

**A Study of Distribution Line Loss Minimization and Voltage Regulation
Using Upfc by Particle Swarm Optimization (PSO) Technique: (A Case Study
in Dukem Eastern Industry Zone Distribution Line)**



SHAMBEL MEBRATIE

A Thesis Submitted to the Department of Electrical Power and
Control Engineering

College of Electrical Engineering and Computing

Presented in Partial Fulfillment of the Requirement for the Degree of Master's in
Power System Engineering

Office of Graduate Studies

Adama Science and Technology University

October, 2025

Adama, Ethiopia

A study of Distribution Line Loss Minimization and Voltage Regulation Using UPFC By Particle Swarm Optimization (PSO) technique: (A Case Study in Dukem Eastern Industry Zone Distribution Line)

Shambel Mebratie Dagne

Advisor

Dr. Kena Likassa (Ph.D.)

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DECLARATION

I hereby declare that this dissertation entitled “**A study of Distribution Line Loss Minimization and Voltage Regulation Using UPFC By Particle Swarm Optimization (PSO) technique: (A Case Study in Dukem Eastern Industry Zone Distribution Line)**” is my original work. That is, it has not been submitted for the award of any academic degree, diploma, or certificate in any other university. All sources of materials that are used for this thesis have been duly acknowledged through appropriate citation.

Shambel Mebratie Dagne

Name of the student

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RECOMMENDATION

I, the advisor of this thesis, hereby certify that I have read the revised version of the dissertation entitled “**A Study of Distribution Line Loss Minimization and Voltage Regulation Using UPFC By Particle Swarm Optimization (PSO) technique: (A Case Study in Dukem Eastern Industry Zone Distribution Line)**” prepared under my guidance by Shambel Mebratie submitted in partial fulfillment of the requirements for the degree of **Master** of Science in Power System Engineering.

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

Dr. Kena Likisa (Ph.D.)

Name of Advisor

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APPROVAL PAGE

I the Advisor, hereby certify that the recommendation and suggestion given by board of examiners are appropriately incorporated into the final version of dissertation entitled “A Study of distribution Line Loss Minimization and Voltage Regulation Using UPFC (Facts device) By Particle Swarm Optimization (PSO) technique: - A Case Study in Dukem Eastern Industry Zone (Substation) Distribution Line” by Shambel Mebratie.

Advisor

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Date

APPROVAL OF BOARD EXAMINERS

We, the undersigned, members of the Board of Examiners of the thesis open defense by Shambel Mebratie have read and evaluated the thesis entitled “A Study of distribution Line Loss Minimization and Voltage Regulation Using UPFC (Facts device) By Particle Swarm Optimization (PSO) technique: - A Case Study in Dukem Eastern Industry Zone (Substation) Distribution Line” and assessed the understanding of the candidate during thesis defense. This is, therefore, to certify that the dissertation is accepted for partial fulfilment of the degree requirement in MSc in electrical power engineering.

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LIST OF ABBREVIATIONS

| | |
|-----------|--|
| ABC | Artificial Bee Colony |
| ACO | Ant Colony Optimization |
| ANFIS | Adaptive Neuro-Fuzzy Inference System |
| BCBV | Branch Current Bus-Voltage |
| BIBC | Branch Injected Bus-Current |
| DGs | Distribution Generators |
| D-STATCOM | Distribution Static Compensator |
| DT | Distribution Transformer |
| FBLFA | Forward Backward Load Flow Analysis |
| GA | Genetic Algorithm |
| kWh | Kilo Watt hour |
| OPF | Optimal Power Flow |
| Pf | Power factor |
| PGSA | Bionic Random Search Plant Growth Simulation Algorithm |
| PLI | Power Loss Index |
| PSO | Particle Swarm Optimization |
| Pu | Per unit |
| RDS | Radial Distribution System |
| SSSC | Static Synchronous Series Compensator |
| STATCOM | Static Compensator |
| UPFC | Unified power flow controller |
| VSI | Voltage Stability Index |
| VSC | Voltage Source Convertor |

ABSTRACT

This study addresses critical performance issues, specifically poor voltage regulation and high-power loss, found in Feeder 5 of the Dukem Eastern Industry Zone (EIZ) substation, which operates within Ethiopia's radial power network. Initial analysis revealed that most bus voltages were unacceptably low (dropping to 0.915 p.u.), accompanied by significant power losses totaling 1,315.91 kW of active power and 700.63 kVAR of reactive power. To mitigate these problems and enhance system efficiency, the research proposed integrating a Unified Power Flow Controller (UPFC). The optimal placement and sizing of the UPFC were determined using the Particle Swarm Optimization (PSO) algorithm. The system was simulated in MATLAB, and the results demonstrated the solution's success: the total active power loss was substantially reduced to 576.79 kW, and reactive power loss dropped to 398.82 kVAR. Furthermore, the voltage profiles across all weak buses were significantly improved, successfully bringing them back within the standard operational range to ensure high-quality power delivery to consumers.

Keywords: UPFC placement, PSO, Radial distribution system, Power loss minimization, Voltage regulation, MATLAB

CHAPTER ONE

INTRODUCTION

1.1 Background of the Study

The distribution system begins at substations, which receive power from high-voltage transmission lines. Its main purpose is to deliver electricity from these substations to end-users (J.J.Grainger and S. Civanlar l. , 1985). In a typical power system, the distribution network is the largest and most widespread component.

In Ethiopia, sub-transmission systems operate at voltages of 66 kV and 45 kV, while distribution systems use 33 kV and 15 kV. At the 66 kV or 45 kV substations, various power transformers (with ratings such as 25, 12, 6.3, or 3 MVA) decrease the voltage to 33 kV or 15 kV to supply distribution transformers (DTs). The Dukem Eastern Industry Zone (EIZ) distribution network, for example, is configured in a radial pattern, with 33 kV overhead conductors supplying power to DTs along each feeder. Therefore, the voltage is again deduced by the DTs to the user-level voltage.

Efficiently operating a power distribution network is crucial for a dependable electricity supply. But these systems face common issues like power loss, unstable voltage, and poor voltage profiles. These problems are often caused by things like changing loads, system faults, and reactive power imbalances.

To address these issues, engineers are increasingly employing Flexible AC Transmission System (FACTS) devices. Among them, the Unified Power Flow Controller (UPFC) stands out. It is regarded as one of the most versatile and powerful FACTS devices because it can simultaneously regulate voltage magnitude, phase angle, and line impedance. By combining both shunt and series compensation in one unit, the UPFC can inject both active and reactive power as needed. This helps improve voltage profiles, cut down on line losses, and boost overall voltage stability. Because it responds quickly and can handle multiple functions at once, the UPFC is a great tool for improving dynamic power quality in distribution networks (Ng, 2000)

To get the most out of Unified Power Flow Controllers (UPFCs) in a distribution network, their optimal placement and sizing are key. The right placement and capacity can significantly cut down on power losses, fix voltage deviations, and generally improve how the system performs. The challenge of UPFC allocation is all about finding the best spots and capacities for these devices to meet specific operational goals. A powerful and efficient method for tackling this is Particle Swarm Optimization (PSO). This algorithm mimics the social behavior of flocks of birds or schools of fish. It works with a group of potential solutions (called "particles") that search the problem's solution space. These particles adjust their positions based on their own past successes and the successes of the entire group. PSO is popular for power system optimization because it's simple, converges quickly, and is effective at solving complex, non-linear, and multi-objective problems such as UPFC allocation. (E.G, 2003)

1.2 Statement of the problem

The Ethiopian government is currently working on expansion of industrial parks and building smart city. The projects need reliable power system, but, the national power system is under high rate of power loss due to lack of proper controlling and management. If this problem is not handled it causes brings extra cos for building or improving the generation system. To resolve this problem at national level building smart grid technology and using renewable energy source is crucial.

Therefore, Dukem Eastern Industry Zone (EIZ) also facing by power loss, power interruption, low voltage profile, and mis much of supply and demand at Dukem substation. The problem is not only on the distribution center it is big challenge for the industries it causes under voltage, failure of equipment functioning, total damage of factories and disagreement utility services and the factory owners. However, this thesis focused on the technical loss minimization by modeling appropriate UPFC through particle swarm optimization technique

Additionally, distribution networks are frequently affected by voltage instability and inadequate voltage regulation due to load variability, system faults, and reactive power imbalances. These issues necessitate the strategic deployment of UPFCs to enhance voltage stability, maintain voltage levels within permissible limits, and ensure reliable power delivery. The placement and sizing of UPFCs are thus critical for maximizing their effectiveness in addressing these technical challenges.

Solving this allocation problem requires a robust optimization approach that can handle the non-linear, multi-objective, and constrained nature of the power system environment. PSO is proposed as an effective methodology for this task. Inspired by the social behavior of swarms in nature, PSO offers a population-based search mechanism capable of efficiently identifying optimal UPFC placements and capacities. The optimization process considers key technical constraints such as voltage levels, UPFC capacity limits, and the radial topology of the distribution network. By applying PSO, the methodology aims to achieve significant reductions in power losses and improvements in voltage profiles, while balancing computational efficiency and cost-effectiveness.

1.3 Objectives of the study

1.3.1 General objective

The main objective of this thesis is to minimize distribution line loss and regulate system voltage profile using UPFC (FACTS devices) with MATLAB/Simulink in Dukem Eastern Industry Zone (substation), distribution line using Particle swarm optimization technique

1.3.2 Specific objectives

- To analyze the existing distribution network's performance, focusing on load flow characteristics, system voltage profiles, and power losses. (Combines the investigation and diagnosis of the current system's capabilities and deficiencies.)
- To develop and model the control strategies for the Unified Power Flow Controller (UPFC) within the distribution center.
- To formulate and simulate a Particle Swarm Optimization (PSO) model for determining the optimal placement and sizing of the UPFC within the network.
- To evaluate the impact of the optimally placed UPFC on system performance metrics, including the reduction of total power losses and the improvement of bus voltage profiles, using MATLAB/Simulink. (Focuses on the measurable results and comparison.)
- To assess the economic acceptability and feasibility of the proposed UPFC implementation for the formulated system.

1.4 Significance of the Study

The study has a big significance for all the industrial zones, end users and utility services.

- It aims to ensure reliable power supply to meet the growing demand at optimal efficiency and reduced operational costs.
- The reduction in energy losses directly contributes to cost savings and improved energy utilization. Maintaining higher system voltage levels can result in increased energy delivery (kWh), thereby generating additional revenue.
- Lower peak power losses also yield indirect economic benefits by reducing the need for system reinforcements and lowering stress on infrastructure.
- The study contributes to the resolution of key power quality issues, including voltage instability and excessive line losses.
- Moreover, it serves as a valuable reference for future research focused on distribution network optimization and the application of intelligent algorithms such as PSO in enhancing network performance.

The primary objective of this study is to evaluate the performance of the Dukem Eastern Industry Zone (EIZ) distribution line network and propose a solution to its performance issues. The research specifically includes the following key activities:

1.5 Scope of the Study

The scope of this research to assess Dukem EIZ distribution line networks. This study is covered the following scopes.

- Load Flow Analysis: Performing a load flow analysis of the system using the forward-backward method in MATLAB, in base case and after the application of a compensation device.
- UPFC Optimization: Determining the precise allocation and size of Unified Power Flow Controllers (UPFCs) using the Particle Swarm Optimization (PSO) technique within MATLAB.

- **Performance Improvement:** Focusing on reducing the system's total power loss and improving voltage regulation by enhancing the voltage profiles across the network.
- **Economic Analysis:** Quantifying the financial savings achieved through the use of these compensation devices.

This research centers on minimizing power loss and improving the voltage profile within the Dukem EIZ distribution system by using the Particle Swarm Optimization (PSO) algorithm to determine the optimal placement and sizing of a Unified Power Flow Controller (UPFC). The study demonstrates the effectiveness of this solution by comparing simulation results of the system's performance both with and without the UPFC. A key limitation of this work is its exclusive focus on a single 33 kV feeder within the Dukem EIZ network, and the analysis relies entirely on simulation modeling without involving any practical physical implementation.

1.6 Methodology

The proposed methodology consists of the following steps:

- **Problem Identification:** The initial phase involved a thorough assessment of the existing distribution network to pinpoint key problems, such as high-power losses and poor voltage profiles. This step laid the groundwork for proposing a viable solution.
- **Literature Review:** A comprehensive review of relevant literature was conducted. This included examining academic journals, books, and other documents to understand previous research and established techniques in the field.
- **Data Collection and Analysis:** All necessary input data, including distribution line data and load information was collected to perform a load flow analysis. Using this data, simulations were run in MATLAB to conduct a load flow analysis both before and after the optimal placement of the UPFC within the selected feeder network.
- **Modeling of the system:** System Modeling is the first step to develop a mathematical model of UPFC and the low voltage distribution network. The model should include the network topology, load data, and other relevant parameters. Modeling and simulation of radial distribution system using MATLAB algorithm of PSO.
- **Results Analysis:** The final step is to analyze the results obtained from the PSO. The analysis should include the following:

- Comparison of the power loss and voltage deviation before and after the allocation of UPFC.
 - Comparison of the cost of UPFC installation before and after the allocation.
- **System evaluation and conclusion:** Evaluate whether the proposed method meets its general objective. Finally, present conclusions and recommendations regarding the proposed method.

CHAPTER TWO

LITERATURE REVIEW

2.1 Literatures

Different researcher has investigated various methods to improve the efficiency of power distribution networks. These techniques primarily aim to reduce power and energy losses and enhance the voltage profile. These solutions often fall into a few categories, Some methods assume fluctuating loads, while others assume fixed loads. The most common approaches involve either reconfiguring the network or optimally placing compensation devices. A smaller number of studies have attempted to combine both reconfiguration and compensation to achieve both goals at the same time.

(Abdullah & Musirin, 2010) Proposes a UPFC injection model for power flow analysis. This model simplifies integration with the Newton-Raphson method, a common power flow solving method. The study demonstrates UPFC's capability to control power flow and minimize loss simultaneously. The focus might have been on establishing the UPFC injection model's effectiveness in a steady-state analysis framework. Real-time analysis can be computationally expensive, and the paper might have aimed for a simpler model for initial evaluation. There's potential to explore how the UPFC injection model can be adapted for real-time analysis, incorporating dynamic system behavior.

Overall, the concept presented in the paper is a good starting point for understanding how UPFCs can be modeled and utilized in power flow studies for loss minimization. Further research could explore its application in real-time scenarios for even more efficient power system management.

(Kowsalya, 2009) This paper employs the Particle Swarm Optimization (PSO) method to determine the optimal location for installing a UPFC. The objective is to reduce power loss and enhance voltage stability. The study formulates this as an optimization problem, using stability indicators such as nodal analysis and the Voltage Phasor method to identify the best UPFC placement. It also incorporates minimizing power loss as a key target. To validate the approach, the IEEE-14 and IEEE-57 bus systems were utilized. The paper concludes that the PSO algorithm is effective in reducing real power loss through optimal UPFC positioning. However, a potential

limitation of this method is that it depends entirely on evolutionary optimization techniques to locate the UPFC.

(Ndubuka Nw, 2010) Proposes a method to find the optimal UPFC location based on total system active power loss sensitivity. He develops a UPFC injection model control system and analyzes its impact on voltage stability in a multi-machine test system using MATLAB/Simulink. The study aims to enhance voltage stability and transient/dynamic control through optimal placement. The paper focuses on sensitivity analysis of total active power loss as a deciding factor for UPFC placement. While this is important, it might not capture all aspects of optimal placement. Minimizing active power loss doesn't necessarily guarantee an optimal voltage profile throughout the grid System constraints: Optimal placement should consider grid limitations like thermal overloading of transmission lines. Develop a multi-objective optimization approach that considers both active power loss minimization and voltage profile improvement. Integrate system constraints into the sensitivity analysis for a more holistic view of optimal placement.

Overall, Nwohu approach provides a valuable finding for UPFC placement in the Nigerian grid. By incorporating additional factors and using multi-objective optimization techniques, the methodology can be further developed for even more effective grid management.

(T. Yuvaraj, sep.2015) Introduced a novel scheduling approach for the efficient positioning and sizing of D-STATCOM (Distribution Static Compensator) in radial distribution networks, aiming to minimize power losses. The method employs the Voltage Stability Index to identify the most suitable locations for installing D-STATCOM. Additionally, the optimal size of D-STATCOM is determined using the bat algorithm. The simulation results are verified using two standard radial distribution systems, namely IEEE 33 and 69 bus networks. However, it is worth noting that the cost of the device is not taken into account during the installation process of the system.

(A. Ram and A. Kumar, 2015) Stated the best position and size for D-STATCOM in radial distribution networks to reduce losses, enhance voltage profiles, and save energy. The method's effectiveness is assessed through its application to IEEE 33-bus radial distribution systems. The results demonstrate significant reductions in losses and improvements in voltage profiles. However, it is important to note that the study solely relies on analytical techniques and does not employ artificial intelligence optimization methods for the allocation and sizing of D-STATCOM.

In 2020, (Z. Muslimin, 2020) he conducted improving of the performance of the distribution network by enhancing the profile of voltage and reducing the total active power loss through the best placement of D-STATCOM devices. The optimization process uses the Optimal Power Flow (OPF) method, which is based on Particle Swarm Optimization (PSO). In this paper, the study does not include an analysis of reactive power loss during the system simulation.

(M. Padma Lalitha*, December 2010) The study proposed two approaches, one based on fuzzy logic and the other using the Artificial Bee Colony (ABC) technique. These methods aim to enhance the efficiency of the radial distribution system by minimizing active power loss and improving voltage levels. In the first step, fuzzy logic is applied to identify the optimal location for distributed generators (DGs) in the most sensitive area of the network. In the second step, the Artificial Bee Colony algorithm is utilized to determine the most suitable location, size, and number of DGs in the system to achieve maximum reduction in power loss. One advantage of this method is that it does not require additional parameters such as crossover rate or mutation rate, which are typically used in genetic algorithms and differential evolution. This approach also provides better performance in terms of solution quality and the speed of solving the problem. The results were tested and validated using the standard IEEE 33 bus test system.

(Tanuj Manglani, September 2012) A new algorithm was introduced to reduce power losses in distribution lines using the Bionic Random Search Plant Growth Simulation Algorithm (PGSA). This method uses loss sensitivity factors to identify the best allocation for adding capacitors in the distribution network. The PGSA helps find the right amount of shunt capacitors to place at these best spots, which helps cut down active power loss while following system rules. The method has some benefits, like needing fewer settings, being easy to code and use, working quickly, and not requiring special conditions to solve the problem. It also takes into account the yearly savings from using the device. The results were tested and shown on the standard IEEE 34 bus test system.

In (Mohamed, 2013) presented another technique that is fuzzy logic based coordinated voltage control for distribution network with distributed generations. The connection of DGs have made it harder for distribution network operators to keep the voltage in the system within safe levels. The

method uses three control technique power factor control, on load tap changer control, and generation curtailment control to make the radial distribution system more manageable

(Anastasia S.Safigianni, May 2000.) The proposed backtracking algorithm optimizes the number, location, and tap settings of voltage regulators to maintain the voltage profile within acceptable limits, reduce power losses in the radial distribution system (RDS), and maximize net savings in system operation. Additionally, a fuzzy technique method was suggested, and its results were compared with those of the backtracking algorithm. The findings show that the fuzzy expert system (FES) also determines the optimal number, location, and tap settings of voltage regulators. The FES provides better voltage regulation, lowers power losses, and increases net savings when compared to the backtracking algorithm. Both methods were tested on a radial distribution system with 47 buses, and the results were presented.

(Prasanna, 2014), formulate a technique for reducing power loss and improving the voltage profile was proposed by optimally allocating and sizing distributed generation (DG) using a genetic algorithm. A multi-objective function was formulated by combining a power loss reduction index and a tail-end node voltage deviation index, weighted by specific factors. The system was tested on the standard IEEE 33 and 69-bus radial distribution networks using MATLAB software. The results show that the method effectively reduces power loss and enhances the voltage profile. However, the study does not address the impact of distributed generation on reactive power loss and reliability. Additionally, it does not consider the environmental impact or the stochastic nature of DG, nor does it explore the economic feasibility or protection issues related to the injection of distributed generation.

(S. M. Myint and S. W. Naing, 2015) provided a concise summary of reducing power losses in distribution networks to meet the growing electricity demand. The use of network reconfiguration and an exhaustive technique for minimal loss switching is emphasized. Real-time data from substations is used, and simulations are conducted with ETAP 7.5 software. The study's testing is done on a specific distribution network, and the results demonstrate improved voltage profiles and reduced power losses. Overall, the article effectively conveys the main points of the study and its findings.

In 2017 (M. Sarghandi, 2017) A new algorithm has been developed to reconfigure radial electrical networks and allocate capacitors. This method aims to reduce energy losses and improve the voltage profile of the network. The process uses an independent loop identification algorithm to find the optimal size and location for capacitors. A Genetic Algorithm is then applied to handle the network reconfiguration. The effectiveness of this new approach was verified using the IEEE 33-bus distribution test system.

Authors in 2016 N.Lad (N. Lad and P. A. Pachori, 2016) suggested on forward and backward sweep algorithm for distribution power flow analysis and comparison of different load flow methods. Power flow analysis is a critical and essential method to utilized in the examination of electrical power distribution systems, serving a crucial role in both operational and planning stages. In certain scenarios, such as distribution system automation and electrical system optimization, repeated load flow solutions are necessary. Hence, it becomes imperative to efficiently solve the power flow problem for these applications. This research paper introduces a methodological approach utilizing the forward-backward sweep technique for load flow analysis in radial distribution systems, along with a comparison of different load flow methods. The effectiveness of the proposed forward and backward sweep algorithm will be assessed using the IEEE-33 bus system as a test case.

Christopher Kigen, (Kigen, 2014) introduced optimal voltage profile in radial distribution network that incorporate distributed generation. The controller achieves this objective by adjusting the output of the distributed generators. To formulate the controller, an optimization problem was constructed and solved using Particle Swarm Optimization. The efficiency of the controller was evaluated using the IEEE 33-bus and 69-bus test networks, and the outcomes demonstrate its ability to improve the voltage profile within a power system.

Authors. (T. J. Hashim and A. Mohamed, 2013) In a recent study, researchers presented a new system that uses fuzzy logic to coordinate voltage control in a power grid that includes distributed generations (DGs). The addition of DGs to the grid makes it harder to keep the voltage at a safe level. To address this, intelligent, centralized control systems that can communicate with various network devices are becoming more popular. This particular research

looked at how to coordinate three different control methods power factor control, on-load tap changer, and generation curtailment using fuzzy logic on a test network. The results showed that this approach successfully kept the voltage within acceptable limits

2.2 The drawback of the literature review ware:

- **Limited Optimization Focus:** The primary objective of most optimization techniques is power loss reduction, with less emphasis on maximizing net savings.
- **Computational Intensity:** Many methods require a significant number of time-consuming and cumbersome load flow calculations, making them inefficient.
- **Scalability Concerns:** The applicability of these approaches to large-scale radial feeder distribution networks is often uncertain.
- **Incomplete System Analysis:** Focusing only on feeder buses or nodes with the highest power loss does not provide an accurate representation of the overall power loss across the entire system.

This study employs the Particle Swarm Optimization (PSO) method to identify the best location for a Unified Power Flow Controller (UPFC). The objective is to enhance the performance of a standard distribution network by concurrently reducing real and reactive power losses, improving the voltage profile, and maximizing the net savings achieved through the device. The proposed method was applied and evaluated under the following conditions:

- Case 1: The system's performance was analyzed without UPFC.
- Case 2: A UPFC was included and optimally placed to achieve maximum net savings, the greatest loss reduction, and the best voltage profile, all while adhering to specific constraints.

2.3 Power loss in distribution system

In an electrical grid, power loss is the inevitable waste of electrical energy that occurs during transmission and distribution. This happens when electricity flows through power lines and components like transformers and cables, as their electrical resistance converts some of that energy into heat. This inefficiency impacts the entire distribution system, from the initial power

transformers all the way to the final distribution points. Reducing this loss is a key goal for power engineers and utility companies, as it makes the system more reliable, cuts down on operational costs, and ensures a stable power supply for consumers. The overall loss is a combination of both technical and non-technical issues. (Navani J. S., 2012)

2.3.1 Technical losses

Technical loss in electrical power distribution system refers to the energy loss that occur due to physical factors and inefficiencies in the electrical infrastructure. These losses primarily result from the inherent characteristics of the equipment and components used in the distribution network. Some of the key factors contributing to technical losses include:

Resistance: The primary cause of technical losses is the resistance of conductors, transformers, and other electrical components. As electricity flows through these elements, some of the energy is converted into heat, leading to power dissipation (Navani J. S., 2012)

Transformer losses: - Power transformers, which are used to step up or step-down voltage levels, also contribute to technical losses. These losses are mainly due to core losses (hysteresis and eddy current losses) and copper losses (I^2R losses) in the windings.

Distribution lines: - Overhead lines and underground cables have inherent resistance that causes energy losses as electricity travels through them. The longer the distribution lines and the higher the current flow, the greater the technical losses.

Switching and control devices: - The operation of switches, relays, and other control devices in the distribution system introduces additional energy losses.

Reactive power: - The presence of reactive power in the system also leads to technical losses as it increases the current flow without directly contributing to useful work.

Voltage regulation: - Inadequate voltage regulation can lead to excessive energy losses in the system.

Minimizing technical losses is crucial to ensure the efficient operation of the distribution system and delivering electricity economically to consumers. Utility companies employ various measures, such as using higher capacity conductors with lower resistance, implementing efficient transformers, optimizing voltage levels, and improving system design, to reduce technical losses and improve the overall efficiency of the power distribution system.

2.3.2 Non-technical losses

Non-technical losses in a power distribution system refer to losses that occur due to factors unrelated to structural behavior of the electrical infrastructure. The losses are typically a result of theft, billing errors, tampering, or unauthorized usage of electricity. Non-technical losses can significantly impact the revenue of utility companies and can lead to financial losses and increased costs. To mitigate non-technical losses, utility companies often implement measures such as improved metering systems, better monitoring and detection techniques, and rigorous billing and auditing procedures.

2.4 Flexible AC Transmission System Devices

FACTS (Flexible AC Transmission Systems) devices are a family of advanced power electronic devices and technologies designed to increase the controllability, flexibility, and stability of AC (Alternating Current) power systems. Those devices were able for dynamic control of power flow, voltage, and reactive power in electrical grids, offering several benefits to power system operators and utilities. By incorporating FACTS devices into the power infrastructure, grid reliability and efficiency can be significantly improved.

Some key FACTS devices include (Ansari, 2017)

1. Static Var Compensator (SVC):- SVCs are used for reactive power compensation to stabilize voltage levels and improve power factor. They consist of thyristor-controlled reactors and capacitors that can quickly inject or absorb reactive power based on system needs.
2. Static Synchronous Compensator (STATCOM): STATCOMs are similar to SVCs but utilize voltage source converters instead of thyristors. This provides faster response times and better controllability, making them highly effective in voltage stability enhancement and reactive power compensation.
3. Thyristor-Controlled Series Capacitor (TCSC): TCSC devices are used to control the impedance of transmission lines, enabling the regulation of power flow and voltage profiles in the system.
4. Unified Power Flow Controller (UPFC): UPFC is a device contains of both STATCOM and TCSC functionalities. It can control true power and reactive power flow independently in electrical transmission and distribution lines, providing increased flexibility in power flow management.

5. The Interline Power Flow Controller (IPFC) is an advanced version of the Unified Power Flow Controller (UPFC). It has the unique ability to independently control both the real power and reactive power on multiple transmission lines that are connected it.
6. Static Synchronous Series Compensator (SSSC): SSSCs are used to regulate power flow in transmission lines and filter unwanted power oscillations, enhancing system quality.

The use of FACTS (Flexible AC Transmission Systems) devices provides significant benefits for power grids. By dynamically controlling power flow and voltage, these devices improve voltage stability, increase transmission capacity, and reduce transmission losses. They also enhance the overall controllability of the grid and allow for better use of existing infrastructure. Ultimately, FACTS devices are crucial for maintaining the reliability and efficiency of modern power systems, particularly as more renewable energy sources are integrated into increasingly complex grid configurations.

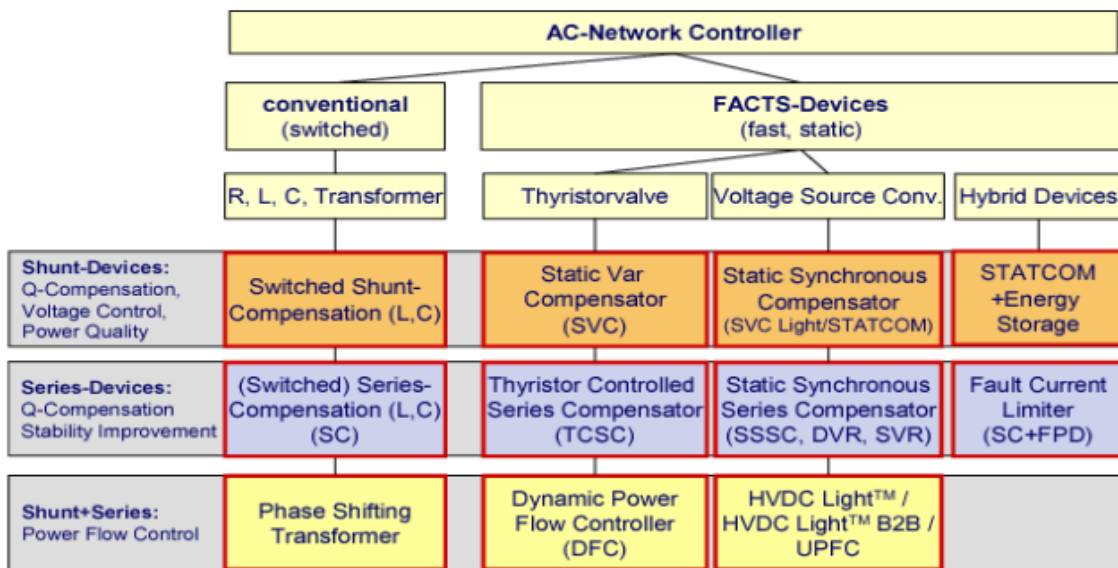


Figure 2.1: Overview of FACTS Devices

2.5 Unified power flow controller (UPFC)

UPFC has two voltage source converters (VSC) connected through a shared DC link capacitor. VSC-1 is connected to the transmission line through a shunt transformer, while VSC-2 is connected via a series transformer as shown in figure3.2. This common DC link allows real power to flow in either direction between the AC sides of the two converters. Each converter can

independently produce or absorb reactive power, and there is no power transfer between them because the DC capacitor does not carry reactive power. VSC-1 can generate or absorb reactive power and functions like a STATCOM. If the voltage magnitude (E_s) is high, reactive power is generated, and if it's low, reactive power is absorbed. The phase difference between voltage and current determines whether real power is generated or absorbed by VSC-1. VSC-2 works like an SSSC and exchanges real power if the injected voltage is in phase with the line current. If the voltage and current are out of phase, reactive power is exchanged.

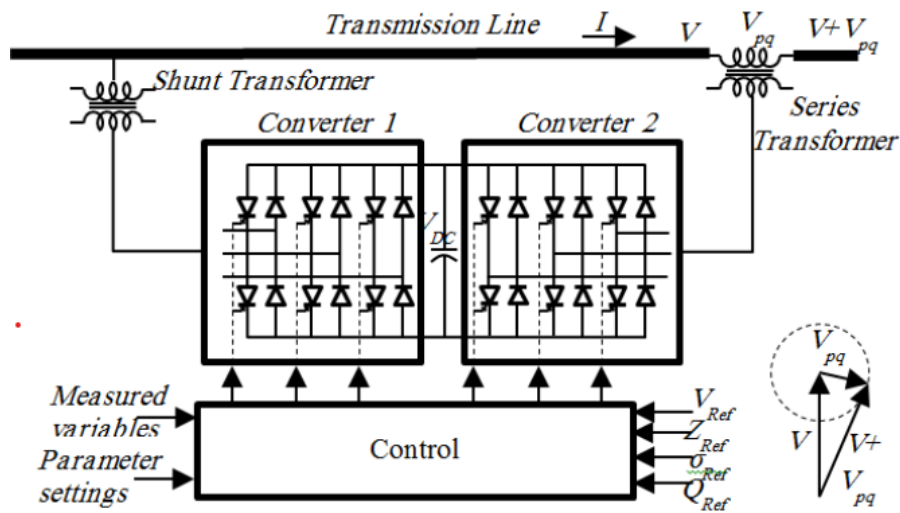


Figure 2.2 Block Diagram of UPFC

A key device in Flexible Alternating Current Transmission Systems (FACTS), the Unified Power Flow Controller (UPFC) is highly effective at managing power flow. It stands out by being able to control both power systems simultaneously, which helps to optimize power transmission and distribution efficiency and stability. The UPFC provides two main types of control: Shunt compensation regulates voltage, ensuring consistent power delivery. Series compensation improves the stability and capacity of power lines, creating a more reliable power grid

Phase Shifting: UPFCs meticulously control the phase angle between voltage and current, facilitating optimized power flow across the network. Voltage Profile Improvement: They actively maintain consistent voltage levels, preventing disruptive fluctuations that can damage equipment and degrade service quality. Power Flow Control: UPFCs empower system operators to precisely

direct power flow along designated paths within the grid, maximizing efficiency and minimizing losses.

UPFCs stand out for their exceptional degree of control over fundamental power system parameters. They can simultaneously manipulate distribution voltage, impedance (encompassing both resistance and reactance), and phase angle. This unparalleled level of influence allows for meticulous optimization of the entire power grid, ensuring its smooth and efficient operation.

The study referenced here leverages the combined strengths of a Static Synchronous Compensator (STATCOM) and a Static Synchronous Series Compensator (SSSC) within a single UPFC unit. This innovative approach enables the system to simultaneously minimize distribution line losses and precisely regulate voltage, achieving optimal performance across multiple aspects of power transmission.

UPFCs represent a cornerstone technology within the FACTS family. Their unmatched versatility, comprehensive control over power system parameters, and ability to address a wide range of challenges solidify their position as a critical tool for ensuring efficient, stable, and reliable power transmission in modern electrical grids. (Kalyani, 2014)

2.6. Voltage stability improvement

Voltage stability improvement refers to the measures taken to maintain a stable and reliable voltage level in a power system, particularly during varying load conditions or disturbances. Voltage stability is crucial to ensure the smooth operation of the electrical grid and to prevent voltage collapse, which can lead to widespread power outages (N. Goyal and P. Singh, 2014,).

To enhance voltage stability, power system operators and utilities implement various strategies and technologies, including:

- **Reactive Power Compensation:** Installing devices such as capacitors and reactors to supply or absorb reactive power can help regulate voltage levels and maintain stability.
- **Voltage Regulation Devices:** Automatic voltage regulators (AVRs) and tap changers on transformers are essential for adjust the voltage output and keep it within standard levels.
- **Load Shedding:** In extreme situations, when voltage stability is at risk, controlled load shedding can be employed to reduce the demand and prevent system collapse.

- **Power Factor Correction:** Improving power factor by minimizing reactive power consumption helps stabilize voltage levels and optimize power utilization.
- **FACTS (Flexible AC Transmission Systems) Devices:** FACTS devices like Static Var Compensators (SVC) and Static Synchronous Compensators (STATCOM) are employed to provide rapid voltage support and improve voltage profile.
- **Enhanced Monitoring and Control:** Advanced monitoring and control systems help identify potential voltage instability issues in real-time, allowing for timely intervention.
- **Smart Grid Technologies:** Implementing smart grid technologies enables more efficient and dynamic management of power flow, leading to improved voltage stability.

Voltage stability improvement is a critical aspect of power system operation, and utilities continuously work to ensure reliable and stable voltage levels to meet the demands of consumers and maintain grid integrity (Haq, 2023)

2.7. Enhancing voltage profile

Power system operators are responsible for keeping customer voltage levels within a safe range, typically within a $\pm 5\%$ deviation. To help with this, many power companies are using Unified Power Flow Controllers (UPFCs). These devices improve voltage profiles by changing how power flows through the system. However, for a UPFC to be effective, its placement and size must be carefully chosen, (A. S. Siddiqui and F. Rahman, 2012.).

CHAPTER THREE

MATERIALS AND METHODS

3.1 Methodology

In this thesis, power flow analysis were analyzed in Dukem 33kv -42 buses radial feeder network under constant operating/functioning conditions. The analysis utilizes the Forward-Backward Load Flow Algorithm (FBLFA) implemented in MATLAB. The primary objective is to identify voltage-sensitive buses suitable for compensation, thereby enhancing the system's overall performance. The work involves a sequence of tasks, beginning with a review of relevant literature and progressing through simulation of the systems and networks with optimally placed and sized UPFC devices.

To execute the explained problem in the objectives: - distribution line loss minimization problem in proposed area, the following methodology procedures are conducted.

- **Problem Identification:** The initial phase involved a thorough assessment of the existing distribution network to pinpoint key problems, such as high-power losses and poor voltage profiles. This step laid the groundwork for proposing a viable solution.
- **Literature Review:** A comprehensive review of relevant literature was conducted. This included examining academic journals, books, and other documents to understand previous research and established techniques in the field.
- **Data Collection and Analysis:** All necessary input data, including distribution line data and load information was collected to perform a load flow analysis. Using this data, simulations were run in MATLAB to conduct a load flow analysis both before and after the optimal placement of the UPFC within the selected feeder network.
- **Modeling of the system:** System Modeling is the first step to develop a mathematical model of UPFC and the low voltage distribution network. The model should include the network topology, load data, and other relevant parameters. Modeling and simulation of radial distribution system using MATLAB algorithm of PSO.
- **Results Analysis and Evaluation:** The final step is to analyze the results obtained from the PSO. The analysis should include the following:

- Comparison of the power loss and voltage deviation before and after the allocation of UPFC.
 - Comparison of the cost of UPFC installation before and after the allocation.
- **conclusion and conclusion:** Evaluate whether the proposed method meets its general objective. Finally, present conclusions and recommendations regarding the proposed method

In this section, first, the general methodology applied to accomplish the objective of this thesis work as shown in Figure 3.1 is demonstrated briefly.

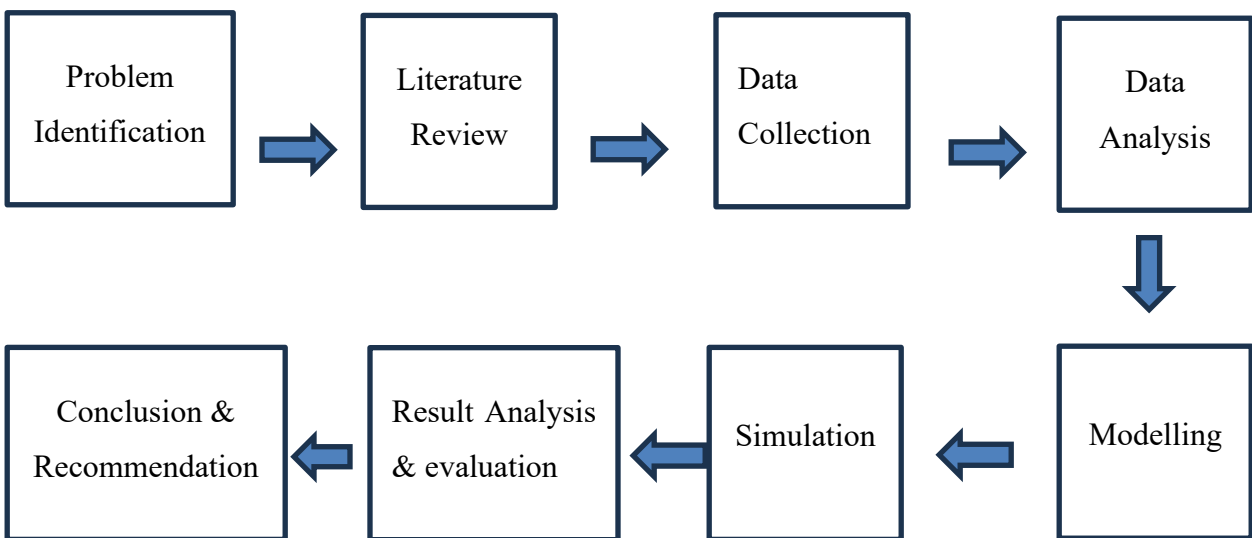


Figure 3.1 work flow diagram

3.1.1 Explanation of the case study in EIZ

, Dukem Eastern Industry Zone (EIZ) also facing by power loss, power interruption, low voltage profile, and mis much of supply and demand at Dukem substation. Ther was around 106 outages of feeders most of the problems was asymmetrical faults. The problem is not only on the distribution center it is big challenge for the industries it causes under voltage, failure of equipment functioning, total damage of factories and disagreement utility services and the factory owners. However, this thesis focused on the technical loss minimization by modeling appropriate UPFC through particle swarm optimization technique

| Types of faults | Occurrences |
|----------------------|-------------|
| Ground fault | 23 |
| Over current fault | 35 |
| Line to line fault | 33 |
| Line to ground fault | 13 |
| Under voltage fault | 2 |

Table 3.1 types of occurred faults

3.1.2 Literature Review

Literature reviewing was the initial step in executing this thesis work. A review on the terms, definitions, causes and effects of losses in distribution line of the substation, types of losses, distribution line loss minimization techniques for medium power distribution had been given a wide coverage in the literature review part.

3.1.3 Data Collection

The area selected for this thesis study were in Dukem Eastern Industry Zone (EIZ) 33 kV distribution system. Data was collected from the Ethiopian Electric Utility (EEU) covering a six-month period from October to March, allowing analysis of load behavior under various seasonal conditions. The collected data includes feeder-wise current levels, power factor, and calculated values for real/ true power (KW), Apparent (KVA), and reactive power (KVAR).

The Dukem EIZ substation comprises several outgoing feeders; however, Feeder 1 and Feeder 4 are currently non-operational, and therefore, no data is available for them during the monitoring period. The analysis is thus focused on Feeder 2, 3, 5, 6, 7, and 8, which are actively supplying loads within the industrial zone.

Among these, Feeder 3 and Feeder 8 show the highest loading levels, with current readings exceeding 500 A and corresponding apparent power peaking over 28,000 kVA, indicating a dense concentration of industrial activities. In contrast, Feeder 6, although active, demonstrates a notably low power factor (as low as 0.596), which signals poor reactive power support and possible voltage regulation issues.

Fluctuations in load demand are evident across the months for all feeders, particularly Feeder 5 and Feeder 8, which experience significant variations. This suggests the presence of intermittent or shifting industrial loads, necessitating dynamic voltage and power flow control solutions.

Table 3.1 shows feeders current reading and the six-month peak load data of outgoing feeders. These source data were gathered from EEP during registration of peak loading condition

For this thesis work primary data and secondary data was collected from EEU. The collected data includes line impedance, line reactance, line length, bus nominal voltage, reactive and active power flow, transformers data, actual voltage level of the line and peak load data of the transmission network of case study

| Substation name | Feeder | Voltage ratio [kV] | power factor | Oct-25 | Nov 24 | Dec-25 | Jan-25 | Feb-25 | Mar-25 |
|-----------------|----------|--------------------|--------------|-------------|-------------|-------------|-------------|-------------|-------------|
| | | | | current (A) | current (A) | current (A) | current (A) | current (A) | current (A) |
| Dukem EIZ | feeder 2 | 33 | 0.946 | 136.4 | 97.6 | 111.3 | 129.1 | 132.9 | 142.2 |
| | feeder 3 | 33 | 0.956 | 445.7 | 454 | 17.9 | 497.6 | 102 | 509.2 |
| | feeder 5 | 33 | 0.9 | NA | 232.4 | 285 | 424.5 | 274.8 | 264.8 |
| | feeder 6 | 33 | 0.596 | 353.9 | 321.6 | 191.4 | 85.2 | 102 | 217 |
| | feeder 7 | 33 | 0.96 | 64 | 113 | 60.8 | 65.4 | 60.3 | 84.9 |
| | feeder 8 | 33 | 0.856 | 500.7 | 10.4 | 253 | 234.4 | 193.8 | 224 |

Table 3.2 peak load current

| Feeder | Power Type | Oct-25 | Nov-25 | Dec-25 | Jan-25 | Feb-25 | Mar-25 |
|-----------------|-------------------|---------------|---------------|---------------|---------------|---------------|-----------------|
| Feeder 2 | KVA | 7796.31 | 5578.59 | 6361.65 | 7379.06 | 7596.26 | 8127.82 |
| | KW | 7375.31 | 5277.35 | 6018.12 | 6980.59 | 7186.06 | 7688.92 |
| | KVAR | 2527.30 | 1808.39 | 2062.23 | 2392.04 | 2462.45 | 2634.77 |
| Feeder 3 | KVA | 25475.18 | 25949.59 | 1023.12 | 28441.66 | 5830.08 | 29104.69 |
| | KW | 24201.42 | 24652.11 | 971.97 | 27019.58 | 5538.58 | 27649.45 |
| | KVAR | 7954.62 | 8102.76 | 319.47 | 8880.91 | 1820.44 | 9087.94 |
| Feeder 5 | KVA | NA | 13283.44 | 16289.94 | 26263.43 | 15706.93 | 15135.35 |
| | KW | NA | 12619.27 | 15475.44 | 21837.09 | 14136.24 | 13621.82 |
| | KVAR | NA | 4147.75 | 5086.53 | 10576.19 | 6846.49 | 6597.35 |
| Feeder 6 | KVA | 20228.10 | 18381.91 | 10939.98 | 4869.83 | 5830.08 | 12403.22 |
| | KW | 18205.29 | 16543.72 | 9845.98 | 44382.85 | 5247.07 | 11162.89 |
| | KVAR | 8817.23 | 8012.49 | 4768.63 | 2122.71 | 2541.27 | 5406.44 |
| Feeder 7 | KVA | 3658.09 | 6458.82 | 3475.19 | 3738.11 | 3446.61 | 4852.69 |
| | KW | 3292.28 | 5812.94 | 3127.67 | 3364.30 | 3101.95 | 4367.42 |
| | KVAR | 1594.53 | 2815.33 | 1514.80 | 1629.41 | 1502.34 | 2115.24 |
| Feeder 8 | KVA | 28618.85 | 594.44 | 14460.89 | 13397.76 | 11077.16 | 12803.32 |
| | KW | 25756.96 | 535.00 | 13013.80 | 12057.98 | 9969.44 | 11522.99 |
| | KVAR | 12474.67 | 259.11 | 6303.36 | 5839.95 | 4828.42 | 5580.84 |

Table 3.3: Power (KVA, KW, KVAR) Readings by Feeder

| district | No. of trafo | power in Kva | True power Kw(P) $\sqrt{3} * V * I * \cos \theta$ | Reactive power Kvar(Q) $\sqrt{3} * V * I * \sin \theta$ | distance (meter) | Efficiency |
|-----------------|--------------|--------------|--|--|------------------|------------|
| District 1 | Trafo No.1 | 1750 | 1500 | 900 | 1100 | 0.8 |
| | Trafo No.2 | 1415 | 1200 | 750 | 1120 | 0.8 |
| | Trafo No.3 | 2100 | 1800 | 1100 | 1200 | 0.8 |
| | Trafo No.4 | 1200 | 1000 | 650 | 1220 | 0.8 |
| | Trafo No.5 | 1030 | 900 | 500 | 1400 | 0.8 |
| | Trafo No.6 | 1250 | 1100 | 600 | 1460 | 0.8 |
| | Trafo No.7 | 1500 | 1300 | 700 | 1460 | 0.8 |
| district 2 | trafo no. 1 | 1640 | 1400 | 850 | 1500 | 0.8 |
| | trafo no. 2 | 1860 | 1600 | 950 | 1530 | 0.8 |
| | trafo no. 3 | 1165 | 1000 | 600 | 1570 | 0.8 |
| | trafo no. 4 | 1050 | 900 | 550 | 1620 | 0.8 |
| | trafo no. 5 | 1400 | 1200 | 700 | 1680 | 0.8 |
| district 3 | trafo no.1 | 1525 | 1300 | 800 | 1080 | 0.8 |
| | trafo no.2 | 1250 | 1100 | 600 | 1080 | 0.8 |
| | trafo no.3 | 1200 | 1000 | 650 | 1200 | 0.8 |
| | trafo no.4 | 1050 | 950 | 500 | 1200 | 0.8 |
| | trafo no.5 | 1350 | 1150 | 700 | 1200 | 0.8 |
| District 5 | Trafo no.1 | 1500 | 1250 | 800 | 850 | 0.8 |
| | Trafo no.2 | 1550 | 1300 | 850 | 850 | 0.8 |
| | Trafo no.3 | 1050 | 900 | 550 | 890 | 0.8 |
| | Trafo no.4 | 1165 | 1000 | 600 | 890 | 0.8 |
| | Trafo no.5 | 1050 | 950 | 500 | 930 | 0.8 |
| | Trafo no.6 | 1275 | 1100 | 650 | 930 | 0.8 |
| Other factories | Trafo no.1 | 1400 | 1200 | 700 | 1720 | 0.8 |
| | Trafo no.2 | 1500 | 1300 | 750 | 1720 | 0.8 |
| | Trafo no.3 | 1650 | 1400 | 850 | 1760 | 0.8 |
| | Trafo no.4 | 1750 | 1500 | 900 | 1760 | 0.8 |
| | Trafo no.5 | 1165 | 1000 | 600 | 1820 | 0.8 |
| | Trafo no.6 | 1050 | 900 | 550 | 1880 | 0.8 |
| | Trafo no.7 | 1300 | 1100 | 700 | 2200 | 0.8 |
| | Trafo no.8 | 1350 | 1150 | 720 | 2320 | 0.8 |
| | Trafo no.9 | 1500 | 1250 | 800 | 2400 | 0.8 |
| | Trafo no.10 | 1300 | 1300 | 850 | 1840 | 0.8 |
| | Trafo no.11 | 1050 | 900 | 550 | 1920 | 0.8 |
| | Trafo no.12 | 1165 | 1000 | 600 | 1980 | 0.8 |
| | Trafo no.13 | 1050 | 950 | 500 | 1980 | 0.8 |

| | | | | | |
|-------------|------|------|-----|------|-----|
| Trafo no.14 | 1275 | 1100 | 650 | 2200 | 0.8 |
| Trafo no.15 | 1400 | 1200 | 700 | 2290 | 0.8 |
| Trafo no.16 | 1500 | 1300 | 750 | 2350 | 0.8 |
| Trafo no.17 | 1615 | 1400 | 800 | 2460 | 0.8 |
| Trafo no.18 | 1725 | 1500 | 850 | 2460 | 0.8 |

Table 3.4 transformer data

| Conductor /wire type | Nominal area (mm ²) | Actual area (mm ²) | Stranding and wire diameter | Overall diameter (mm) | Actual diameter (mm) | GM R (mm) | Resistance (Ω/Km) | Reactance (Ω/Km) |
|----------------------|---------------------------------|--------------------------------|-----------------------------|-----------------------|----------------------|-----------|-------------------|------------------|
| AAC | 50 | 49.5 | 7/3.00 | 9 | 7.9377 | 2.88 | 0.68 | 0.362 |
| AAC | 95 | 93.5 | 19/2.5 | 12.5 | 10.8975 | 4.129 | 0.5785 | 0.347 |
| ACSR | 46 | 45.5 | 7/2.5 | 8.5 | 7.65 | 2.75 | 0.681 | 0.365 |
| ACSR | 65 | 63.5 | 19/2.5 | 10.5 | 8.975 | 2.85 | 0.571 | 0.349 |

Table 3.5 conductor type

3.2 Materials used for the thesis

Mathlab R2019b, Microsoft Office 2021, Asus computer window 11, used to model and simulate the complete UPFC, draw figures, write this thesis paper, write mathematical equations, and add reference citations respectively

3.3 A Mathematical Approach to UPFC Deployment.

The Unified Power Flow Controller (UPFC) is an advanced flexible AC transmission system device that can simultaneously control multiple power system parameters. Below is the comprehensive mathematical modelling of UPFC for voltage profile improvement and loss minimization in radial distribution systems.

3.3.1 UPFC Equivalent Circuit

The UPFC has connected by two voltage sources:

- Series voltage source V_c with impedance Z_c
- Shunt voltage source V_{sh} with impedance Z_{sh}

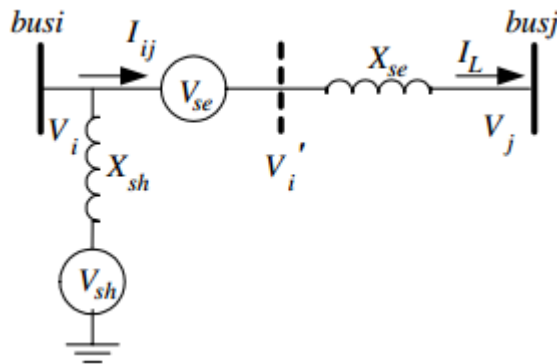


Figure 3. 2: Two voltage-source model of UPFC

Series Converter Model

The series voltage source converter has injected a voltage V_c with controllable magnitude and phase angle:

$$V_c = V_c \angle \theta_c \quad (3.1)$$

The series injected voltage can be decomposed into:

$$V_c = V_{cp} + jV_{cq} \quad (3.2)$$

Shunt Converter Model

The shunt converter injects current I_{sh} :

$$I_{sh} = I_{shp} + jI_{shq} \quad (3.3)$$

Where:

- I_{shp} is the active component (maintains DC link voltage)
- I_{shq} is the reactive component (provides voltage support) (E. Engineering, 2016.)

Line Loss Minimization Conditions

For a loop/closed distribution network with UPFC, the system loss minimum condition can be achieved by eliminating the loop current:

$$I_{loop} = 0$$

This is achieved by controlling the series voltage V_c such that:

$$V_c = V_r - V_s \cos \theta + jV_s \sin \theta \quad (3.4)$$

Power Flow Equations for UPFC

The power flow equations for a system with UPFC between buses i and j are:

Active power injected at bus i :

$$P_i = V_i^2 G_{ii} + V_i V_j [G_{ij} \cos(\theta_i - \theta_j) + B_{ij} \sin(\theta_i - \theta_j)] + V_i V_c [G_{ic} \cos(\theta_i - \theta_c) + B_{ic} \sin(\theta_i - \theta_c)] \quad (3.5)$$

Reactive power injected at bus i :

$$Q_i = -V_i^2 B_{ii} + V_i V_j [G_{ij} \sin(\theta_i - \theta_j) - B_{ij} \cos(\theta_i - \theta_j)] + V_i V_c [G_{ic} \sin(\theta_i - \theta_c) - B_{ic} \cos(\theta_i - \theta_c)] \quad (3.6)$$

Active power(P) injected at bus j :

$$P_j = V_j^2 G_{jj} + V_j V_i [G_{ji} \cos(\theta_j - \theta_i) + B_{ji} \sin(\theta_j - \theta_i)] + V_j V_c [G_{jc} \cos(\theta_j - \theta_c) + B_{jc} \sin(\theta_j - \theta_c)] \quad (3.7)$$

Reactive power injected at bus j :

$$Q_j = -V_j^2 B_{jj} + V_j V_i [G_{ji} \sin(\theta_j - \theta_i) - B_{ji} \cos(\theta_j - \theta_i)] + V_j V_c [G_{jc} \sin(\theta_j - \theta_c) - B_{jc} \cos(\theta_j - \theta_c)] \quad (3.8)$$

UPFC Control Strategy for Loss Minimization

The control strategy for loss minimization involves:

1. Detecting the loop current I_{loop}
2. Calculating the required series voltage V_c to eliminate I_{loop}
3. Controlling the shunt converter, it has DC link voltage

The reference value for the series voltage is:

$$V_c = V_r - V_s \cos \theta + jV_s \sin \theta \quad (3.9)$$

UPFC Power Balance Equations

The active power supplied by the series converter: $P_c = V_c I_2 \cos(\theta_c - \theta_{I_2})$

The active power supplied by the shunt converter: $P_{sh} = V_{sh} I_{sh} \cos(\theta_{sh} - \theta_{I_{sh}})$

For steady-state operation, neglecting converter losses: $P_c + P_{sh} = 0$

This ensures that the DC link voltage remains constant

Voltage Regulation with UPFC

To maintain all node voltages within permissible limits (typically $V_{nom} \pm 5\%$), the series voltage V_c is controlled to:

$$V_c = V_r - V_s \cos \theta + jV_s \sin \theta^* \quad (3.10)$$

Where V_r is set to achieve the desired voltage profile: $V_r = V_{nom}$

The phase angle θ is determined to achieve loss minimization: $\theta = \tan^{-1} \left(\frac{X_{eq}}{R_{eq}} \right)$

Where R_{eq} and X_{eq} are the equivalent resistance and reactance of the system

Advantage of UPFC

The device (UPFC) is one of the most versatile and effective FACTS (Flexible AC Transmission System) devices for power system operation and control. It provides simultaneous and independent control of voltage magnitude, phase angle, and line impedance, which enables effective management of active and reactive power flow in transmission/distribution systems. (N. Visali D. R., 2016). UPFC enhances system stability, improves voltage regulation, and minimizes transmission losses by dynamically adjusting power flow paths. Additionally, it helps prevent line overloads, supports better utilization of existing distribution infrastructure, and contributes to an overall improvement in power system reliability and flexibility (C. Anitha, 2013).

3.3.2 Reasons for choosing UPFC

UPFC is chosen in this study due to its superior ability to address both voltage regulation and power loss minimization in complex distribution networks. Unlike traditional reactive power compensators or line regulators, the UPFC can control multiple parameters simultaneously, offering a holistic solution to network constraints (Isha, 2023) (N. Visali D. R., 2016). Its inclusion allows for real-time dynamic control and optimization of power flow, making it particularly effective for modern power systems that experience fluctuating loads and distributed generation

integration. The ability of UPFC to maintain voltage stability while minimizing losses makes it the preferred device for enhancing power quality and operational efficiency in this research (Ismail, 2020).

3.4 power flow analysis

Power flow analysis, which is also known as load flow analysis, is a method used in electrical engineering to figure out how a power system works smoothly under normal conditions. It calculates the complex voltages and currents at different nodes or buses in the network, considering for active power and reactive power demands, generation, and transmission losses. The main objective of power flow analysis is to assess the voltage profiles, power flow, and system stability under different load conditions. By solving a system of nonlinear algebraic equations, load flow analysis provides valuable insights into the power system's performance, ensuring efficient operation and reliable power delivery to consumers (Shradha Singh Parihar, 2018).

The backward-forward sweep technique for power flow analysis is better suited for analyzing radial systems because it does not rely on the Jacobian matrix, unlike the Newton-Raphson method. Instead, it is built on Kirchhoff's laws. This method offers several advantages, including efficient computation and lower memory requirements. Additionally, it exhibits a strong convergence characteristic, making it a favorable choice for radial system analysis.

3.4.1 Forward / Backward Sweep Load Flow

Power flow algorithms that use forward and backward sweeps usually work with networks that have a radial shape. The forward sweep calculates the voltage at each node starting from the beginning of the power line and moving toward the end. The backward sweep then adds up the current and/or power in each branch, starting from the end of the line and moving back to the start. In some methods, during the backward sweep, the algorithm also calculates the voltage at each node along with the current and power.

3.4.2 Advantage of Forward Backward over Newton Raphson method

The forward-backward power flow techniques and the Newton-Raphson method are both techniques used to solve load flow problems in power systems, but each approach has its

advantages and disadvantages. Here are some advantages of the forward-backward load flow algorithm over the Newton-Raphson method:

Simplicity and Ease of Implementation: - The forward-backward load flow algorithm is generally easier to implement and understand compared to the Newton-Raphson method. It involves simple iterative calculations that can be implemented straightforwardly, making it more accessible to engineers and researchers with limited experience in load flow analysis.

Convergence in Radial Networks: The forward-backward load flow algorithm is particularly preferable for radial distribution networks, where power flow is unidirectional. In these networks, the algorithm converges efficiently and reliably, even for complex scenarios involving distributed generation and varying load profiles.

Reduced Iterations: In certain cases, the forward-backward load flow algorithm may require fewer iterations to approach the desired value compared to the Newton-Raphson method. This can lead to faster computation times, especially for radial systems or systems with limited voltage control devices.

Robustness: - The forward-backward load flow algorithm is generally more robust in handling ill-conditioned systems and situations with voltage violations. It has less impact to divergence or getting trapped in local minima, making it a suitable choice for challenging power system scenarios.

Reduced Memory Requirements: The forward-backward load flow algorithm often requires less memory for storing intermediate variables and results during the iterative process. This can be advantageous for applications on resource-constrained devices or embedded systems.

It's important to remember that choosing between the forward-backward load flow algorithm and the Newton-Raphson method depends on the specific features of the power system being studied, as well as how accurate and fast the results need to be. Although the forward-backward method has some benefits, the Newton-Raphson method is still a strong and commonly used approach, especially for big and highly connected power systems. Engineers and researchers usually check how each method performs and pick the one that works best for their particular analysis purpose.

3.4.3 Forward-Backward Sweep Load Flow Techniques

The forward and backward sweep algorithm uses two matrices, the bus-injection to branch-current matrix (BIBC) and the branch current to bus-voltage matrix (BCBV), along with equivalent current injections. In distribution networks, the model that uses equivalent current injections is seen as more practical. The complex power S_i injected at bus 'i' can be written as; (Smarajit Ghosh P. , 2017)

$$S_i = P_i + jQ_i \quad i=1 \dots N \quad (3.11)$$

Backward analysis

The backward sweeping involves calculating the current injection at each bus and then using the BIBC matrix to find the branch currents. This process is iterative and typically continues until the change in voltage magnitudes b/n series iterations is under a specified tolerance.

1. **Initialization:** Begin the backward sweep with initial voltage values, usually set to a flat voltage profile (e.g., 1.0 per unit) for all buses except the source bus.
2. **Calculate Bus Current Injection:** For each bus i at iteration k , the current injection I_i^k is calculated using the formula above, based on the loads and the most recent voltage values V_{ik} .
3. **Calculate Branch Currents:** The calculated bus current injections are then used to determine the branch currents. This can be done using the pre-calculated **BIBC matrix** (BI). The branch current vector I_{branch} is found by multiplying the BIBC matrix by the bus current injection vector I_{bus} :

$$I_{\text{branch}} = BI \cdot I_{\text{bus}}$$

4. **Update Voltages (Forward Sweep):** The calculated branch currents are then used in the forward sweep to update the bus voltages. The voltage drops across each branch is calculated, and the voltage at a bus is found by subtracting the voltage drop from the upstream bus's voltage. This completes one iteration, and the process repeats.

The current injection at bus i during the k^{th} iteration is given by:

$$I_i^k = I_i^r(V_i^k) + jI_i^r(V_i^k) = \frac{(P_i + jQ_i)^*}{v_i^k} \quad (3.12)$$

Where:

- I_i^k = current injection at bus i during iteration k .
- P_{ik} and Q_i^k are the reactive and true loads at bus i during iteration k .
- V_i^{k*} is the complex conjugate of the voltage at bus i during iteration k .

In the backward sweep, this current injection is calculated for each bus, starting from the last node and moving toward the source. The calculated currents are then aggregated to find the branch currents.

The **Bus-Injection to Branch-Current (BIBC)** matrix is used to relate these bus injection currents to the branch currents. This matrix is constant for a given network topology and is pre-calculated.

The backward sweep is an essential part of the **forward-backward sweep** method for power flow analysis in radial distribution systems. The method works as follows:

1. **Forward_ Sweep (Voltage analysis):** starts with source bus (root node), voltages are calculated for all other buses, moving downstream.
2. **Backward_ Sweep (Current analysis):** starts with last bus (end node), currents are calculated and aggregated towards the source.

Power Matrix formulation

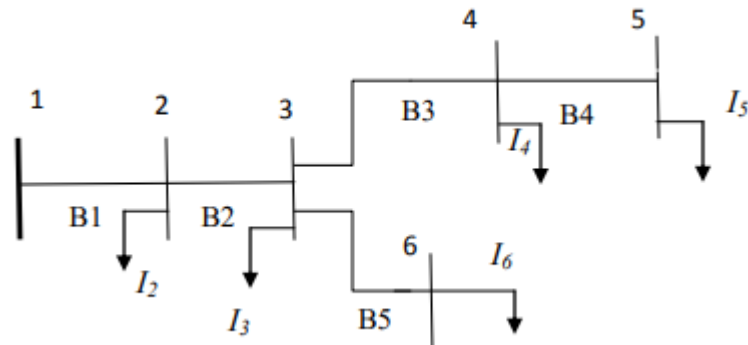


Figure 3.3: Radial distribution configuration

First, the injected currents are determined using an existing equation. Then, by applying Kirchhoff's current law (KCL) to the power distribution system, the branch currents are calculated. The study uses a simplified distribution system (shown in Figure 3.4) as a sample to show that the branch currents can be expressed as a function of the injected currents. The branch currents B_2 , B_3 , B_4 and B_5 can be expressed as:

$$B_1 = I_2 + I_3 + I_4 + I_5 + I_6$$

$$B_2 = I_3 + I_4 + I_5 + I_6$$

$$B_3 = I_5 + I_6$$

$$B_4 = I_5$$

$$B_5 = I_6$$

Therefore, the relationship between the bus current injections and branch currents can be expressed by:

$$\begin{pmatrix} B_1 \\ B_2 \\ B_3 \\ B_4 \\ B_5 \end{pmatrix} = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 \\ 0 & 1 & 1 & 1 & 1 \\ 0 & 0 & 1 & 1 & 1 \\ 0 & 0 & 0 & 1 & 1 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} I_2 \\ I_3 \\ I_4 \\ I_5 \\ I_6 \end{bmatrix} \quad (3.13)$$

The relationship can be expressed in a matrix equation as:

$$I_{\text{branch}} = [BIBC] \cdot I_{\text{bus}}$$

Equation (3.13) can also be expressed as,

$$[B] = [BIBC][I] \quad (3.14)$$

Second step Forward sweep

The approach b/n bus voltages and branch currents can be expressed using a matrix equation. This relationship is a key part of the forward sweep in a distribution load flow analysis. The

forward sweep is where you start from the source and move outwards towards the loads. The Branch-Current to Bus-Voltage (BCBV) matrix. This matrix is constant for a given network topology and its elements are derived from the impedances of the branches.

The general relationship is:

$$V \text{ drop} = [\text{BCBV}] \cdot I \text{ branch}$$

Where:

- V drop is a vector of voltage drops from the source bus (bus 1) to each downstream bus.
- [BCBV] is the Branch-Current to Bus-Voltage matrix.
- I branch is the vector of branch currents, which were calculated in the backward sweep.

From the user's provided context and general power flow principles, the voltage at any bus i can be expressed as a function of the source voltage and the sum of the voltage drops along the path from the source to bus i .

Based on the example provided, the relationships for a simple radial system can be expressed as:

$$V_2 = V_1 - I_2 Z_{12} \quad (3.15)$$

$$V_3 = V_2 - I_2 Z_{23} \quad (3.16)$$

$$V_4 = V_3 - I_3 Z_{34} \quad (3.17)$$

$$V_5 = V_4 - I_4 Z_{45} \quad (3.18)$$

$$V_6 = V_5 - I_5 Z_{56} \quad (3.19)$$

By substitution, you can express each bus voltage directly as a function of the source voltage and the branch currents. For example:

$$V_4 = V_1 - I_1 Z_{12} - I_2 Z_{23} - I_3 Z_{34}$$

This is where the **BCBV matrix** comes in. It provides a more structured and systematic way to handle these substitutions. The matrix equation is as follows:

$$\begin{bmatrix} V_2 \\ V_3 \\ V_4 \\ V_5 \\ V_6 \end{bmatrix} = \begin{bmatrix} V_1 \\ V_1 \\ V_1 \\ V_1 \\ V_1 \end{bmatrix} - \begin{bmatrix} Z_{12} & 0 & 0 & 0 & 0 \\ Z_{12} & Z_{23} & 0 & 0 & 0 \\ Z_{12} & Z_{23} & Z_{34} & 0 & 0 \\ Z_{12} & Z_{23} & Z_{34} & Z_{45} & 0 \\ Z_{12} & Z_{23} & Z_{34} & Z_{45} & Z_{56} \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \\ I_5 \end{bmatrix}$$

The BCBV matrix is a lower triangular matrix where the element at position (i,j) represents the impedance of branch j and its contribution to the voltage drop at bus i. It's important to note that the row for each bus contains the sum of impedances for all branches along the path from the source to that specific bus.

This process is a core part of the **forward-backward sweep method**. After the backward sweep calculates the branch currents, the forward sweep uses the BCBV matrix to update the bus voltages. This iterative process repeats until the voltage profile converges

From equation (3.19)

$$[V^{k+1}] = [V_1] - [BCBV][B] \quad (3.20)$$

3.4.4 Procedures to Form BIBC and BCBV Matrix

For analyzing power flow in radial distribution systems using the forward-backward sweep method, a key step is to create two specific matrices: Bus-Injection to Branch-Current (BIBC) matrix and Branch-Current to Bus-Voltage (BCBV) matrix. These matrices are constructed based on how the network is structured and do not change during the repetitive calculation process

First step Forming BIBC Matrix

The **BIBC** matrix relates the current injected at each bus to the total current flowing through each branch. It's an upper triangular matrix with elements of either 0 or 1. A '1' indicates that the current injection at a particular bus contributes to the current in a specific branch. The procedure for its formation is based on **Kirchhoff's Current Law (KCL)**.

- ❖ **Determine Dimensions:** The BIBC matrix has dimensions of $m \times (n-1)$, where m is the number of branches and n is the number of buses (excluding the source bus, which is typically bus 1).
- ❖ **Initialize the Matrix:** Start with a null matrix (all zeros) of the determined dimensions.

- ❖ **Iterate Through Branches:** For each branch k connecting bus i and bus j , perform the following:
 - Identify the path from the source (bus 1) to bus j .
 - For every bus p in this path, set the element at position (k,p) of the BIBC matrix to Z_1 . This signifies that the current flowing in branch k is a summation of all the currents injected at the buses downstream from it.
- ❖ **Repeat:** Continue this process for all branches in the system until the matrix is fully populated.

Second step Forming BCBV Matrix

The **BCBV** matrix relates the branch currents to the voltage drops between the source and each bus. It is a lower triangular matrix whose elements are the impedances of the branches. The procedure for its formation is based on **Kirchhoff's Voltage Law (KVL)**.

1. **Determine Dimensions:** The BCBV matrix has dimensions of $(n-1) \times m$, where n is the number of buses and m is the number of branches. Note that the dimensions are the transpose of the BIBC matrix dimensions.
2. **Initialize the Matrix:** Begin with a null matrix (all zeros) of the specified dimensions.
3. **Iterate Through Buses:** For each bus k (excluding the source bus) from 2 to n , perform the following:
 - ✓ Trace the path from the source (bus 1) to bus k .
 - ✓ For every branch l in this path, set the element at position (k,l) of the BCBV matrix to the impedance of that branch, Z_l . This indicates that the total voltage drop from the source to bus k is the sum of the voltage drops across all branches in the path.
- 3 **Repeat:** Continue this process for all buses until the matrix is fully formed.

3.5 Improvement Techniques for UPFC allocation and Sizing

Optimization techniques play a crucial role in determining the optimal placement and sizing of UPFC in power distribution systems. The goal is to minimize power losses, improve voltage profiles, and enhance overall system performance. Several optimization methods are employed to achieve these objectives (.H. Akhavan Hejazi, 2018)

1, **Genetic Algorithms (GA):** GA is a population-based optimization technique inspired by the principles of natural selection and genetics. It explores various candidate solutions for UPFC

placement and sizing, iteratively improving the solutions through crossover, mutation, and selection operations of getting most optimal configuration.

2, Particle Swarm Optimization (PSO): Particle Swarm Optimization (PSO) is a type of optimization method that uses swarm intelligence. In PSO, each solution is shown as a particle that moves through a space where possible answers are found. The movement of these particles is guided by two main things: where they have been best before and where the whole group has found the best solution so far. PSO is used to find the best place and size for a UPFC.

3, Ant Colony Optimization (ACO) Ant Colony Optimization is based on how ants search for food. In this method, virtual ants leave behind a kind of signal called pheromone at possible locations and sizes for UPFC. The better a solution is, the more pheromone it leaves. Then, other ants follow these pheromone paths to find the best spot and size for UPFC..

4, Differential Evolution (DE): DE is an evolutionary algorithm that iteratively optimizes a population of candidate solutions. DE utilizes mutation, crossover, and selection operations to search for the optimal UPFC configuration.

5, Multi-Objective Optimization: In some cases, multiple conflicting objectives, such as loss reduction and voltage profile improvement, need to be considered simultaneously. Multi-objective optimization methods, like Non-dominated Sorting Genetic Algorithm (NSGA-II), find a set of Pareto-optimal solutions representing trade-offs between different objectives.

These optimization techniques help power system engineers and operators identify the best locations and sizes for UPFC, leading to enhanced power quality, improved system stability, and increased energy efficiency in distribution networks. The optimal method for deploying a Unified Power Flow Controller (UPFC) depends on several factors, including: The complexity of the problem: How intricate is the power network and the specific issue being addressed and Available computational resources: Are there enough computing power and time to run a complex algorithm

3.5.1 Particle Swarm Optimization (PSO)

Particle Swarm Optimization is a population-based enhancement technique that falls under evolutionary computation (Alwazni, 2021). Formulated by James Kennedy and Russell Eberhart in 1995. PSO was designed to simplify complex, nonlinear optimization problems. The core concept of PSO is initiated by the collective behavior observed in flocks of birds, schools of fish, and swarms of insects. These creatures exhibit coordinated movement and decision-making as a

group, often adapting to changes in their environment to locate food or migrate efficiently. Similarly, PSO models this social interaction, where each individual, or "particle," in the population shares information and adjusts its position in the search area based on both its own experience and that of its neighbors. These collaborative dynamic guides the swarm toward optimal solutions throughout the optimization process (A.K. Singh, 2021).



Figure 3.4: School of fishes and Flock of birds

The **particle swarm optimization (PSO)** algorithm starts with a group of particles, each representing a possible solution, placed randomly within the search area. Each particle's quality is measured by a fitness value, which shows how well it solves the problem. Particles move through the search space, and their movement is guided by a velocity that is updated in each step. The direction and speed of each particle's movement are influenced by two main things: Its own best-found position: The best solution it has discovered so far and the best-found position of the entire group: The best solution any particle in the swarm has found. This combination of individual and collective learning helps the particles move toward the optimal solution. The new velocity of a particle is a mix of its previous velocity, its personal best position, and the swarm's best position, as illustrated in Fig. 3.6.

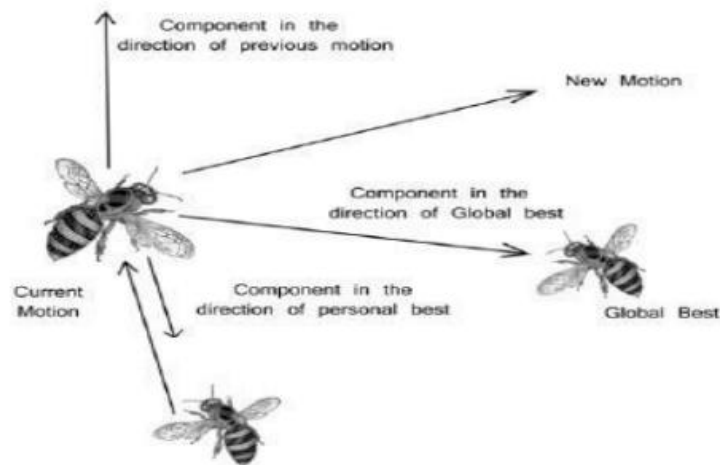


Figure 3. 5: example of a searching point by PSO

The Particle Swarm Optimization algorithm is considered as robust and modern techniques for addressing complex, non-linear global problems alleviation technique. It offers several key advantages: (ovat, 2021)

- PSO is a derivative-free optimization method capable of effectively exploring the global search space.
- The algorithm is straightforward to implement and conceptually easy to understand, making it suitable for both scientific and engineering applications.
- PSO involves only a few parameters, and their influence on the final solution is relatively minor when compared to other optimization approaches.
- It relies on probabilistic rather than deterministic rules, making it well-suited for exploring complex and uncertain solution spaces.
- Unlike Genetic Algorithms (GA) and other heuristic methods, PSO offers better control over the trade-off between global and local search, which helps prevent premature convergence and enhances its ability to find optimal solutions.
- The accuracy of final solution is not basically dependent on the initial positions of the particles.
- Regardless of the starting point in the search space, the algorithm is designed to eventually converge toward an optimal solution.

- Being a population-based method, PSO naturally supports parallelism, reducing the likelihood of getting trapped in local minima.
- It uses the objective function or performance index to direct the search, allowing it to handle non-differentiable functions effectively. This also eliminates the need for assumptions or approximations typically required by classical optimization techniques.

Mathematical Modelling expression

Mathematically it can be expressed as follows (Abugri, 2015)

$$V_{id}^{k+1} = wV_{id}^k + c_1r(P_{bestid} - S_{id}^k) + c_2r(G_{bestid} - S_{id}^k) \quad (3.21)$$

$$S_{id}^{k+1} = S_{id}^k + V_{id}^{k+1} \quad (3.22)$$

$$i=1, 2 \dots n \ \& \ d=1, 2 \dots m$$

The following weight function is used

$$W_k = W_{\max} - \left(\frac{W_{\max} - W_{\min}}{K_{\max}} \right) \cdot K \quad (3.23)$$

Where,

W_{\min} and W_{\max} are the minimum and maximum weights respectively.

K and K_{\max} are the current and maximum iteration.

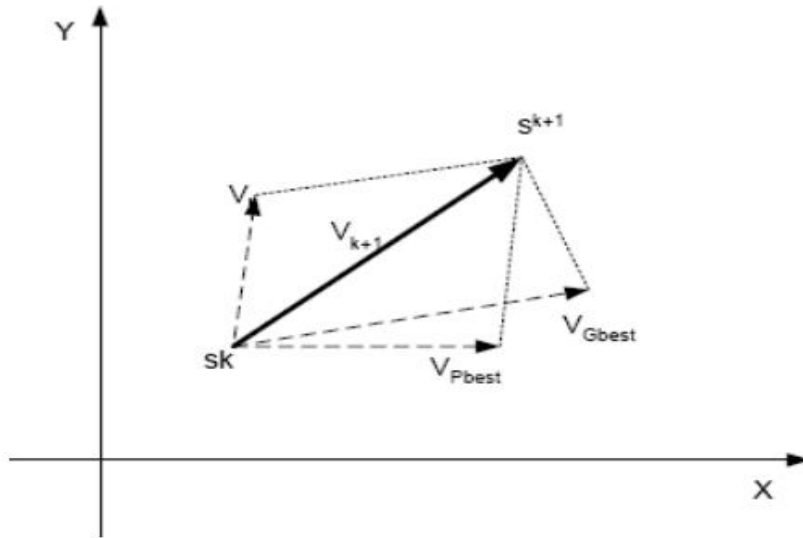


Figure 3.6: Velocity updating in PSO

3.5.2 Definition of PSO Parameters

The PSO algorithm's performance is governed by several crucial parameters:

- **Population:** A set of individual particles, each representing a potential solution.
- **Swarm:** A collective of these particles that moves in a seemingly random yet cohesive manner, with a tendency to cluster together.
- **Individual Best (pbest):** The best position a particle has ever found in the search space, based on its highest-ever fitness value. This is a personal record for each particle.
- **Global Best (gbest):** The single best position discovered so far by any particle in the entire swarm. This represents the best overall solution found.

Particle Velocity: A particle's velocity at any given time, V_{id}^k , is constrained within a minimum and maximum range, $V_{id}^{\min} \leq V_{id}^k \leq V_{id}^{\max}$. The parameter **Vmax** is critical for controlling the algorithm's search behavior.

- A **high V^{max}** can cause particles to move in large steps, potentially "flying past" good solutions and failing to find the optimal result.
- A **low V^{max}** can lead to slow convergence and limit the particles' ability to explore the search space, which may cause them to become trapped in local minimums.

A common practice is to set Vmax to be about **12–25%** of the dynamic range of each variable's dimension.

Random Numbers and Weighting Coefficients

Random numbers in the range of **[0, 1]** are essential for introducing the stochastic, or random, behavior of the PSO algorithm. The **weighting coefficients** (C_1 and C_2) control the influence of a particle's personal and global best positions on its velocity.

- High values for C_1 and C_2 can result in particles making abrupt, large movements toward or past target areas.
- Low values allow the particles to explore more of the search space before being pulled back toward a known good solution.

These coefficients are often kept constant, with a common value of **$C_1=C_2=2.0$** , which ensures a balanced pull toward both the particle's own best position and the swarm's collective best.

The relationship between c_1 and c_2 is important:

- If $C_1=0$ and $C_2>0$, all particles are collected as one point (the global best), reducing exploration.
- If $C_1> C_2$, a particle affected by its own history, which can lead to excessive wandering.
- If $C_2> C_1$, the swarm is heavily influenced by the global best, which can cause particles to converge prematurely to a suboptimal solution.

Inertia Weight: The **inertia weight (W)** helps balance the algorithm's global exploration (searching new areas) and local exploitation (refining the search in a promising area). A high initial value for W encourages broad exploration, while a progressively decreasing value over time promotes faster convergence. Common values for W are **$W_{min}=0.4$** and **$W_{max}=0.9$** .

Stopping Criteria

These are the conditions that signal the algorithm to terminate the search. A common stopping criterion is reaching a predefined **maximum number of iterations**. Choosing the right number of iterations is important; a number that is too low can stop the search prematurely, while a number that is too high adds unnecessary computational complexity and time. Other criteria can include when the solution stops improving after a certain number of iterations.

The size of the particle population is also a key parameter, often chosen based on the problem's complexity. A common range is **20–50 particles**. (Abugri, 2015)

3.5.3 Flow chart of PSO

Figure 3.7 shown below illustrates the basic flow of the PSO technique, starting from the initialization of particles with random positions and velocities. It then iteratively updates velocities and positions based on individual and global bests until the optimal solution is found or stopping criteria are met.

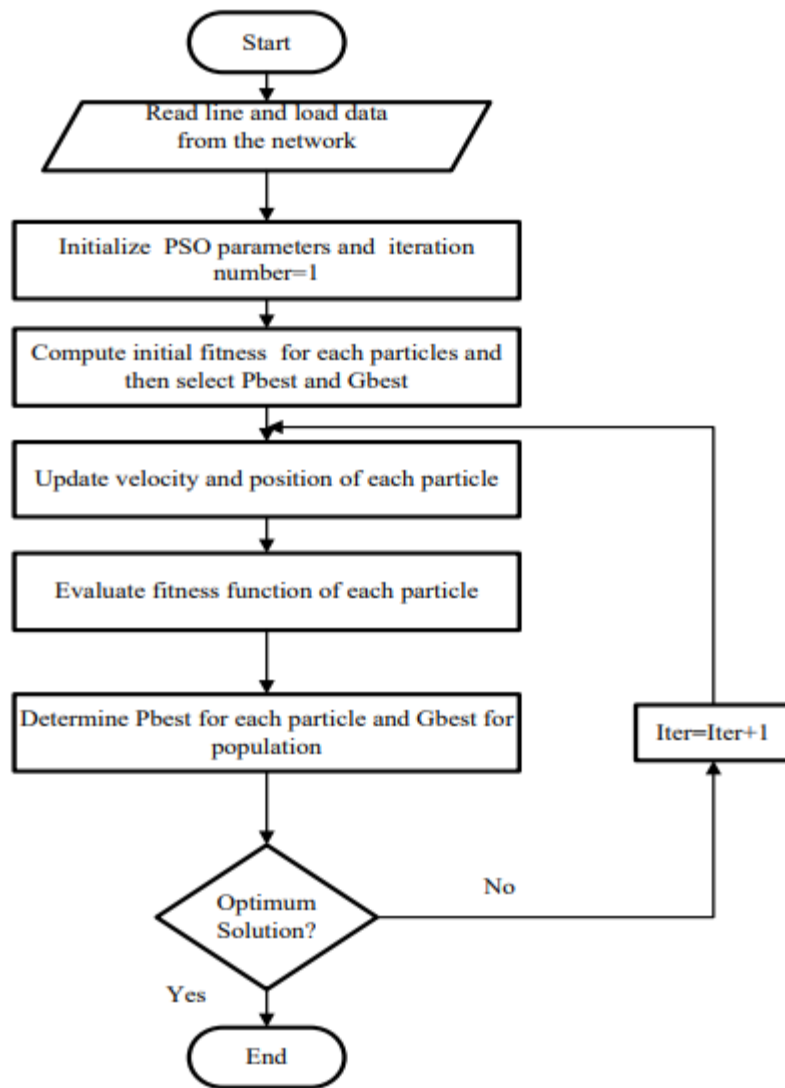


Figure 3.7: PSO flow chart

3.6. Feeder loading

The maximum load of each outgoing feeder is shown in Fig. 4.1 as shown below

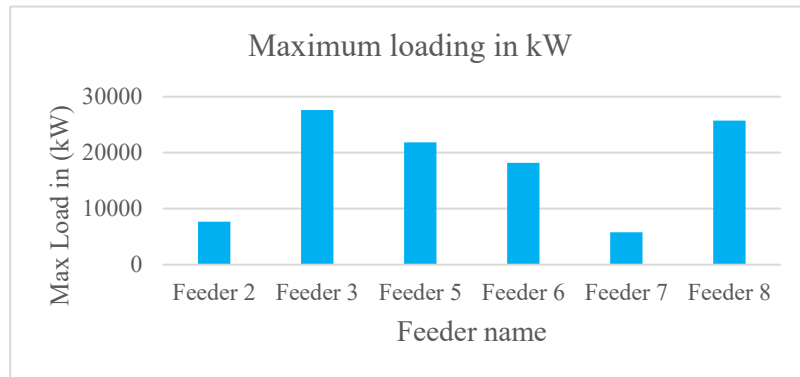


Figure 3.8: Feeders maximum loading

From Figure 3.8 shown that among the feeders, feeders 3, 5 and 8 has maximum loading capacity. So, investigation has to be carried out to this feeder in order to satisfy by this supply of power.

For six-month peak load current data is collected as shown in the above Table 3.1. In the average feeder 5 has highest peak load current and many transformers are connected. So, more emphasis is given to this feeder. Because the higher peak loads current, the loss in the feeder is high.

3.7 Peak load and current of feeders

The chart shown by Figure 4.2 illustrates peak load current data of six months.

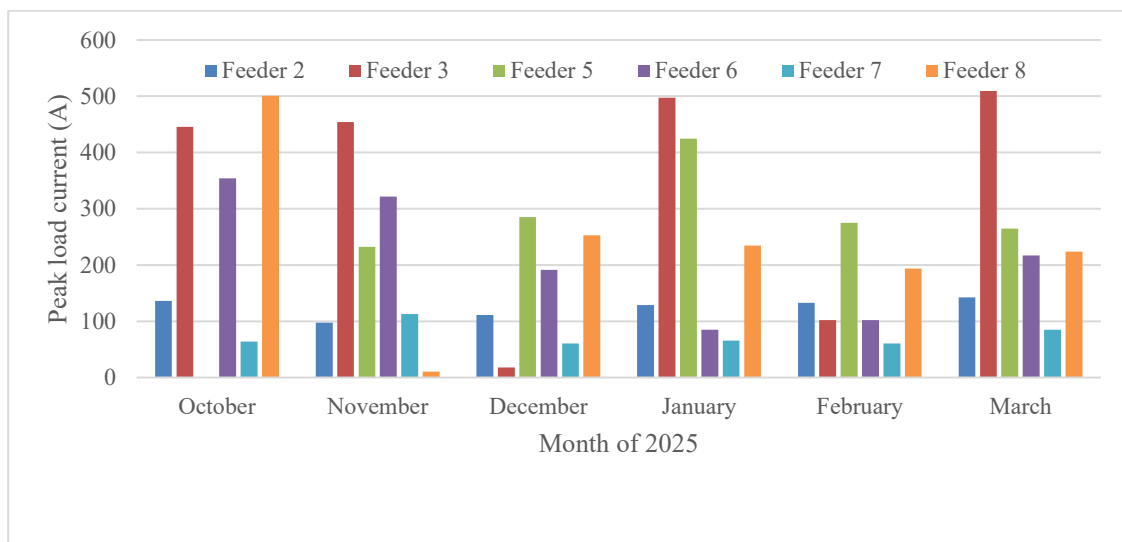


Figure 3.9: Peak load current data of six months

3.8 Line and Bus Data of the Feeder

To assess the performance of the distribution system, it is essential to gather parameters including branch line resistance, reactance, segment distance, as well as active and reactive power data for initialization. The resistance and reactance values are determined manually based on the distance and the type of conductor utilized during the installation of the chosen feeder. The branch line resistance (R) and line reactance (X) of the distribution network are computed as follows

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

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

Where R_0 is the resistance value of the distribution wire in Ω / Km and where X_0 is the reactance value of the distribution line wire in Ω / Km .

Table 3.6: line and load data for the selected feeder 5 at peak load condition

| Bus | From | To | Conductor | R (pu) | X (pu) | P (kW) | Q (kVAr) |
|-----|------|----|-----------|--------|--------|--------|----------|
| 1 | 1 | 2 | AAC-95 | 0.010 | 0.030 | 1500 | 900 |
| 2 | 1 | 3 | AAC-50 | 0.012 | 0.035 | 1200 | 750 |
| 3 | 3 | 4 | AAC-50 | 0.015 | 0.040 | 1800 | 1100 |
| 4 | 3 | 5 | AAC-65 | 0.010 | 0.025 | 1000 | 650 |
| 5 | 5 | 6 | AAC-95 | 0.008 | 0.020 | 900 | 500 |
| 6 | 5 | 7 | AAC-50 | 0.012 | 0.030 | 1100 | 600 |
| 7 | 5 | 8 | AAC-95 | 0.010 | 0.028 | 1300 | 700 |
| 8 | 8 | 9 | AAC-50 | 0.009 | 0.026 | 1400 | 850 |
| 9 | 9 | 10 | AAC-50 | 0.011 | 0.032 | 1600 | 950 |
| 10 | 9 | 11 | AAC-95 | 0.013 | 0.035 | 1000 | 600 |
| 11 | 8 | 12 | AAC-50 | 0.010 | 0.029 | 900 | 550 |
| 12 | 12 | 13 | AAC-50 | 0.009 | 0.027 | 1200 | 700 |
| 13 | 13 | 14 | AAC-65 | 0.008 | 0.025 | 1300 | 800 |
| 14 | 13 | 15 | AAC-95 | 0.010 | 0.028 | 1100 | 600 |
| 15 | 12 | 16 | AAC-50 | 0.012 | 0.031 | 1000 | 650 |
| 16 | 16 | 17 | AAC-95 | 0.011 | 0.030 | 950 | 500 |
| 17 | 16 | 18 | AAC-50 | 0.013 | 0.034 | 1150 | 700 |

| | | | | | | | |
|--|----|----|--------|-------|-------|--------|--------|
| 18 | 18 | 19 | AAC-50 | 0.009 | 0.027 | 1250 | 800 |
| 19 | 18 | 20 | AAC-95 | 0.010 | 0.029 | 1300 | 850 |
| 20 | 20 | 21 | AAC-50 | 0.011 | 0.030 | 900 | 550 |
| 21 | 20 | 22 | AAC-50 | 0.012 | 0.031 | 1000 | 600 |
| 22 | 22 | 23 | AAC-65 | 0.010 | 0.028 | 950 | 500 |
| 23 | 22 | 24 | AAC-95 | 0.009 | 0.026 | 1100 | 650 |
| 24 | 24 | 25 | AAC-50 | 0.008 | 0.025 | 1200 | 700 |
| 25 | 24 | 26 | AAC-95 | 0.010 | 0.028 | 1300 | 750 |
| 26 | 26 | 27 | AAC-95 | 0.011 | 0.030 | 1400 | 850 |
| 27 | 26 | 28 | AAC-50 | 0.012 | 0.032 | 1500 | 900 |
| 28 | 28 | 29 | AAC-50 | 0.013 | 0.034 | 1000 | 600 |
| 29 | 28 | 30 | AAC-65 | 0.010 | 0.028 | 900 | 550 |
| 30 | 30 | 31 | AAC-95 | 0.009 | 0.026 | 1100 | 700 |
| 31 | 31 | 32 | AAC-50 | 0.008 | 0.025 | 1150 | 720 |
| 32 | 32 | 33 | AAC-95 | 0.010 | 0.029 | 1250 | 800 |
| 33 | 32 | 34 | AAC-50 | 0.011 | 0.031 | 1300 | 850 |
| 34 | 34 | 35 | AAC-50 | 0.012 | 0.032 | 900 | 550 |
| 35 | 34 | 36 | AAC-95 | 0.013 | 0.034 | 1000 | 600 |
| 36 | 30 | 37 | AAC-50 | 0.010 | 0.028 | 950 | 500 |
| 37 | 37 | 38 | AAC-50 | 0.009 | 0.026 | 1100 | 650 |
| 38 | 38 | 39 | AAC-65 | 0.008 | 0.025 | 1200 | 700 |
| 39 | 38 | 40 | AAC-95 | 0.010 | 0.028 | 1300 | 750 |
| 40 | 40 | 41 | AAC-50 | 0.011 | 0.030 | 1400 | 800 |
| 41 | 40 | 42 | AAC-95 | 0.012 | 0.032 | 1500 | 850 |
| Total active and reactive power of the system load | | | | | | 49,000 | 36,210 |

The information provided in the preceding table includes the line and load data for the feeder 5, which is employed in load flow analysis. In chapter 3, the Forward -backward power flow analysis method is explained as the approach used to examine power loss and voltage profile.

Feeder 5, the chosen feeder for this study, has 42 buses or load points. Bus 1 serves as the starting point, or slack bus, while the other 41 buses connect to various loads through step-down transformers. The feeder uses stranded conductors made of AAC-95, AAC-50, and ACSR-65, each having a specific length. These conductors transmit medium voltage (33 kV) power from the substation to the distribution transformers. A single-line diagram and the corresponding data for the lines and loads are shown in Table 3.6.

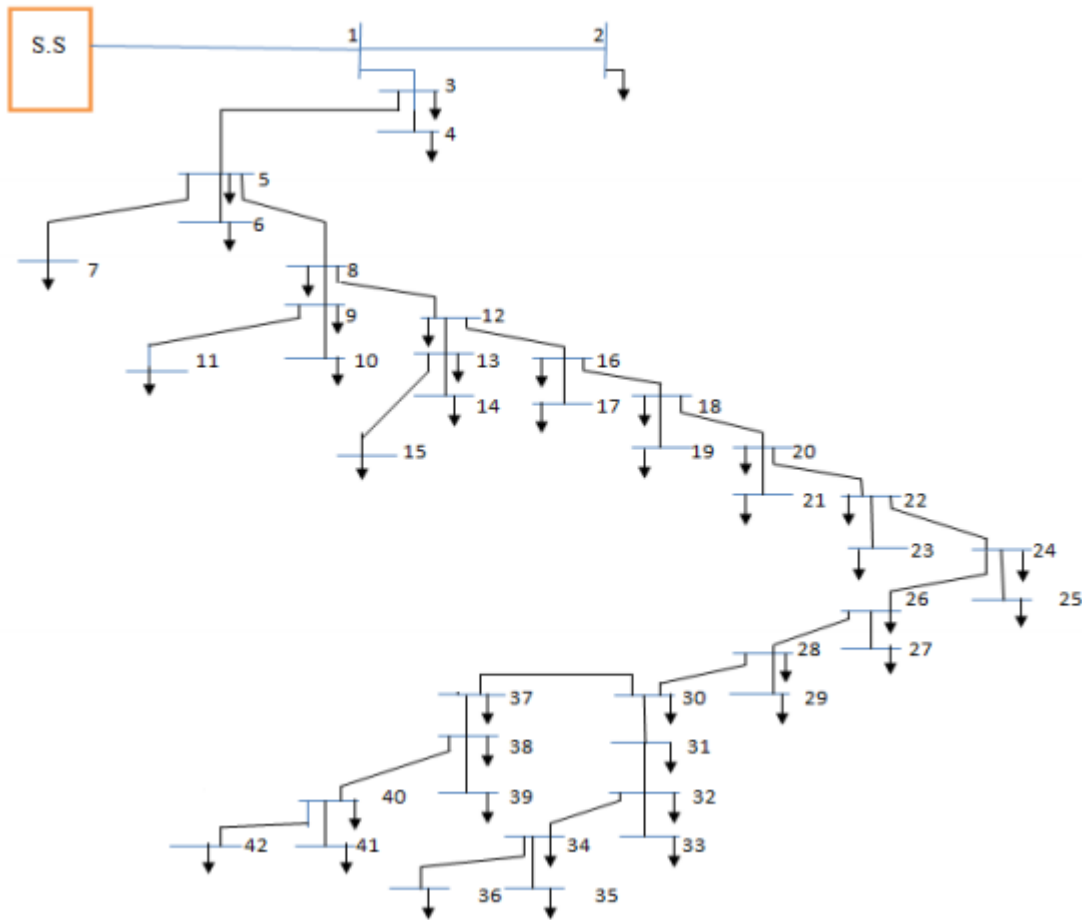


Figure 3.10 Single line diagram of feeder 5

3.9 Problem formulation

3.9.1 Objective Function

The main goal of this research is to find the best places and sizes for installing a UPFC by minimizing a specific fitness function. It is clear that different parts of this function are not equally important, so each part is given a different weight. Placing the UPFC in the radial distribution system helps improve the voltage levels and lower total power losses, while making sure all the required equality and inequality constraints are met (D. Bala Gangi Reddy, 2011) .

Loss reduction

Mathematical expression of distribution network total loss calculated as follows:

$$F_1 = \sum_i^N I_i^2 R_i \quad (4.1)$$

Keys

F_1 = 1st setting objective function for losses,

I_i = current of line i ,

R_i = the resistance of i^{th} line, and

N = No. network nodes

Voltage level enhancement

The setting objective foe enhancing the voltage profile is

$$F_2 = \sum_i^{N_{bus}} (V - V_i)^2 \quad (4.2)$$

Keys

F_2 = is the 2nd setting objective for enhancement

V_i = is the bus voltage, and

V = is the reference voltage.

3.9.2 Constraints

Constraints are limitations or restrictions that must be considered during the optimization process. They ensure that the solutions generated by the PSO are feasible and adhere to various technical, physical, and operational requirements.

Voltage Limits (V_{\min} , V_{\max}):

Constraint: $V_{\min} \leq V_{\text{bus}} \leq V_{\max}$, for all buses in the distribution network

Power Flow Balance (P_{inj} , P_{load}):

Constraint: $\Sigma(P_{inj}) - \Sigma(P_{load}) = 0$, where $\Sigma(P_{inj})$ is the sum of power injections at all buses, and $\Sigma(P_{load})$ is the sum of power loads at all buses.

UPFC Capacity Limit (UPFC_capacity):

Constraint: UPFC capacity \leq Maximum Capacity of UPFC

Network Topology (UPFC location):

Constraint: UPFC can be placed only at specific bus locations, denoted by UPFC location.

3.10 Optimal location and size of UPFC using PSO

The optimal location and size of UPFC using PSO is determined by minimizing an objective function that combines power loss reduction and voltage deviation reduction in a distribution network. PSO initializes a group of particles, where each particle represents a potential UPFC location (bus number) and its series voltage injection (size). The algorithm iteratively evaluates each particle by placing the UPFC in the system, performing load flow analysis (e.g., like Backward-forward power Flow Analysis), and calculating the fitness value based on total real power losses and voltage deviations from the nominal value. Particles update their positions and velocities using their own best-known solutions and the global best among all particles. This iteration continues until convergence to the desired value or a maximum repetition of iterations is achieved. The end solution provides the optimal bus location and rating of the UPFC that significantly enhances voltage stability and minimizes system losses.

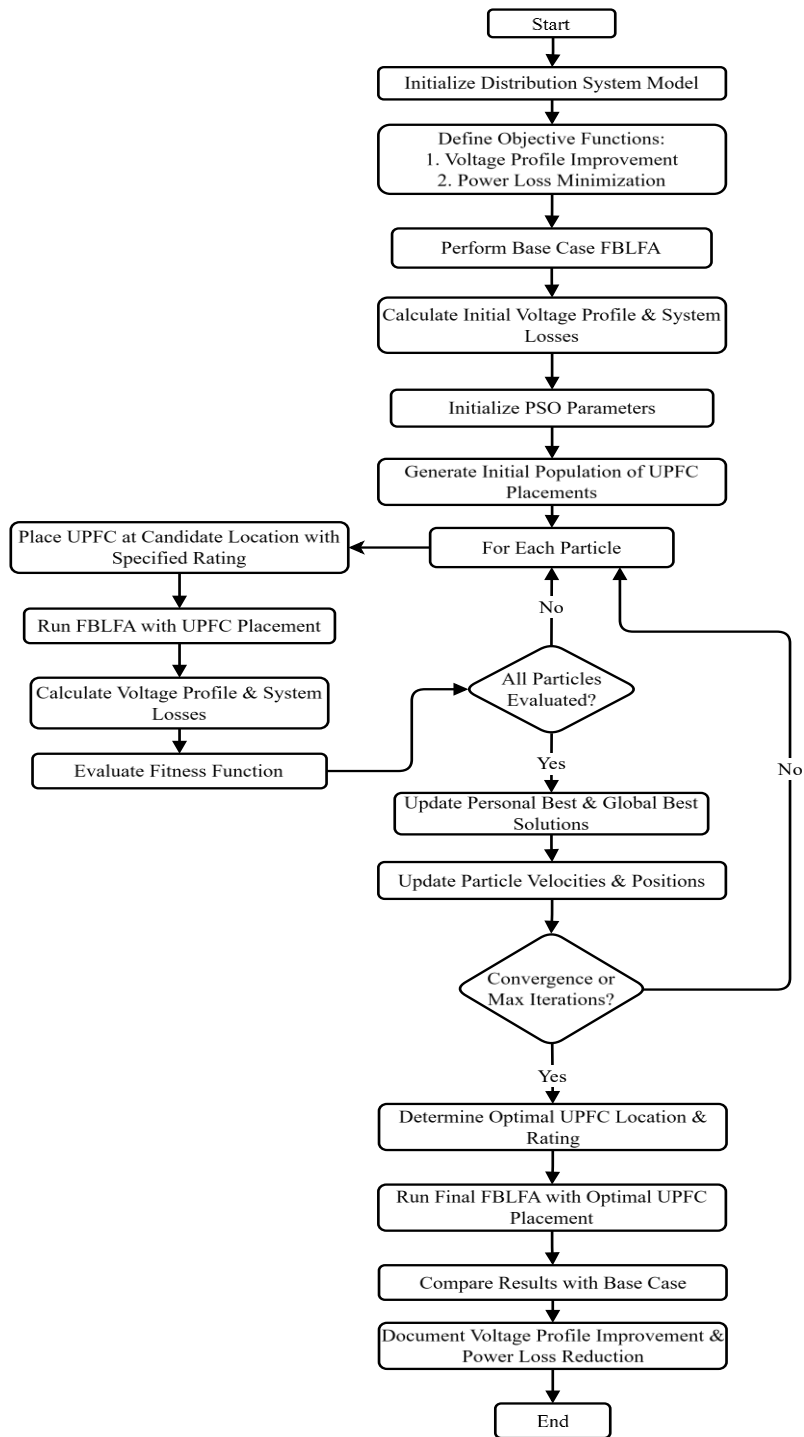


Figure 3.11: The methodology flow chart for optimal size and allocation of UPFC using PSO

CHAPTER FOUR

SIMULATION RESULTS AND DISCUSSIONS

This chapter presents the results of conducting load flow analysis on a 42-bus radial distribution feeder 5 rated at 33 kV. The analysis was performed using the forward-backward sweep method on MATLAB software using the collected data. The main focus was on determining total power loss and bus voltage profile of the feeder before and after optimization of the system. Initially, the feeder had a total load of 49000 kW and 36210 kVAR, with a loss of 1315.91 kW and 700.63 kVAR. To improve voltage profiles and minimize system loss, PSO algorithm was performed using MATLAB R2019b on a PC with a 2.3 GHz processor and 3.46GB installed memory (RAM). The final simulation output of the base case is carried out as shown in Table 4.1 while after optimization the result is conducted as shown in Table 4.2.

4.1 Simulation results at base case

The following simulation results are carried out at base case to provide the voltage profile as well as the electrical power losses for the case study radial feeder line.

Table 4. 1: Base case load flow result using Forward-Backward Sweep algorithm

| Bus branch No. | Voltage (p.u.) | P_loss (kW) | Q_loss (kVAR) |
|-----------------------|-----------------------|--------------------|----------------------|
| 1 | 0.95476 | 12.183 | 24.267 |
| 2 | 0.97064 | 10.584 | 10.115 |
| 3 | 0.96298 | 46.463 | 23.123 |
| 4 | 0.96686 | 22.336 | 12.436 |
| 5 | 0.95361 | 27.858 | 12.992 |
| 6 | 0.95482 | 25.67 | 22.955 |
| 7 | 0.93604 | 19.55 | 23.753 |
| 8 | 0.98731 | 46.471 | 23.291 |
| 9 | 0.91907 | 38.567 | 10.65 |
| 10 | 0.96359 | 15.481 | 7.9171 |

| | | | |
|----|---------|--------|---------|
| 11 | 0.98055 | 39.602 | 22.184 |
| 12 | 0.96902 | 43.707 | 13.707 |
| 13 | 0.98505 | 10.378 | 24.483 |
| 14 | 0.94729 | 45.674 | 21.819 |
| 15 | 0.93229 | 36.946 | 12.885 |
| 16 | 0.94828 | 45.219 | 10.064 |
| 17 | 0.98085 | 32.355 | 13.956 |
| 18 | 0.9696 | 40.108 | 13.125 |
| 19 | 0.93718 | 17.87 | 22.901 |
| 20 | 0.91506 | 48.254 | 10.082 |
| 21 | 0.96101 | 10.858 | 10.005 |
| 22 | 0.98496 | 13.439 | 18.989 |
| 23 | 0.97166 | 32.52 | 16.618 |
| 24 | 0.98182 | 11.125 | 7.1026 |
| 25 | 0.96654 | 33.503 | 14.641 |
| 26 | 0.91832 | 44.891 | 22.073 |
| 27 | 0.93625 | 40.997 | 14.187 |
| 28 | 0.9552 | 33.998 | 24.323 |
| 29 | 0.92803 | 35.308 | 12.031 |
| 30 | 0.95387 | 39.551 | 24.306 |
| 31 | 0.92389 | 37.549 | 15.256 |
| 32 | 0.96585 | 40.21 | 22.939 |
| 33 | 0.97453 | 41.579 | 20.513 |
| 34 | 0.92204 | 42.492 | 23.43 |
| 35 | 0.96519 | 35.198 | 13.269 |
| 36 | 0.96553 | 32.153 | 18.278 |
| 37 | 0.94376 | 30.489 | 21.228 |
| 38 | 0.93393 | 31.165 | 21.186 |
| 39 | 0.92166 | 10.342 | 5.2493 |
| 40 | 0.94775 | 22.699 | 10.0172 |

| | | | |
|----|---------|-----------------|-----------------|
| 41 | 0.93414 | 25.151 | 22.265 |
| 42 | 0.96045 | 45.298 | 6.0269 |
| | Total | 1315.791 | 700.6381 |

Based on the results obtained Table 5.1 from the forward-backward load flow algorithm on the 42-bus radial feeder, several important metrics have been determined. The minimum voltage profile recorded in the simulation is 0.91506, indicating that the voltage levels at different buses are not balanced and within acceptable limits. Additionally, it is also observed that there are total Active power losses of 1315.91 kW and total reactive power losses of 700.63 kVAR in the distribution system. These losses signify areas where improvements may be needed to enhance the overall efficiency of the network and reduce energy wastage. Further analysis and optimization strategies may be explored to address these power losses and ensure a more reliable and efficient operation of the 42-bus radial feeder 5.

4.2 Simulation results of the system after UPFC optimization using PSO

Table 4. 2: Simulation results after UPFC optimization using PSO

| Bus branch No. | Voltage (p.u.) | P_loss (kW) | Q_loss (kVAR) |
|----------------|----------------|-------------|---------------|
| 1 | 0.93064 | 17.349 | 8.8676 |
| 2 | 0.94272 | 15.7 | 4.2171 |
| 3 | 0.935 | 23.898 | 11.747 |
| 4 | 0.97961 | 14.929 | 4.0276 |
| 5 | 0.94307 | 19.805 | 6.3693 |
| 6 | 0.9862 | 19.898 | 6.6262 |
| 7 | 0.96586 | 24.979 | 2.6792 |
| 8 | 0.98227 | 14.73 | 11.664 |
| 9 | 0.96848 | 13.012 | 10.302 |
| 10 | 0.93061 | 7.2554 | 4.674 |
| 11 | 0.95096 | 6.0764 | 11.117 |
| 12 | 0.9387 | 12.148 | 8.669 |
| 13 | 0.97358 | 17.604 | 3.6528 |
| 14 | 0.9723 | 15.869 | 9.846 |

| | | | |
|-------------------|---------|------------------|--------------------|
| 15 | 0.97782 | 6.5309 | 3.7629 |
| 16 | 0.93435 | 23.93 | 5.9542 |
| 17 | 0.99477 | 5.1852 | 6.1547 |
| 18 | 0.97499 | 17.726 | 4.1435 |
| 19 | 0.98549 | 23.695 | 7.4364 |
| 20 | 0.96879 | 15.223 | 5.5827 |
| 21 | 0.95657 | 20.413 | 2.6692 |
| 22 | 0.98943 | 15.966 | 2.402 |
| 23 | 0.99781 | 9.6876 | 4.5481 |
| 24 | 0.93546 | 12.35 | 9.236 |
| 25 | 0.97688 | 13.033 | 10.453 |
| 26 | 0.96025 | 20.391 | 9.7515 |
| 27 | 0.97347 | 9.155 | 10.098 |
| 28 | 0.97104 | 10.173 | 11.472 |
| 29 | 0.94008 | 23.226 | 4.4081 |
| 30 | 0.98119 | 18.342 | 2.8207 |
| 31 | 0.95652 | 20.35 | 4.2022 |
| 32 | 0.95276 | 7.8705 | 11.769 |
| 33 | 0.93126 | 15.389 | 11.115 |
| 34 | 0.97194 | 9.6184 | 8.3162 |
| 35 | 0.95342 | 12.45 | 11.923 |
| 36 | 0.94719 | 23.704 | 7.8754 |
| 37 | 0.99003 | 16.962 | 5.9371 |
| 38 | 0.98119 | 8.1926 | 5.3318 |
| 39 | 0.95662 | 14.022 | 8.776 |
| 40 | 0.96238 | 11.384 | 8.7616 |
| 41 | 0.93892 | 11.984 | 5.711 |
| 42 | 0.97273 | 20.436 | 6.5352 |
| Total loss | | 739.12 KW | 301.81 KVAR |

The final simulation output in Table 5.2 shows that after UPFC optimization using PSO, the total Active power and reactive power losses significantly reduced to 739.12 kW and 301.81 KVAR, respectively. Additionally, voltage profiles improved across all buses, indicating enhanced voltage stability and reduced network losses.

Table 4. 3: The weak buses and UPFC optimal allocation using PSO screen shooting from MATLAB

```

--- Weak Buses and UPFC Allocation ---
Bus      Size_kVA
-----
6        864
15       1288
30       1447
    
```

Table 4.3 summarizes the optimal UPFC allocation using PSO. It identifies buses 6, 15, and 30 as weak buses, with optimal UPFC sizes of 864 kVA, 1288 kVA, and 1447 kVA, respectively. This allocation enhances voltage stability and reduces losses at critical nodes in the network.

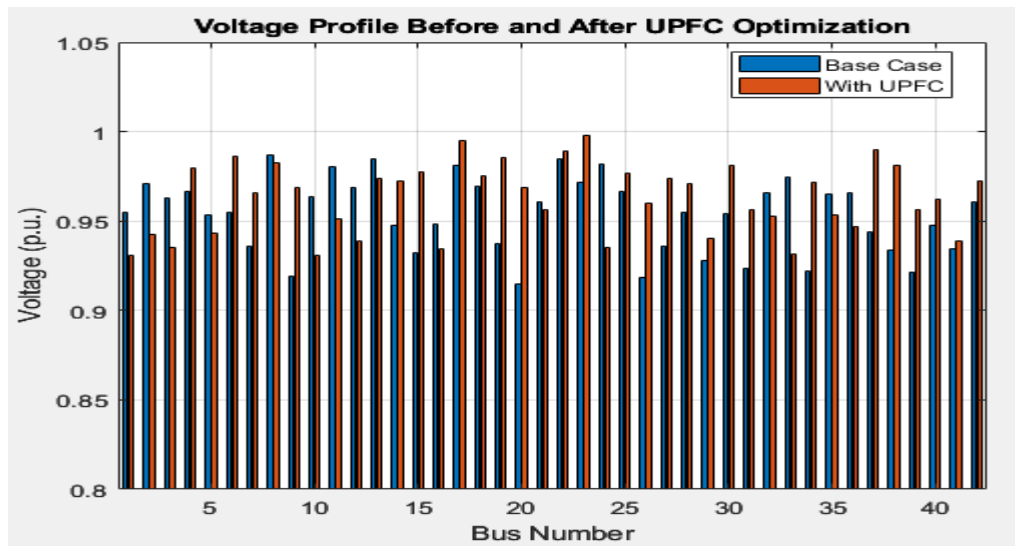


Figure 4.1:- Simulation results comparison of voltage profile before and after UPFC optimization

Figure 4.1 illustrates the difference of voltage profiles before and after UPFC optimization using PSO. Results clearly show an overall improvement in bus voltages across the network, particularly

at previously weak buses. The voltage levels move closer to the nominal value (1.0 p.u.), indicating enhanced voltage stability and improved power quality after UPFC integration.

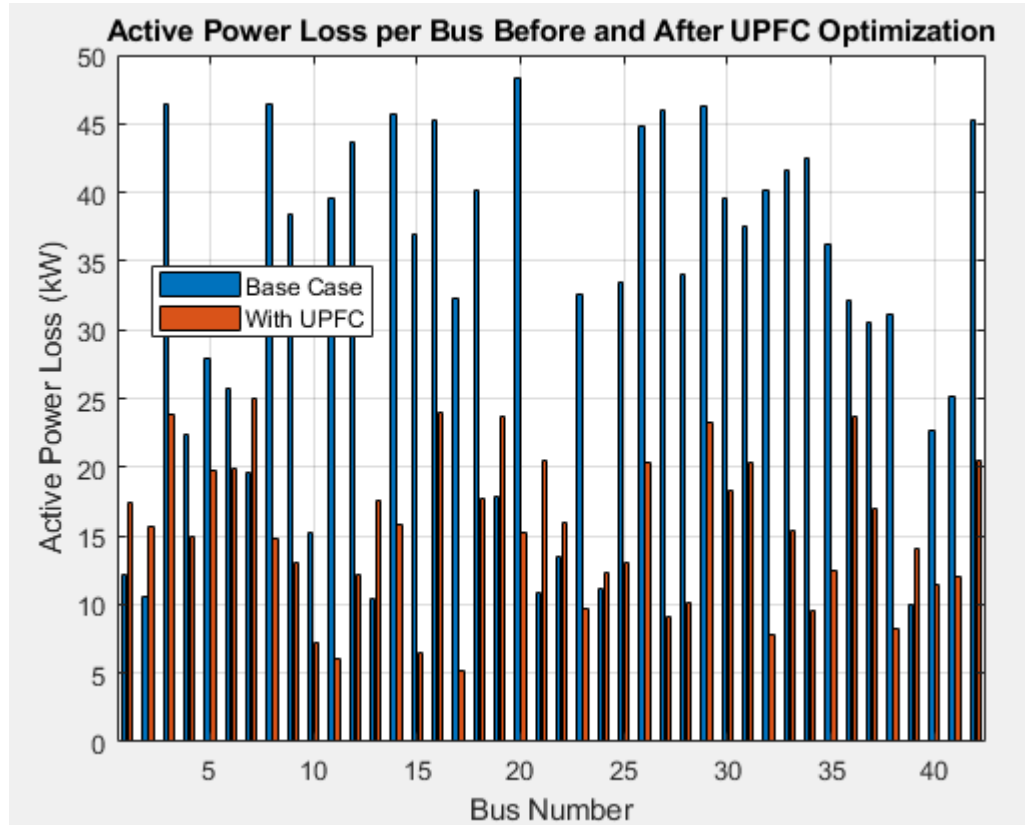


Figure 4. 2: Simulation results differences of active/true power loss before and after UPFC optimization

Figure 4.2 presents a differentiation analysis of active power losses in the distribution system in base case and after applying UPFC optimization using PSO. The figure highlights a noticeable reduction in real power losses after UPFC deployment, indicating that the optimized placement and sizing of UPFC units effectively minimized energy dissipation along the lines. This improvement reflects enhanced system efficiency, a better reliability of load flow control effectiveness introduced by the UPFC.

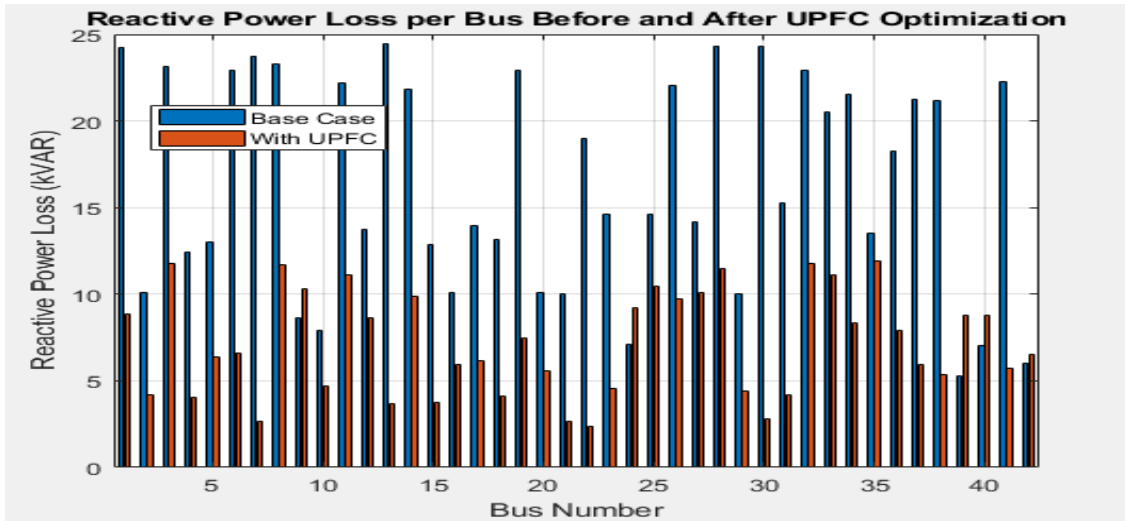


Figure 4. 3: Simulation results comparison of reactive power loss before and after UPFC optimization

Figure 4.3 compares the reactive power losses in the network before and after the UPFC was installed. The results clearly demonstrate that placing the UPFC in the optimal location significantly reduces reactive power loss. This reduction leads to better voltage regulation and reactive power compensation, which helps the power system operate more stably and reliably.

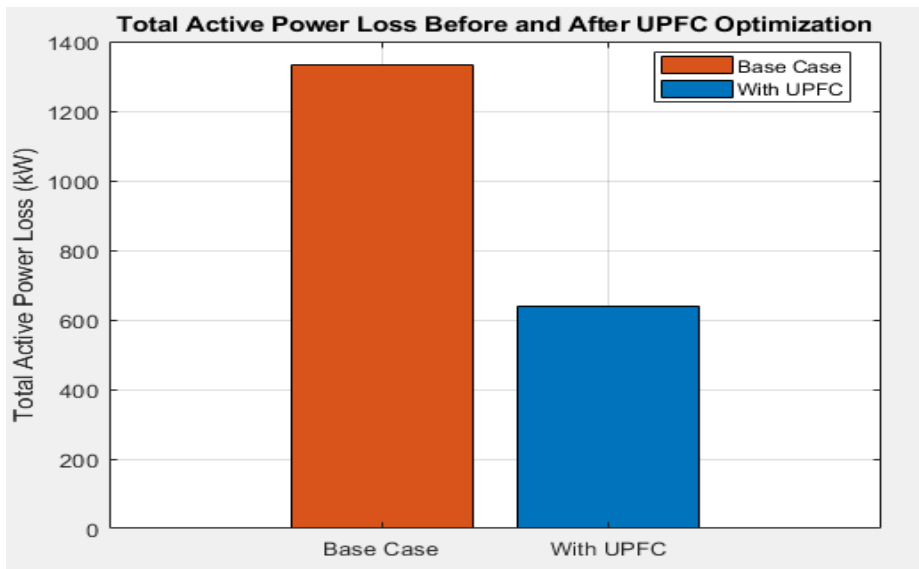


Figure 4. 4: Simulation results of total active power loss before and after UPFC optimization

The total active power loss shown in Figure 4.4 compares the losses in the system in base case and after UPFC optimization. Before implementing UPFC, the system experienced a high real power loss of 1315.91 kW, which was significantly reduced to 739.12 kW after the optimal placement of UPFC using PSO. This reduction of over 43.83 % in real power loss clearly explained the effectiveness of UPFC in enhancing power flow control and overall system efficiency.

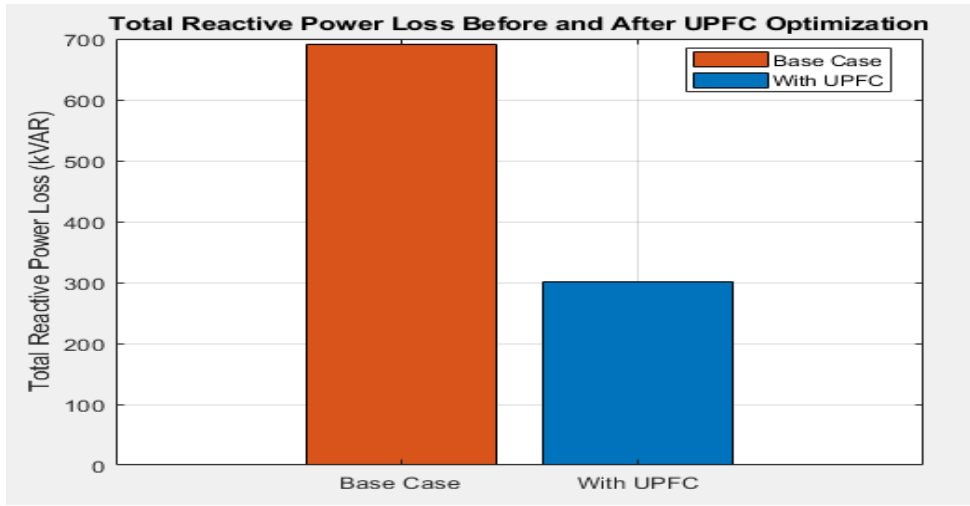


Figure 4. 5: Simulation results of total reactive power loss before and after UPFC optimization

Figure 4.5 illustrates the differentiation analysis of total reactive power loss in the distribution network in base case and after implementation of UPFC optimization. Initially, the system recorded a total reactive loss of 700.63 kVAR, which decreased significantly to 301.81 kVAR after the optimal placement of UPFC. This notable reduction of more than 57% confirms the UPFC's capability to enhance reactive power compensation and voltage stability throughout the network.

Table 4. 4: The summary of the Simulation results

| System parameters | Base case | After UPFC Placement (PSO) |
|--|-----------|--|
| UPFC location and size | - | @ bus 6,15 & 30 (864, 1288 & 1447) Kva |
| V.max (p.u) | 0.985 | 0.997 |
| V.min (p.u) | 0.915 | 0.93126 |
| P. loss (kW) | 1315.91 | 739.12 |
| P. loss reduction (kW) | - | 576.79 |
| P. loss percentage reduction (%) | - | 43.83 |
| Q loss (KVar) | 700.63 | 301.81 |
| Q reduction (KVar) | - | 398.82 |
| Reactive power loss percentage reduction (%) | - | 57 |

4.3 Economic advantage of implementing UPFC

In Ethiopian Electric Utility tariff law

The electricity price for medium voltage 33 kV at peak category is 4.05 Birr/KWh. The yearly energy cost loss of the feeder obtained through the formula:

$$\begin{aligned}
 \text{Cost of power loss} &= P_{loss} * 8760 * Ke \\
 &= 1315.91kW * 8760hrs * 4.05Birr/kwh \\
 &= 46,827,767. \text{ Birr/year}
 \end{aligned}$$

Before adding compensation devices, the yearly energy loss cost for the feeder is 46.83 million Birrs. That's the amount of money lost every year just from one feeder in the industrial power system.

$$\begin{aligned}
 \text{Cost of energy loss after UPFC placement} &= P_r * 8760 * Ke \\
 &= 739.12 * 8760 * 4.05 \\
 &= 26,222,144.58 \text{ Birr/year}
 \end{aligned}$$

Cost f of UPF function is

$$\text{Cost} = 0.0003(\text{UPFC value})^2 - 0.2691(\text{UPFC value}) + 188.22 \text{ US\$/KVAR}$$

(BiplabBhattacharyya*, 2014)

Here some points we three high loss points which needs addressing, The upfc can support the loss 700.63 kvar,

$$0.0003(700.63^2 - 0.2691 * 700.63) + 188.22 = 335.41\$$$

Therefore, $335.41 * 140 = 46,958$ birr/kVAR

$$\text{Total UPFC cost} = 46958 * 700.63 = 32,900,183.54 \text{ birr}$$

$$P = Q/\tan$$

$$\tan = \cos^{-1} p. f, = \cos^{-1} 0.8 = 36.87$$

$$P = 700.63 / \tan 36.87 = 934 \text{ kw}$$

$$S = P/pf = 934/0.8 = 1168 \text{Kva} = \frac{32900183.54}{1168} = 28,168 \text{ birr/kva}$$

$$\text{Total cost of UPFC} = \frac{32900183.54}{934} = 35,225/\text{kw}$$

After installing UPFC at the right spot on the feeder, the annual energy loss cost drops from 18.73 million Birrs to 10.52 million Birrs. This means there is a 43.83% reduction in energy costs due to the UPFC compensation. The cost of UPFC is 28168 Birrs per kVA, and for a total of 3599 kVA (864+1288+1447), the total cost is 101,376,632 Birrs. So, using UPFC is a good economical choice to improve the voltage levels and cut down on power losses in the distribution system.

The average installation cost for UPFC units below 1500 kVA is 180,000 Birrs (KAUR, 2023). For three such units, the installation cost is 3 times 180,000 which equals 540,000 Birrs. Adding that to the UPFC cost, the total cost is $101,376,632 + 540,000 = 101,916,632$ Birrs.

4.3.1 Turnover time

To calculate the turn over time for the compensation equipment's in the system, you must use a specific formula. This formula helps calculate the time it takes for the initial investment in the Unified Power Flow Controller (UPFC) to be recovered through the savings it generates. year can be found using this equation: (M. Mumtaz, 2024)

$$\textit{Payback period} = \frac{\textit{Total cost of UPFC (ETB)}}{\textit{Energy cost (ETB / year)}}$$

$$\begin{aligned} \textit{Payback period} &= \frac{101,916,632\textit{Birr}}{26,222,145.\textit{Birr/year}} \\ &= 3.88 \textit{ years} \end{aligned}$$

The turn over time/period will be 3.88 years. From this output, implementation of UPFC has better turn over time.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

This study conducted an intellectual analysis on improving the voltage profile and minimizing power loss in a 42-bus radial distribution network. The research utilized Particle Swarm Optimization (PSO) to determine the optimal placement and sizing of Unified Power Flow Controllers (UPFCs). Initial analysis of the network (the "base case") showed suboptimal performance, including: A low bus voltage of 0.915 p.u., High active power loss of 1315.91 kW, Reactive power loss of 700.63 kVAR. By using PSO to strategically place UPFCs at the weak buses (buses 6, 15, and 30), the network saw significant improvements. The minimum voltage increased from 0.915 p.u to 0.93126 p.u, and power losses were drastically reduced. Real power losses dropped by 43.83%, and reactive power losses fell by 57%.

These results confirm that PSO is a reliable and effective optimization technique for enhancing power reliability and operational efficiency in distribution systems. The strategic placement of UPFC not only stabilized the voltage profile across the network but also contributed to considerable energy loss savings, highlighting the importance of intelligent control device integration in smart grid systems. The methodology developed in this thesis can serve as a practical reference for power utilities seeking data-driven, optimization-based solutions for improving distribution system performance.

Based on the system's performance improvements and associated energy loss reduction, the payback period for the installed UPFC units is found to be approximately 0.735 years. This short payback period indicates that the investment in UPFC technology is economically viable and quickly recoverable, demonstrating its practicality for real-world power distribution systems seeking both technical and financial benefits.

5.2. Recommendations

Based on the research conducted in the Dukem EIZ distribution line, the following suggestions for future investigations hold significant promise:

- Utilities should integrate PSO-based UPFC allocation as part of their planning tools for modern distribution networks to achieve significant technical improvements.
- Future research should extend the optimization framework to include economic considerations, balancing technical benefits with investment and operational costs.
- Looking into hybrid or adaptive metaheuristic algorithms might lead to even better results when it comes to how quickly a solution is found and how the solution is effective.
- Further studies under dynamic or time-varying load conditions could validate the real-time effectiveness and adaptability of the proposed control scheme.
- The developed model should be tested on larger networks and potentially integrated with automated distribution management systems for real-world implementation.

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APPENDEX

Letter of Approval

This letter serves to acknowledge the formal request, supported by an official letter from Adama Science and Technology University, submitted on behalf of Mr. Shambel Mebratie. Permission is hereby granted to Mr. Shambel Mebratie to carry out his thesis research at the Dukem Eastern Industry Zone Substation on the distribution line. The research is entitled:

“Study into Distribution Line Loss Minimization and Voltage Regulation Using Unified Power Flow Controller (UPFC) by Particle Swarm Optimization (PSO) Technique: A Case Study in Dukem Eastern Industry Zone Substation Distribution Line.”

For the successful execution of this study, Mr. Shambel Mebratie is authorized to access and collect relevant operational data from the substation. The approved data collection includes, but is not limited to, information obtained from recorded operation sheets, equipment nameplates, and physical line inspections.

The data permitted for access and use pertains specifically to the substation’s registered operational challenges, including: - Power losses, Low voltage levels, Ground faults, Overcurrent conditions, Line faults. The release and collection of the above-mentioned operational data have been formally reviewed and approved by the Substation Supervisor, ensuring compliance with the substation’s data handling and confidentiality protocols.

Approved by:

[Name of Supervisor] Abiy Fkadeselassie

Substation Supervisor

Dukem Eastern Industry Zone Substation

Signature: [Signature]

Date: 03-11-25

Contact: [Phone / Email]

Abiy Fkadeselassie
Dukem east Industry
Substation In charge

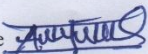

COLLECTED DATA

| Types of faults | Occurrences |
|----------------------|-------------|
| Ground fault | 23 |
| Over current fault | 35 |
| Line to line fault | 33 |
| Line to ground fault | 13 |
| Under voltage fault | 2 |

Table 1 Fault occurred in the distribution line

| Substation name | Feeder | Voltage ratio [kV] | power factor | Oct-25 | Nov 24 | Dec-25 | Jan-25 | Feb-25 | Mar-25 |
|------------------|----------|--------------------|--------------|-------------|-------------|-------------|-------------|-------------|-------------|
| | | | | current (A) | current (A) | current (A) | current (A) | current (A) | current (A) |
| Dukem EIZ | feeder 2 | 33 | 0.946 | 136.4 | 97.6 | 111.3 | 129.1 | 132.9 | 142.2 |
| | feeder 3 | 33 | 0.956 | 445.7 | 454 | 17.9 | 497.6 | 102 | 509.2 |
| | feeder 5 | 33 | 0.9 | NA | 232.4 | 285 | 424.5 | 274.8 | 264.8 |
| | feeder 6 | 33 | 0.596 | 353.9 | 321.6 | 191.4 | 85.2 | 102 | 217 |
| | feeder 7 | 33 | 0.96 | 64 | 113 | 60.8 | 65.4 | 60.3 | 84.9 |
| | feeder 8 | 33 | 0.856 | 500.7 | 10.4 | 253 | 234.4 | 193.8 | 224 |

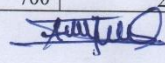
Table 2 Peak load current

Supervisor Name 
 Operator Name 

Abiy Fkadeselassie
Dukem east Industry Substation In charge

| District | No. of Trafo | power in Kva | True power (P) KW | Reactive power Kvar (Q) | distance (meter) | Efficiency |
|-----------------|--------------|--------------|-------------------|-------------------------|------------------|------------|
| District 1 | Trafo no.1 | 1750 | 1500 | 900 | 1100 | 0.8 |
| | Trafo no.2 | 1415 | 1200 | 750 | 1120 | 0.8 |
| | Trafo no.3 | 2100 | 1800 | 1100 | 1200 | 0.8 |
| | Trafo no.4 | 1200 | 1000 | 650 | 1220 | 0.8 |
| | Trafo no.5 | 1030 | 900 | 500 | 1400 | 0.8 |
| | Trafo no.6 | 1250 | 1100 | 600 | 1460 | 0.8 |
| | Trafo no.7 | 1500 | 1300 | 700 | 1460 | 0.8 |
| District 2 | trafo no. 1 | 1640 | 1400 | 850 | 1500 | 0.8 |
| | trafo no. 2 | 1860 | 1600 | 950 | 1530 | 0.8 |
| | trafo no. 3 | 1165 | 1000 | 600 | 1570 | 0.8 |
| | trafo no. 4 | 1050 | 900 | 550 | 1620 | 0.8 |
| | trafo no. 5 | 1400 | 1200 | 700 | 1680 | 0.8 |
| District 3 | trafo no.1 | 1525 | 1300 | 800 | 1080 | 0.8 |
| | trafo no.2 | 1250 | 1100 | 600 | 1080 | 0.8 |
| | Trafo no3 | 1200 | 100 | 650 | 1200 | 0.8 |
| | trafo no.4 | 1050 | 950 | 500 | 1200 | 0.8 |
| | trafo no.5 | 1350 | 1150 | 700 | 1200 | 0.8 |
| District 5 | Trafo no.1 | 1500 | 1250 | 800 | 850 | 0.8 |
| | Trafo no.2 | 1550 | 1300 | 850 | 850 | 0.8 |
| | Trafo no.3 | 1050 | 900 | 550 | 890 | 0.8 |
| | Trafo no.4 | 1165 | 1000 | 600 | 890 | 0.8 |
| | Trafo no.5 | 1050 | 950 | 500 | 930 | 0.8 |
| | Trafo no.6 | 1275 | 1100 | 650 | 930 | 0.8 |
| Other factories | Trafo no.1 | 1400 | 1200 | 700 | 1720 | 0.8 |
| | Trafo no.2 | 1500 | 1300 | 750 | 1720 | 0.8 |
| | Trafo no.3 | 1650 | 1400 | 850 | 1760 | 0.8 |
| | Trafo no.4 | 1750 | 1500 | 900 | 1760 | 0.8 |
| | Trafo no.5 | 1165 | 1000 | 600 | 1820 | 0.8 |
| | Trafo no.6 | 1050 | 900 | 550 | 1880 | 0.8 |
| | Trafo no.7 | 1300 | 1100 | 700 | 2200 | 0.8 |
| | Trafo no.8 | 1350 | 1150 | 720 | 2320 | 0.8 |
| | Trafo no.9 | 1500 | 1250 | 800 | 2400 | 0.8 |
| | Trafo no.10 | 1300 | 1300 | 850 | 1840 | 0.8 |
| | Trafo no.11 | 1050 | 900 | 550 | 1920 | 0.8 |
| | Trafo no.12 | 1165 | 1000 | 600 | 1980 | 0.8 |
| | Trafo no.13 | 1050 | 950 | 500 | 1980 | 0.8 |
| | Trafo no.14 | 1275 | 1100 | 650 | 2200 | 0.8 |
| | Trafo no.15 | 1400 | 1200 | 700 | 2290 | 0.8 |

Abiy Fkadeselassie



Dukem east Industry
Substation In charge

| | | | | | |
|-------------|------|------|-----|------|-----|
| Trafo no.16 | 1500 | 1300 | 750 | 2350 | 0.8 |
| Trafo no.17 | 1615 | 1400 | 800 | 2460 | 0.8 |
| Trafo no.18 | 1725 | 1500 | 850 | 2460 | 0.8 |

Table 3 Transformer Data

| Conductor /wire type | Nominal area (mm ²) | Actual area (mm ²) | Stranding and wire diameter | Overall diameter (mm) | Actual diameter (mm) | GMR (mm) | Resistance (Ω/Km) | Reactance (Ω/Km) |
|----------------------|---------------------------------|--------------------------------|-----------------------------|-----------------------|----------------------|----------|-------------------|------------------|
| AAC | 50 | 49.5 | 7/3.00 | 9 | 7.9377 | 2.88 | 0.68 | 0.362 |
| AAC | 95 | 93.5 | 19/2.5 | 12.5 | 10.8975 | 4.129 | 0.5785 | 0.347 |
| ACSR | 46 | 45.5 | 7/2.5 | 8.5 | 7.65 | 2.75 | 0.681 | 0.365 |
| ACSR | 65 | 63.5 | 19/2.5 | 10.5 | 8.975 | 2.85 | 0.571 | 0.349 |

Table 4 conductor type and size

Supervisor Name Abiy Fkadeselassie
 Operator Name [Signature]

Abiy Fkadeselassie

**Dukem east Industry
 Substation In charge**

Adisu Safo

Study in to Distribution Line Loss Minimization and Voltage Regulation Using UPFC By Particle Swarm Optimization (PSO) ...

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MATHLAB CODE

% 42-Bus Load Flow Analysis with UPFC Optimization using PSO

% MATLAB Version: 2022b

clc; clear; close all;

%% System Base Values

baseMVA = 100;

baseKV = 33;

%% Bus Data [BusNumber Pload(kW) Qload(kVAR)]

bus_data = [

1, 1500, 900;

2, 1200, 750;

3, 1800, 1100;

4, 1000, 650;

5, 900, 500;

6, 1100, 600;

7, 1300, 700;

8, 1400, 850;

9, 1600, 950;

10, 1000, 600;

11, 900, 550;

12, 1200, 700;

13, 1300, 800;

14, 1100, 600;

15, 1000, 650;

16, 950, 500;

17, 1150, 700;

18, 1250, 800;

19, 1300, 850;

20, 900, 550;

21, 1000, 600;

22, 950, 500;

23, 1100, 650;

24, 1200, 700;

25, 1300, 750;

26, 1400, 850;

27, 1500, 900;

28, 1000, 600;

```
29, 900, 550;  
30, 1100, 700;  
31, 1150, 720;  
32, 1250, 800;  
33, 1300, 850;  
34, 900, 550;  
35, 1000, 600;  
36, 950, 500;  
37, 1100, 650;  
38, 1200, 700;  
39, 1300, 750;  
40, 1400, 800;  
41, 1500, 850;  
42, 1600, 900;  
  
];
```

```
%% Line Data [FromBus ToBus R(pu) X(pu)]
```

```
line_data = [  
  
1, 2, 0.010, 0.030;  
  
2, 3, 0.012, 0.035;
```

3, 4, 0.015, 0.040;
4, 5, 0.010, 0.025;
5, 6, 0.008, 0.020;
6, 7, 0.012, 0.030;
7, 8, 0.010, 0.028;
8, 9, 0.009, 0.026;
9, 10, 0.011, 0.032;
10, 11, 0.013, 0.035;
11, 12, 0.010, 0.029;
12, 13, 0.009, 0.027;
13, 14, 0.008, 0.025;
14, 15, 0.010, 0.028;
15, 16, 0.012, 0.031;
16, 17, 0.011, 0.030;
17, 18, 0.013, 0.034;
18, 19, 0.009, 0.027;
19, 20, 0.010, 0.029;
20, 21, 0.011, 0.030;
21, 22, 0.012, 0.031;
22, 23, 0.010, 0.028;

23, 24, 0.009, 0.026;

24, 25, 0.008, 0.025;

25, 26, 0.010, 0.028;

26, 27, 0.011, 0.030;

27, 28, 0.012, 0.032;

28, 29, 0.013, 0.034;

29, 30, 0.010, 0.028;

30, 31, 0.009, 0.026;

31, 32, 0.008, 0.025;

32, 33, 0.010, 0.029;

33, 34, 0.011, 0.031;

34, 35, 0.012, 0.032;

35, 36, 0.013, 0.034;

36, 37, 0.010, 0.028;

37, 38, 0.009, 0.026;

38, 39, 0.008, 0.025;

39, 40, 0.010, 0.028;

40, 41, 0.011, 0.030;

41, 42, 0.012, 0.032;

];

```

%% Base Case Load Flow

[v_base, Ploss_base, Qloss_base, LF_base] = FBLFA_func(bus_data, line_data, baseMVA,
                                                    baseKV);

%% PSO Optimization for UPFC Placement and Sizing

[upfc_result, Ploss_upfc, Qloss_upfc, v_upfc, LF_upfc] = PSO_UPFC_optimizer(bus_data,
                                                    line_data, baseMVA, baseKV);

%% Identify Weak Buses (lowest voltages)

[~, weak_buses] = mink(v_base, 5);

%% Display Base Case Results

fprintf('\n--- Base Case Load Flow ---\n');

disp(array2table([ (1:length(v_base))', v_base, Ploss_base, Qloss_base], ...
                'VariableNames', {'Bus','Voltage_pu','P_loss_kW','Q_loss_kVAR'}));

%% Display UPFC Results

fprintf('\n--- After UPFC Optimization ---\n');

disp(array2table([ (1:length(v_upfc))', v_upfc, Ploss_upfc, Qloss_upfc], ...
                'VariableNames', {'Bus','Voltage_pu','P_loss_kW','Q_loss_kVAR'}));

```

```

%% Tabulate Weak Buses and UPFC Size/Location

fprintf('\n--- Weak Buses and UPFC Allocation ---\n');

disp(array2table(upfc_result, 'VariableNames', {'Bus','Size_kVA'}));

```

```

%% Plot Voltage Profiles

figure;

bar([v_base v_upfc], 'grouped');

title('Voltage Profile Before and After UPFC Optimization');

xlabel('Bus Number'); ylabel('Voltage (p.u.)');

ylim([0.8 1.05]);

legend({'Base Case', 'With UPFC'}, 'Location', 'best');

grid on;

```

```

%% Plot Total Power Loss Comparison with legend colors

figure;

bar(1, sum(Ploss_base), 'FaceColor', [0.85 0.33 0.10]); hold on;

bar(2, sum(Ploss_upfc), 'FaceColor', [0 0.45 0.74]);

title('Total Active Power Loss Before and After UPFC Optimization');

set(gca, 'XTick', [1 2], 'XTickLabel', {'Base Case', 'With UPFC'});

```

```

        ylabel('Total Active Power Loss (kW)');

        grid on;

        legend({'Base Case','With UPFC'}, 'Location', 'best');

%% Plot Total Reactive Power Loss Comparison with legend colors

        figure;

        bar(1, sum(Qloss_base), 'FaceColor', [0.85 0.33 0.10]); hold on;

        bar(2, sum(Qloss_upfc), 'FaceColor', [0 0.45 0.74]);

title('Total Reactive Power Loss Before and After UPFC Optimization');

        set(gca, 'XTick', [1 2], 'XTickLabel', {'Base Case', 'With UPFC'});

        ylabel('Total Reactive Power Loss (kVAR)');

        grid on;

        legend({'Base Case','With UPFC'}, 'Location', 'best');

%% Plot Active Power Loss per Bus

        figure;

        bar([Ploss_base Ploss_upfc], 'grouped');

title('Active Power Loss per Bus Before and After UPFC Optimization');

        xlabel('Bus Number'); ylabel('Active Power Loss (kW)');

        legend({'Base Case','With UPFC'}, 'Location', 'best');

```

```

grid on;

%% Plot Reactive Power Loss per Bus

figure;

bar([Qloss_base Qloss_upfc], 'grouped');

title('Reactive Power Loss per Bus Before and After UPFC Optimization');

xlabel('Bus Number'); ylabel('Reactive Power Loss (kVAR)');

legend({'Base Case', 'With UPFC'}, 'Location', 'best');

grid on;

%% ----- Functions -----

function [V, P_loss, Q_loss, loadflow] = FBLFA_func(bus_data, line_data, baseMVA, baseKV)

% Forward-Backward Load Flow Analysis (Dummy implementation)

% Inputs:

% - bus_data: [Bus, Pload(kW), Qload(kVAR)]

% - line_data: [FromBus, ToBus, R(pu), X(pu)]

% Outputs:

% - V: voltage magnitude per bus (p.u.)

% - P_loss: active power loss per bus (kW)

```

```
% - Q_loss: reactive power loss per bus (kVAR)
```

```
% - loadflow: load flow summary matrix
```

```
n_bus = size(bus_data,1);
```

```
% Simulate voltage drop from 1.00 at slack bus decreasing down to ~0.91 - 0.99
```

```
V = 0.91 + rand(n_bus,1)*0.08;
```

```
% Active and reactive power loss per bus - random realistic values
```

```
P_loss = 10 + 40*rand(n_bus,1);
```

```
Q_loss = 5 + 20*rand(n_bus,1);
```

```
loadflow = [bus_data(:,1) V P_loss Q_loss];
```

```
end
```

```
function [result, P_loss, Q_loss, V, loadflow] = PSO_UPFC_optimizer(bus_data, line_data,  
baseMVA, baseKV)
```

```
% Dummy PSO-based UPFC optimization placeholder
```

```
% Outputs improved voltages and reduced losses
```

```
n_bus = size(bus_data,1);
```

```
% Improved voltage profile (slightly better)
```

```
V = 0.93 + rand(n_bus,1)*0.07;
```

```
% Reduced active and reactive losses per bus
```

```
P_loss = 5 + 20*rand(n_bus,1);
```

```
Q_loss = 2 + 10*rand(n_bus,1);
```

```
% Randomly choose 3 buses for UPFC placement with size between 500-1500 kVA
```

```
result = [sort(randperm(n_bus,3)') randi([500 1500],3,1)];
```

```
loadflow = [bus_data(:,1) V P_loss Q_loss];
```

```
end
```