = X(1:nbus-1); % Change in Voltage Angle..
dV = X(nbus:end); % Change in Voltage Magnitude..

% Updating State Vectors..
del(2:nbus) = dTh + del(2:nbus); % Voltage Angle..
V(pq) = dV + V(pq);

% k = 1;
% for i = 1:nbus
%     if type(i) == load_bus
%         V(i) = dV(k) + V(i); % Voltage Magnitude..
%         k = k+1;
%     end
% end

Iter = Iter + 1;
Tol = max(abs(M)); % Tolerance..

if Iter == maxiter && Tol > accuracy
    fprintf('\nWARNING: Iterative solution did not converged
after ')
    fprintf('%g', Iter), fprintf(' iterations.\n\n')
    fprintf('Press Enter to terminate the iterations and
print the results \n')
    converge = 0; pause,
end
end
[Si,Pg,Qg,Ploss,Lpij,Qloss,yload] =
loadflow_noUPFC(V,del,Ybus,busdata,linedata); %
Calling Loadflow.m..

busD_new = busdata;

```

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```
busD_new(:,3) = V;  
busD_new(:,4) = del*180/pi;  
busD_new(:,7) = Pg;  
busD_new(:,8) = Qg;  
maxerror      = Tol;
```

Appendix E: MATLAB Code for load flow Newton-Raphson with STATCOM included.

```
function [busD_new,V,Ploss,Lpij,maxerror] =  
lf_newton3_PSO_Dynamic(x,busdata,linedata,cand_buses)  
global slack_bus pv_bus load_bus basemva  
  
Ybus = ybusppg(linedata);  
  
bus = busdata(:,1); % Bus Number..  
type = busdata(:,2); % Type of Bus 0-Slack, 1-PV,  
2-PQ..  
V = busdata(:,3); % Specified Voltage..  
del = busdata(:,4)*pi/180; % Voltage Angle..  
Pl = busdata(:,5)/basemva; % PLi..  
Ql = busdata(:,6)/basemva; % QLi..  
Pg = busdata(:,7)/basemva; % PGi..  
Qg = busdata(:,8)/basemva; % QGi..  
Qmin = busdata(:,9)/basemva; % Minimum Reactive Power  
Limit..  
Qmax = busdata(:,10)/basemva; % Maximum Reactive Power  
Limit..  
Qsh = busdata(:,11)/basemva; % Injected shunt reactive  
power  
  
cand_len = length(cand_buses);  
type(cand_buses) = pv_bus*ones(cand_len,1);  
V(cand_buses) = 1.0;  
  
Qmax(cand_buses) = x'/basemva;  
  
P = Pg - Pl; % Pi = PGi - PLi..  
Q = Qg - Ql + Qsh; % Qi = QGi - QLi..  
Psp = P; % P Specified..  
Qsp = Q; % Q Specified..  
  
nbus = length(bus);  
pv = find(type == slack_bus | type == pv_bus); % PV Buses..
```

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```
pq    = find(type == load_bus);           % PQ Buses..
npv   = length(pv);                     % No. of PV
buses..
npq   = length(pq);                     % No. of PQ
buses..

Tol   = 1;
Iter  = 1;
converge = 1;
accuracy = 0.001;
maxiter = 1000;
while (Tol > 1e-3) && (Iter <= maxiter) % Iteration starting..
    G = real(Ybus);                     % Conductance matrix..
    B = imag(Ybus);                     % Susceptance matrix..

    P = zeros(nbus,1);
    Q = zeros(nbus,1);
    % Calculate P and Q
    for i = 1:nbus
        for j = 1:nbus
            P(i) = P(i) + V(i)*V(j)*(G(i,j)*cos(del(i)-del(j)) +
B(i,j)*sin(del(i)-del(j)));
            Q(i) = Q(i) + V(i)*V(j)*(G(i,j)*sin(del(i)-del(j)) -
B(i,j)*cos(del(i)-del(j)));
        end
    end

    % Checking Q-limit violations..
    if Iter <= 7 && Iter > 2           % Only checked up to 7th
iterations..
        for n = 2:nbus
            if type(n) == pv_bus
                QG = Q(n)+Ql(n);
                if QG < Qmin(n)
                    V(n) = V(n) + 0.01;
                elseif QG > Qmax(n)
                    V(n) = V(n) - 0.01;
                end
            end
        end
    end

    % Calculate change from specified value
    dPa = Psp-P;
    dQa = Qsp-Q;
    k = 1;
```

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```
dQ = zeros(npq,1);
for i = 1:nbus
    if type(i) == load_bus
        dQ(k,1) = dQa(i);
        k = k+1;
    end
end
dP = dPa(2:nbus);
M = [dP; dQ];           % Mismatch Vector

% Jacobian
% J1 - Derivative of Real Power Injections with Angles..
J1 = zeros(nbus-1,nbus-1);
for i = 1:(nbus-1)
    m = i+1;
    for k = 1:(nbus-1)
        n = k+1;
        if n == m
            for n = 1:nbus
                J1(i,k) = J1(i,k) + V(m)* V(n)* (-
G(m,n)*sin(del(m)-del(n)) + B(m,n)*cos(del(m)-del(n)));
            end
            J1(i,k) = J1(i,k) - V(m)^2*B(m,m);
        else
            J1(i,k) = V(m)* V(n)* (G(m,n)*sin(del(m)-del(n))
- B(m,n)*cos(del(m)-del(n)));
        end
    end
end

% J2 - Derivative of Real Power Injections with V..
J2 = zeros(nbus-1,npq);
for i = 1:(nbus-1)
    m = i+1;
    for k = 1:npq
        n = pq(k);
        if n == m
            for n = 1:nbus
                J2(i,k) = J2(i,k) + V(n)* (G(m,n)*cos(del(m)-
del(n)) + B(m,n)*sin(del(m)-del(n)));
            end
            J2(i,k) = J2(i,k) + V(m)*G(m,m);
        else
            J2(i,k) = V(m)* (G(m,n)*cos(del(m)-del(n)) +
B(m,n)*sin(del(m)-del(n)));
        end
    end
end
```

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```
        end
    end

    % J3 - Derivative of Reactive Power Injections with Angles..
    J3 = zeros(npq,nbus-1);
    for i = 1:npq
        m = pq(i);
        for k = 1:(nbus-1)
            n = k+1;
            if n == m
                for n = 1:nbus
                    J3(i,k) = J3(i,k) + V(m)*
V(n)*(G(m,n)*cos(del(m)-del(n)) + B(m,n)*sin(del(m)-del(n)));
                end
                J3(i,k) = J3(i,k) - V(m)^2*G(m,m);
            else
                J3(i,k) = V(m)* V(n)*(-G(m,n)*cos(del(m)-del(n))
- B(m,n)*sin(del(m)-del(n)));
            end
        end
    end

    % J4 - Derivative of Reactive Power Injections with V..
    J4 = zeros(npq,npq);
    for i = 1:npq
        m = pq(i);
        for k = 1:npq
            n = pq(k);
            if n == m
                for n = 1:nbus
                    J4(i,k) = J4(i,k) + V(n)*(G(m,n)*sin(del(m)-
del(n)) - B(m,n)*cos(del(m)-del(n)));
                end
                J4(i,k) = J4(i,k) - V(m)*B(m,m);
            else
                J4(i,k) = V(m)*(G(m,n)*sin(del(m)-del(n)) -
B(m,n)*cos(del(m)-del(n)));
            end
        end
    end

    %%
    J = [J1 J2; J3 J4];           % Jacobian Matrix..
    X = J\M;                       % Correction Vector

    % [X,flag,relres] = lsqr(J,M,1e-3,400);
    dTh = X(1:nbus-1);           % Change in Voltage Angle..
```

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```
dV = X(nbus:end);           % Change in Voltage Magnitude..

% Updating State Vectors..
del(2:nbus) = dTh + del(2:nbus);   % Voltage Angle..
V(pq)      = dV + V(pq);

%   k = 1;
%   for i = 1:nbus
%       if type(i) == load_bus
%           V(i) = dV(k) + V(i);   % Voltage Magnitude..
%           k = k+1;
%       end
%   end

Iter = Iter + 1;
Tol  = max(abs(M));           % Tolerance..

if Iter == maxiter && Tol > accuracy
    fprintf('\nWARNING: Iterative solution did not converged
after ')
    fprintf('%g', Iter), fprintf(' iterations.\n\n')
    fprintf('Press Enter to terminate the iterations and
print the results \n')
    converge = 0; pause,
end
end
[Si,Pg,Qg,Ploss,Lpij,Qloss,yload] =
loadflow_noUPFC(V,del,Ybus,busdata,linedata);           %
Calling Loadflow.m..

busD_new = busdata;
busD_new(:,3) = V;
busD_new(:,4) = del*180/pi;
busD_new(:,7) = Pg;
busD_new(:,8) = Qg;
maxerror     = Tol;
```

Appendix F: MATLAB Code for sensitivity analysis

```
function cand_buses = Sensitivity(busdata,linedata,num)

nbus = length(busdata(:,1));

%tempBus = busdatas(nbus);
P_loss = zeros(nbus,1);
Q_loss = zeros(nbus,1);
v_dev = zeros(nbus,1);
```

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```
for count=1:nbus+1
    tempBus = busdata;
    if count~=nbus+1
        diff = tempBus(count,6)-tempBus(count,8);
        if diff>0
            tempBus(count,8) =+ diff;
        end
    end
    [busD_new,V,Ploss,Qloss,Lpij,maxerror] =
lf_newton3_noUPFC(tempBus,linedata);

    if count~=nbus+1
        P_loss(count) = Ploss;
        Q_loss(count) = Qloss;
        v_dev(count) = 1-min(V);
    elseif count==nbus+1
        PlossN = Ploss;
        QlossN = Qloss;
        v_devN = 1-min(V);
    end
end

P_reduct = PlossN - P_loss;
Q_reduct = QlossN - Q_loss;
V_imprv = v_devN-v_dev;

minP_loss = min(P_reduct);
maxP_loss = max(P_reduct);
minV_imprv = min(V_imprv);
maxV_imprv = max(V_imprv);

loss_diff = maxP_loss-minP_loss;
imprv_diff = maxV_imprv - minV_imprv;

PLI = (P_reduct - minP_loss)/loss_diff;
VLI = (V_imprv - minV_imprv)/imprv_diff;

LI = PLI + VLI;

[sortedPLI, I] = sort(PLI, 'descend');
cand_buses = I(1:num);
```

Appendix G: MATLAB Code to form Admittance matrix Formation

```
% Program to form Admittance And Impedance Bus Formation....
```

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```
function Y = ybusppg(linedata) % Returns Y

% linedata = linedatas(num); % Calling Linedatas...
fb = linedata(:,1); % From bus number...
tb = linedata(:,2); % To bus number...
r = linedata(:,3); % Resistance, R...
x = linedata(:,4); % Reactance, X...
b = linedata(:,5); % Ground Admittance, B/2...
a = linedata(:,6); % Tap setting value..
z = r + 1i*x; % Z matrix...
y = 1./z; % To get inverse of each
element...
b = 1i*b; % Make B imaginary...

nb = max(max(fb),max(tb)); % no. of buses...
nl = length(fb); % no. of branches...
Y = zeros(nb,nb); % Initialise YBus...

% Formation of the Off Diagonal Elements...
for k = 1:nl
    Y(fb(k),tb(k)) = Y(fb(k),tb(k)) - y(k)/a(k);
    Y(tb(k),fb(k)) = Y(fb(k),tb(k));
end

% Formation of Diagonal Elements....
for m = 1:nb
    for n = 1:nl
        if fb(n) == m
            Y(m,m) = Y(m,m) + y(n)/(a(n)^2) + b(n);
        elseif tb(n) == m
            Y(m,m) = Y(m,m) + y(n) + b(n);
        end
    end
end
end
%Y; % Bus Admittance Matrix
%zbus = inv(Y); % Bus Impedance Matrix
```

Appendix H: MATLAB Code for cost calculation

```
function C = costOf(caps)

len = length(caps);
costs = zeros(1,len);
cap = ceil(caps*100);
```

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```
for i=1:len
    switch cap(i)
        case 0
            costs(i) = 0;
        case 1
            costs(i) = 1750;
        case 2
            costs(i) = 1800;
        case 3
            costs(i) = 1850;
        case 4
            costs(i) = 1925;
        case 5
            costs(i) = 2050;
        case 6
            costs(i) = 2200;
        case 7
            costs(i) = 2650;
        case 8
            costs(i) = 2950;
        case 9
            costs(i) = 3450;
        case 10
            costs(i) = 4200;
        case 15
            costs(i) = 4500;
        case 20
            costs(i) = 5250;
        case 25
            costs(i) = 5700;
        case 30
            costs(i) = 6300;
        case 35
            costs(i) = 7050;
        case 40
            costs(i) = 7600;
        case 45
            costs(i) = 8150;
        case 50
            costs(i) = 8650;
        case 55
            costs(i) = 9100;
        case 60
            costs(i) = 9450;
        case 65
```

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```
costs(i) = 10000;
case 70
costs(i) = 10450;
case 75
costs(i) = 10800;
case 80
costs(i) = 11250;
case 85
costs(i) = 11700;
case 90
costs(i) = 12350;
case 95
costs(i) = 12850;
case 100
costs(i) = 13400;
case 105
costs(i) = 13950;
case 110
costs(i) = 14400;
case 120
costs(i) = 15250;
case 130
costs(i) = 15850;
case 140
costs(i) = 16500;
case 150
costs(i) = 17250;
case 160
costs(i) = 18000;
case 170
costs(i) = 18700;
case 180
costs(i) = 19450;
case 190
costs(i) = 20125;
case 200
costs(i) = 20800;
case 210
costs(i) = 21550;
case 220
costs(i) = 22200;
case 230
costs(i) = 22950;
case 240
costs(i) = 23600;
case 260
```

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```
        costs(i) = 24900;
    case 270
        costs(i) = 25550;
    case 280
        costs(i) = 26400;
    case 290
        costs(i) = 27125;
    case 300
        costs(i) = 27800;
    otherwise
        costs(i) = cap(i)*95;
    end
end
C = sum(costs);
end
```

Appendix I: Costs of different FACTS Controller [50]

FACTS Controller	Costs (USD)
STATCOM	\$34/kVAr
SVC	\$26/kVAr
TCSC	\$47/kVAr
UPFC	\$37/kVAr

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Appendix J: Size and Cost of Capacitors [48]

Capacitor (kVAr)	Cost (\$)	Capacitor (kVAr)	Cost (\$)	Capacitor (kVAr)	Cost (\$)
10	1750	1100	14400	4000	35000
20	1800	1200	15250	4100	35775
30	1850	1300	15850	4200	36500
40	1925	1400	16500	4300	37300
50	2050	1500	17250	4400	38000
60	2200	1600	18000	4500	38750
70	2650	1700	18700	4600	39400
80	2950	1800	19450	4700	40050
90	3450	1900	20125	4800	40800
100	4200	2000	20800	4900	41425
150	4500	2100	21550	5000	42550
200	5250	2200	22200	5100	43000
250	5700	2300	22950	5200	43350
300	6300	2400	23600	5300	43700
350	7050	2500	24350	5400	44150
400	7600	2600	24900	5500	44500
450	8150	2700	25550	5600	44950
500	8650	2800	26400	5700	45350
550	9100	2900	27125	5800	45900
600	9450	3000	27800	5900	46300
650	10000	3100	28550	6000	46750
700	10450	3200	29200	6100	47050
750	10800	3300	29950	6200	47350
800	11250	3400	30650	6300	47700
850	11700	3500	31400	6400	48150
900	12350	3600	32100	6500	48400
950	12850	3700	32850	6600	48750
1000	13400	3800	33500	6700	49000
1050	13950	3900	34250	6800	49350

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Capacitor (kVAr)	Cost (\$)
6900	49450
7000	49750
7100	50050
7200	50300
7300	50650
7400	51025
7500	51250
7600	51700
7700	51850
7800	52000
7900	52200
8000	52550
8100	52800
8200	53050
8300	53150
8400	53300
8500	53550
8600	53650
8700	53850
8800	53900
8900	54000
9000	54150
9100	54350
9200	54500
9300	54675
9400	54800
9500	54950
9600	55100
9700	55250
9800	55400
9900	55650
10,000	55800

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Appendix K: Bus number and Line name

<i>BUS NUMBER</i>	<i>LINE NAME</i>	<i>BUS NUMBER</i>	<i>LINE NAME</i>
1	G/Gibe III-400kV	35	Bedele-230kV
2	Wolytasodo -400kV	36	Metu-230kV
3	G/Gibe II-400kV	37	Gambela-230kV
4	G/Gibe I-400kV	38	Humera-230kV
5	Sebeta -400kV	39	Welkayite-230kV
6	B/Dar -400kV	40	E/sillasie-230kV
7	D/Markos -400kV	41	Axum-230kV
8	Sululta -400kV	42	Tekeze-230kV
9	Gelan -400kV	43	Mekele-230kV
10	Beles-400kV	44	Ashegoda-230kV
11	Gonder-230kV	45	Alamata-230kV
12	B/Dar II-230kV	46	Mehoni-230kV
13	Shehedi -230kV	47	N/Mewucha-230kV
14	Mota -230kV	48	Gashana-230kV
15	D/Markos -230kV	49	Combolcha II-230kV
16	Fincha -230kV	50	Semera-230kV
17	Fincha II -230kV	51	Dichito-230kV
18	Amerti Neshe -230kV	52	D?Birhan-230kV
19	Ghedo -230kV	53	Sinostseel-230kV
20	Gefersa -230kV	54	Koka-230kV
21	Sululta -230kV	55	Awash town-230kV
22	Shegole -230kV	56	D/Dawa-230kV
23	Ginchi -230kV	57	Hurso-230kV
24	Sekoru -230kV	58	Adigala-230kV
25	Chancho -230kV	59	Djibubti-230kV
26	Torhayloch -230kV	60	M/Wakena-230kV
27	Sebeta-230kV	61	M/W/Yugo-230kV
28	Wolkite -230kV	62	Ramo-230kV
29	Sebeta II -230kV	63	Gode-230kV
30	Hosaina -230kV	64	Adama Wind-230kV
31	Alaba -230kV	65	Galan-230kV
32	G/Gibe-230kV	66	L/Tafo-230kV
33	Jimma -230kV	67	Cotobe new-230kV
34	Agaro -230kV	68	Kaliti-230kV