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Load Flow Analysis in Power Distribution: A Case Study of 33/11KV Power Substation, JBVNL Naisaray, Ramgarh, Jharkhand

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Abstract - Results indicate that the existing network suffers from low feeder voltages (up to −4.18%), poor power factors (0.78–0.81), and high technical losses (~2.9%), translating into an annual financial burden of approximately ₹85.9 lakhs. Load redistribution relieved overburdened feeders and reduced losses to 2.4%, while capacitor bank installation improved the power factor above 0.90 and reduced losses to 2.1%. The combined optimization strategy yielded the most significant benefits, with feeder voltages maintained within ±2% tolerance, an overall system power factor of 0.94, and losses reduced to 1.8%, resulting in annual savings of ~₹32 lakhs.

Validation using the IEEE 4-bus test system confirmed the robustness of the methodology, where Newton-Raphson proved superior to Gauss-Seidel in terms of convergence and accuracy. Comparative analysis with literature demonstrates consistency with global research trends, while highlighting the unique role of feeder redistribution in underutilized distribution networks.

This thesis contributes a practically viable and replicable framework for substation optimization that combines reactive power compensation with feeder reconfiguration. The recommendations provide actionable insights for JBVNL and similar utilities, bridging the gap between academic research and real-world distribution challenges.

Keywords: *Load Flow Analysis*, *Power Distribution System*, *ETAP Simulation*
Feeder Load Balancing, Power Factor Improvement, Technical Loss Reduction, Reactive Power Compensation, Gauss-Seidel Method, Newton-Raphson Method

CHAPTER 1 INTRODUCTION

1.1 Background

Electric power systems form the backbone of modern civilization, enabling industrial growth, urbanization, rural electrification, and socio-economic development. The availability of reliable and affordable electricity is one of the most critical enablers for a country's growth trajectory [1]. A power system can be broadly divided into three hierarchical domains: generation, transmission, and distribution [2]. While generation and transmission have witnessed significant technological and infrastructural advancements in India, the distribution segment continues to be plagued with inefficiencies.

India, as one of the fastest-growing economies, has rapidly expanded its generation capacity, achieving an installed base exceeding 400 GW in 2025. However, the benefits of such expansion are often undermined by operational deficiencies in distribution. Distribution utilities especially state-run ones such as the Jharkhand Bijli Vitran Nigam Limited (JBVNL)face high technical losses, inadequate voltage regulation, transformer overloading, and poor consumer-end reliability [3] [4]. According to Central Electricity Authority (CEA) reports, aggregate technical and commercial (AT&C) losses in India remain around 17–20%, with certain states reporting losses above 25%. These inefficiencies directly impact both utility revenue and consumer satisfaction.

The 33/11 kV substations represent the critical interface between the high-voltage sub-transmission system and the 11 kV distribution network. Their performance significantly influences downstream feeder reliability and voltage stability [5] [6]. A poorly optimized substation can result in imbalanced load sharing, excessive voltage drops, low power factor, and frequent breakdowns.

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This makes substations the "nerve centres" of the distribution network and underscores the necessity of scientific analysis and optimization techniques [7] [8].

1.2 Importance of Load Flow Analysis in Distribution Systems

Load flow analysis (LFA), also termed power flow analysis, is a fundamental tool for evaluating the steady-state performance of a power system [1] [9]. It provides critical insights into:

- Voltage profile across all buses (ensuring it remains within permissible ±5% limits).
- Active and reactive power flows through transformers and feeders.
- Power factor assessment for efficient utilization of infrastructure.
- System losses (line and transformer losses, both load and no-load).
- Identification of stressed components such as overloaded feeders or transformers.

Traditionally, load flow analysis was more commonly applied to transmission systems due to their scale and complexity. However, with the increasing demand for distribution network reliability, LFA has emerged as an indispensable diagnostic and planning tool at the 33/11 kV substation level [3] [4].

Software platforms such as ETAP (Electrical Transient Analyzer Program), CYME, and DigSILENT Power Factory allow engineers to simulate realistic substation models, apply numerical methods such as Gauss-Seidel and Newton-Raphson, and predict system behaviour under varying load scenarios [10] [11]. Such analysis enables informed decision-making, from capacitor placement for reactive power compensation to feeder reconfiguration for loss minimization [5] [12].

Figure 1.1 Naisaray 33/11 kV Substation, JBVNL Ramgarh

1.3 The Indian Distribution Sector: Challenges

Despite extensive electrification, India's distribution sector continues to face:

1. High Technical Losses:
   Poor conductor sizing, aging infrastructure, and long feeder lengths contribute to resistive (I^2R) losses. Technical losses at 33/11 kV substations can be as high as 8–10%.

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2. Poor Voltage Regulation:
   Voltage at consumer ends often falls below permissible levels, especially in rural feeders where loads are predominantly inductive [6].

3. Transformer Overloading:
   Transformers frequently operate above 70% loading due to uneven feeder distribution, increasing the risk of failure [3].

4. Low Power Factor:
   Agricultural pumps, induction motors, and institutional loads draw excessive reactive power, depressing system power factor to as low as 0.75–0.80 [5].

5. Lack of Automation:
   Many substations, including the Naisaray case study, lack SCADA (Supervisory Control and Data Acquisition) systems, capacitor banks, and load tap changers. As a result, operators rely on manual monitoring [8] [9], which is reactive rather than preventive.

6. Idle Infrastructure:
   Spare feeders remain unused while others are overloaded, leading to inefficient asset utilization [7].

1.4 Case Study Context: Naisaray 33/11 kV Substation, JBVNL Ramgarh

The Naisaray substation under JBVNL in Ramgarh, Jharkhand, epitomizes these operational challenges [7] [8]. It consists of:

- Two transformers (10 MVA and 5 MVA, Dyn11 configuration) operating in parallel.
- Eight feeders, of which six are active (Ramgarh Town, Rural, Argada, Jail, Mandu, CCL Hospital) and two are spare (Industrial, Ghutua).
- Serves a mixed load profile: residential, agricultural, institutional, and commercial.

Field data reveals:

- Rural feeder is heavily loaded (72% utilization), whereas the Industrial and Ghutua feeders remain idle.
- Significant voltage drops (up to 4.18%) are observed on long rural feeders.
- Poor power factor (~0.78) for rural and institutional feeders, causing high reactive power demand [5] [11].
- Transformer loading imbalance leading to thermal stress [8].

These inefficiencies justify the need for a systematic load flow analysis to optimize performance, balance loads, reduce losses, and propose corrective strategies [4] [12].

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Figure 1.2 Operational inefficiencies in the 33/11 kV Naisaray Substation

1.5 Role of ETAP Simulation in the Study

ETAP offers an advanced simulation environment to replicate the Naisaray substation's Single Line Diagram (SLD) and execute load flow simulations under varying scenarios [11]. This study uses:

- Gauss-Seidel Method: Simple, iterative method suitable for radial distribution networks [10].
- Newton-Raphson Method: More accurate and faster convergence for complex networks [9].

By simulating normal load conditions and peak load conditions, ETAP facilitates identification of:

- Weak buses (under-voltage).
- Overloaded transformers or feeders.
- Total system technical losses.
- Potential corrective strategies such as load redistribution, capacitor bank installation, and combined optimization [12] [11].

Scope and Research Findings

This thesis is designed to answer the following research questions:

- Operational inefficiencies in the 33/11 kV Naisaray Substation.
- Load flow analysis using ETAP quantify and visualize these inefficiencies.
- Corrective strategies (redistribution, capacitors, automation) that yield the most significant improvements.
- Replicable model for other substations under JBVNL and beyond.

Scope of Study:

- Focused on steady-state load flow analysis (not transient or fault studies).
- Limited to technical parameters (voltage, PF, losses, loading).
- Field data validated through ETAP modeling.
- Practical, low-cost corrective measures prioritized for recommendations.

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Contribution of the Research

The research contributes in the following ways:

- Provides a detailed diagnostic analysis of a real-world substation under JBVNL.
- Demonstrates the utility of ETAP simulation for distribution-level planning [4] [10].
- Offers corrective strategies that are both technically sound and economically feasible [5].
- Establishes a replicable methodology for similar substations across Jharkhand and India [12].

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

Load flow analysis (LFA) has been a central theme in power system research for more than five decades, largely in the context of transmission networks. However, distribution systems present unique challenges due to their predominantly radial structure, higher resistance-to-reactance (R/X) ratios, and unbalanced loads, which make traditional transmission-based methods less efficient. With the increasing emphasis on reliability, efficiency, and the integration of distributed energy resources, research has shifted toward optimizing load flow techniques at the 33/11 kV substation and feeder levels, where operational inefficiencies and technical losses are most evident [7]. This chapter reviews existing literature on classical methods, distribution-specific algorithms, case studies, and smart grid integration, with the aim of identifying gaps relevant to the present study on the Naisaray substation in Jharkhand.

2.2 Classical Load Flow Methods

Classical methods such as the Gauss-Seidel (G-S), Newton-Raphson (N-R), and Fast Decoupled Load Flow (FDLF) approaches remain fundamental to power flow studies. The Gauss-Seidel method, one of the earliest iterative techniques, is computationally simple and suitable for small-scale radial systems, but it converges slowly and may diverge for large or weakly meshed networks [2][10]. The Newton-Raphson method is widely applied due to its quadratic convergence and accuracy, making it particularly effective for large and complex systems, albeit at the cost of computational intensity because of repeated Jacobian updates [1]. ETAP software, commonly used in power system analysis, relies heavily on this method for substation-level simulations [4][12]. The Fast Decoupled Load Flow method reduces the computational burden of N-R by decoupling real and reactive power calculations, enabling faster execution. However, it performs best in high-voltage transmission systems and is less reliable in low-voltage distribution networks with high R/X ratios [6][11]. These methods highlight the balance between computational efficiency and accuracy, providing a foundation for more advanced approaches suited to distribution networks.

2.3 Distribution-Specific Methods

Because classical methods were designed primarily for transmission systems, researchers have developed techniques specifically for Radial Distribution Systems (RDS). The Backward/Forward Sweep method has gained popularity due to its computational efficiency, lower memory requirements, and rapid convergence, particularly in radial and weakly meshed networks [4][6]. Another notable approach is the BIBC/BCBV matrix method, which transforms bus injections into branch currents and then into bus voltages, eliminating the need for Jacobian manipulation and thereby reducing computational complexity [11]. The ZBUS Gauss method incorporates impedance matrices to better model unbalanced loads, making it highly applicable to rural feeders with heterogeneous load profiles [12]. Similarly, the Loop Impedance method bypasses nodal equations and uses loop analysis to achieve faster convergence without significant computational overhead [5]. These innovations demonstrate the effort to adapt LFA techniques for the unique constraints of distribution substations such as Naisaray, where feeders are often mixed, unbalanced, and heavily loaded.

2.4 Case Studies on 33/11 kV Substations

Several regional and international studies highlight the application of these methods in real-world distribution networks. In Nigeria, ETAP-based Newton-Raphson analysis was applied to the Borokiri 33/11 kV substation, identifying undervoltage and overload issues, and recommending interventions such as capacitor banks and feeder bifurcation [4]. Similar work in India on the Ratnagiri 33/11 kV substation identified feeder-level voltage instabilities and suggested distributed generation (DG) integration as a corrective measure [6]. In Nepal, combined load flow with fault analysis was used to identify weak buses, emphasizing the lack of renewable integration [11]. In Nigeria, the Gauss-Seidel method showed that reconductoring could reduce technical losses by up to 57 percent [2]. A four-bus ETAP model also confirmed the superiority of N-R in terms of convergence speed and accuracy [12]. Distribution

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system studies with photovoltaic (PV) integration noted a marginal rise in fault currents, highlighting the need for adaptive protection [5]. Within the Jharkhand context, JBVNL field data revealed overloaded rural feeders (72 percent), poor power factor (0.78) in agricultural loads, and underutilized industrial feeders, underscoring the inefficiencies in current operations [7][8][9].

2.5 Smart Grid and IoT Integration

While classical and distribution-oriented methods provide effective computational tools, modern power systems increasingly incorporate smart grid technologies to improve monitoring and automation. IoT-based metering solutions using ESP32-GSM modules have enabled theft detection, real-time monitoring, and improved billing efficiency [12]. Similarly, DSTATCOM applications in distribution networks, optimized using particle swarm optimization (PSO), have outperformed conventional capacitor banks in voltage stabilization and reactive power management [11]. In advanced utilities worldwide, Supervisory Control and Data Acquisition (SCADA) systems are now widely deployed for automated feeder switching, voltage monitoring, and transformer protection. However, the absence of SCADA in Jharkhand's substations highlights a significant research and infrastructure gap [7][8]. These advancements show the potential of combining computational load flow techniques with automation and IoT-enabled frameworks to enhance both technical and economic efficiency.

1. Gauss-Seidel Method (G-S)
2. Newton-Raphson Method (N-R)
3. Fast Decoupled Load Flow (FDLF)

2.6 Distribution-Specific Methods

Researchers recognized that traditional methods struggle with radial distribution systems (RDS). Innovations include:

Backward/Forward Sweep Method

- Based on Kirchhoff's laws, efficient for radial and weakly meshed systems.
- Requires less memory and converges quickly.

BIBC/BCBV Matrix Approach

- Bus-Injection to Branch-Current (BIBC) and Branch-Current to Bus-Voltage (BCBV) matrices reduce computational complexity.
- Eliminates need for Jacobian manipulation, improving efficiency.

- ZBUS Gauss Method

- Incorporates impedance matrices to handle unbalanced loads effectively.
- Useful for unbalanced three-phase feeders.

- Loop Impedance Method

  - Uses loop analysis rather than nodal equations.
  - Provides rapid convergence without Jacobian involvement.

These approaches are particularly relevant to distribution substations like Naisaray, where loads are heterogeneous and unbalanced.

2.7 Case Studies on 33/11 kV Substations

1. Borokiri 33/11 kV Substation, Nigeria

- Ogbonna & Oniyeburutan (2023) applied N-R method in ETAP.
- Found undervoltage and overload issues; proposed capacitor banks and feeder bifurcation.

2. Ratnagiri 33/11 kV Substation, India

- Tayshete et al. (2021) analyzed feeder under/over-voltage issues using ETAP.

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- Recommended distributed generation (DG) integration.

3. Central Nepal Distribution Network

- Rijal et al. (2025) applied load flow + fault simulations.
- Identified weak buses and emphasized lack of renewable integration.

4. Borokiri & Enugu Networks, Nigeria

- Onodugo et al. (2021) simulated technical losses due to undersized conductors.
- Demonstrated 57% loss reduction through reconductoring.

5. Medical Square 33/11 kV Substation, India

- Holey et al. (2025) modeled a 4-bus ETAP system.
- Showed N-R convergence superiority and quantified voltage drops.

6. Nsukka 30-Bus Network with PV Integration, Nigeria

- Okwe et al. (2025) studied short-circuits with PV integration.
- Highlighted marginal rise in fault currents and need for adaptive protection.

7. Jharkhand Case (Present Study Context)

- Field data from JBVNL revealed:
  - Rural feeder overloaded at 72%
  - Poor PF (0.78) on agricultural loads
  - Idle feeders (Industrial, Ghutua)

2.8 Smart Grid and IoT Integration

While classical methods emphasize power flow computations, modern research integrates real-time monitoring and smart grid elements:

- IoT-Based Smart Meters
  - Chatterjee et al. (2022) developed ESP32-GSM-based meters.
  - Enabled theft detection, real-time monitoring, and improved billing efficiency.
- Zelibe & Oshevire (2025) demonstrated the use of DSTATCOM with PSO optimization for voltage stability and reactive power support.
- Outperformed capacitor banks in loss minimization.

SCADA Systems

- Global utilities now adopt Supervisory Control and Data Acquisition (SCADA) for automated feeder switching, voltage monitoring, and transformer protection.
- Lack of SCADA in Jharkhand substations is a major research gap.

2.9 Research Gaps

Despite considerable progress, several research gaps remain. Most studies have emphasized voltage stability and technical loss analysis, but economic optimization, such as annual loss cost evaluation and payback periods for corrective interventions, has not

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been adequately addressed. Similarly, renewable energy integration at the distribution level remains underexplored in South Asian contexts, where case studies remain sparse compared to regions like Nigeria or Nepal. Moreover, few studies have investigated automation-based optimization using SCADA, IoT, or FACTS devices in rural feeders, despite their potential to improve performance. Another limitation is the widespread assumption of balanced loads in simulations, which diverges significantly from the real conditions observed in mixed rural-urban distribution networks. Finally, Jharkhand's 33/11 kV substations remain largely undocumented in academic literature, creating an opportunity for the present study to address a clear gap.

From the reviewed literature:

1. Most studies emphasize voltage and loss analysis, but economic optimization (annual loss cost, payback from interventions) remains underexplored.
2. Renewable energy integration at distribution level is scarcely studied in South Asian contexts.
3. Limited research exists on automation-based optimization (SCADA, IoT, DSTATCOM) for rural feeders.
4. Case-specific studies exist (Nigeria, Nepal, Ratnagiri), but Jharkhand's substations lack documented research.
5. Many simulations assume balanced loads, which diverges from reality in mixed rural-urban feeders.

2.10 Comparative Summary of Literature

Study	Objective	Methodology	Key Findings	Software	Research Gaps
Ogbonna & Oniyeburutan (2023)	Borokiri 33/11 kV LFA	N-R in ETAP	Capacitors + reconfiguration improved PF, voltage	ETAP	No renewable integration
Tayshete et al. (2021)	Ratnagiri 33/11 kV	ETAP, N-R	Detected undervoltage; DG integration suggested	ETAP	Static load assumption
Rijal et al. (2025)	Central Nepal feeders	Load flow + faults	Weak buses identified	ETAP	No dynamic modeling
Onodugo et al. (2021)	Enugu 33/11 kV	Gauss-Seidel	Loss reduction via reconductoring	ETAP	Limited to technical losses
Holey et al. (2025)	4-Bus Substation	N-R, ETAP	N-R convergence superior	ETAP	Simplified 4-bus model
Okwe et al. (2025)	Nsukka + PV	ETAP, IEEE 30-bus	PV increased fault current	ETAP	Focused only on faults
Chatterjee et al. (2022)	Smart Metering	IoT + ESP32	Theft detection, billing efficiency	IoT	No LFA simulation
Zelibe & Oshevire (2025)	DSTATCOM in RDS	PSO + Simulation	Reduced losses, improved voltage	ETAP	High cost, not field-tested

2.11 Conclusion of Literature Review

The literature clearly establishes the importance of ETAP-based LFA for substation diagnostics. Studies consistently show that reactive power compensation, feeder reconfiguration, and automation can significantly improve reliability and reduce losses. However, Jharkhand's substations—including Naisaray—remain under-researched despite being prone to chronic voltage drops, high technical losses, and poor PF.

This research thesis therefore fills a critical research gap by:

- Conducting real-world ETAP simulations of Naisaray 33/11 kV substation.

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- Testing low-cost corrective strategies (redistribution + capacitors).
- Quantifying technical and financial savings.
- Providing a replicable model for other substations in Jharkhand.

CHAPTER 3: PROBLEM FORMULATION

3.1 Introduction to Problem Context

The 33/11 kV substation serves as the critical interface between the sub-transmission system and the primary distribution feeders. Its role is to step down power from 33 kV to 11 kV and distribute it through feeders to various consumer categories—residential, agricultural, institutional, and industrial. The performance of these substations directly affects power quality, reliability, and consumer satisfaction.

In developing regions like Jharkhand, substations face persistent operational issues:

- High technical losses (I^2R losses in lines, load and no-load transformer losses).
- Poor voltage regulation in long feeders, especially rural and agricultural ones.
- Transformer overloading due to uneven feeder loading.
- Low power factor in inductive loads.
- Absence of modern monitoring and automation systems.

The Naisaray Substation (JBVNL, Ramgarh) exemplifies these issues. The substation supplies electricity to urban, semi-urban, rural, and institutional consumers, yet its performance is constrained by imbalanced loads and absence of compensatory infrastructure.

3.2 Field Observations

Based on site surveys, JBVNL load records, and ETAP modeling, the following inefficiencies were observed:

1. Feeder Load Imbalance

- Rural feeder operates at 72% loading, near critical capacity.
- Jail feeder also shows high utilization.
- Industrial and Ghutua feeders remain idle, despite being fully operational.
- Result: Uneven load sharing stresses selected feeders while others remain underutilized.

2. Voltage Drop Issues

- Rural feeder bus recorded 10.54 kV, a 4.18% drop from nominal 11 kV.
- Jail feeder showed 3.72% voltage drop, close to the statutory limit of ±5%.
- Long line lengths combined with high inductive loading exacerbate voltage sag.

3. Low Power Factor

- Agricultural pumps and induction motors in rural areas operate at PF = 0.78–0.81.
- Institutional feeders (hospitals, government buildings) also show lagging PF.
- Low PF increases reactive power demand, causing poor voltage regulation and higher transformer burden.

4. Transformer Loading

- 10 MVA transformer: 72% loaded under peak.
- 5 MVA transformer: 66% loaded.

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- Although within acceptable ranges, uneven feeder loads increase risk of thermal stress and reduce asset life.

5. System Losses

- Total system losses estimated at 2.9% of power flow, equivalent to 104.42 k$ annually.
- Breakdown:
  - Line losses: 14.03 kW
  - Transformer load losses: 78.72 kW
  - Transformer no-load losses: 26.46 kW

6. Lack of Automation and Compensation

- No capacitor banks installed for reactive power support.
- No SCADA or AVR (Automatic Voltage Regulators) for real-time monitoring.
- Load management is reactive, relying solely on manual operator intervention.

3.3 Problem Statement

The Naisaray 33/11 kV substation under JBVNL is currently unable to operate at its optimal efficiency due to:

- Imbalanced feeder loading, resulting in transformer stress and underutilized infrastructure.
- Voltage drops beyond acceptable limits in long feeders, especially rural.
- Poor power factor caused by inductive loads, raising losses and reactive burden.
- Significant technical losses (≈2.9%), leading to high financial cost.
- Absence of automation and reactive power compensation mechanisms.

These factors jeopardize system reliability, cause frequent consumer complaints (low voltage, outages), and impose higher operational costs on the utility. Unless addressed through systematic interventions, the problems may escalate into equipment failure, higher AT&C losses, and consumer dissatisfaction.

3.4 Research Objectives

This thesis aims to diagnose, quantify, and optimize the performance of the Naisaray substation using load flow analysis (LFA) in ETAP software. The key objectives are:

1. Data Collection & System Modeling

- Gather real-time feeder load data, transformer specifications, and system parameters from JBVNL records and site surveys.
- Develop an accurate Single Line Diagram (SLD) in ETAP.

2. Load Flow Analysis

- Simulate normal and peak load scenarios using Gauss-Seidel and Newton-Raphson methods.
- Quantify voltage profiles, feeder and transformer loading, power factors, and losses.

3. Identification of Critical Issues

- Detect feeders with voltage drops beyond ±5%.
- Evaluate transformer loading imbalance.
- Identify feeders with poor PF (<0.85).

4. Simulation of Corrective Strategies

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- Scenario 1: Load Redistribution from overloaded feeders (Rural, Jail) to spare feeders (Industrial, Ghutua).
- Scenario 2: Capacitor Bank Installation to improve PF and support reactive demand.
- Scenario 3: Combined Optimization for maximum improvement.

5. Result Evaluation

- Compare base case and improved scenarios in terms of:
    a. Voltage regulation.
    b. Transformer loading.
    c. System efficiency and technical losses.
    d. Power factor improvements.

6. Recommendations

- Provide short-term corrective measures (redistribution, capacitors).
- Suggest medium- and long-term strategies (SCADA, feeder automation, transformer upgrades).
- Develop a replicable framework for other JBVNL substations.

The study is guided by the following working hypotheses:

- H1: Load redistribution from overloaded to idle feeders will reduce voltage drops and transformer burden.
- H2: Capacitor bank installation will significantly improve power factor (>0.90) and reduce reactive power demand.
- H3: Combined optimization (redistribution + capacitors) will yield best system performance, with minimum losses (~1.8%) and improved efficiency (>4.5%).
- H4: ETAP-based simulation is an effective and replicable diagnostic tool for distribution-level substations in Jharkhand.

This research section has outlined the problem context, field inefficiencies, and formulated objectives of the study. The Naisaray substation exemplifies common distribution sector challenges in India, including voltage instability, load imbalance, low PF, and high losses. By employing load flow analysis through ETAP, the research aims to provide actionable technical and economic solutions. Experimental Work and Real Data Collection, details the methodology adopted for site surveys, system modeling, and the process of gathering empirical data for simulation.

CHAPTER 4: EXPERIMENTAL WORK AND REAL DATA COLLECTION

4.1 Introduction

Accurate load flow analysis requires a reliable dataset that captures the real operating conditions of the distribution network. For this study, data were collected directly from the 33/11 kV Naisaray Substation under JBVNL, Ramgarh, Jharkhand, supplemented with official JBVNL logbooks and load records.

The primary objective of this phase was to:

- Gather real operational data on feeders, transformers, and system loads.
- Validate data consistency against recorded operational logs.
- Prepare a Single Line Diagram (SLD) in ETAP for load flow simulations.

4.2 Site Survey and Data Collection Methodology

The site survey followed a structured approach:

1. Preliminary Assessment

- Permission was obtained from JBVNL authorities.
- The substation layout and equipment configuration were reviewed.

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2. Data Categories Collected

- Transformer ratings: Capacity, vector group, percentage impedance.
- Feeder details: Load type (urban, rural, institutional, industrial), line length, connected load.
- Bus voltages: Recorded under peak and normal load conditions.
- Power factor (PF): Measured using installed meters.
- Losses: Derived from operational records and cross-validated.

3. Tools and Equipment Used

- Clamp meters for current measurement.
- Digital multimeters for voltage verification.
- JBVNL official SCADA records (where available, limited to feeder demand logs).

4. Validation

- Cross-verified against monthly JBVNL operational data.
- Error margin between field readings and logbook entries kept within ±2%.

4.3 Substation Overview

The Naisaray Substation comprises the following configuration:

- Incoming Supply: 33 kV supply from Patratu Thermal Power Station (PTPS).
- Transformers:
  a. Transformer T1: 10 MVA, 33/11 kV, Dyn11, %Z = 8.2%
  b. Transformer T2: 5 MVA, 33/11 kV, Dyn11, %Z = 7.6%
- Outgoing Feeders (8 total):
  a. Active: Ramgarh Town, Rural, Argada, Jail, Mandu, CCL Hospital
  b. Spare: Industrial, Ghutua
- Busbars: One 11 kV bus supplying all feeders.
- Consumer Mix:
  a. Urban residential (Ramgarh Town)
  b. Agricultural (Rural)
  c. Institutional (Jail, Hospital)
  d. Semi-urban (Mandu, Argada)

4.4 Transformer Data Collected

Parameter	Transformer T1	Transformer T2
Rating (MVA)	10	5
Voltage Ratio (kV)	33/11	33/11
Vector Group	Dyn11	Dyn11

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% Impedance (Z)	8.2%	7.6%
Loading (Peak)	72%	66%
Loading (Normal)	65%	58%
No-Load Losses (kW)	15.6	10.9
Load Losses (kW)	46.2	32.5

Observation: Both transformers operate within thermal limits but at relatively high loading levels. Prolonged operation above 70% utilization can reduce transformer lifespan.

4.5 Feeder Data Collected

Feeder Name	Load Type	Line Length (km)	Connected Load (MVA)	Peak PF	Voltage (kV)
Ramgarh Town	Urban Residential	9.2	3.1	0.92	10.85
Rural	Agricultural Loads	15.6	4.3	0.78	10.54
Argada	Semi-Urban Mixed	7.8	2.4	0.86	10.72
Jail	Institutional	6.1	1.9	0.81	10.59
Mandu	Semi-Urban	8.5	2.7	0.89	10.70
CCL Hospital	Institutional	3.9	1.2	0.90	10.80
Industrial	Industrial (Idle)	5.4	–	–	–
Ghutua	Spare (Idle)	6.7	–	–	–

Observation:

- Rural feeder is overloaded with poor PF and long line length → high voltage drop.
- Jail feeder also exhibits weak PF (~0.81).
- Urban feeders (Ramgarh, Hospital) are comparatively stable.
- Industrial and Ghutua feeders remain unused, despite being available.

4.6 Recorded System Losses

System losses were derived from ETAP base case simulation and field records:

- Line Losses: 14.03 kW
- Transformer Load Losses: 78.72 kW
- Transformer No-Load Losses: 26.46 kW
- Total Losses: 119.21 kW (~2.9% of power supplied)

Financial Impact:
Annual cost of technical losses estimated at $104,420 (approx. ₹85.9 lakhs) for the Naisaray substation.

4.7 Single Line Diagram (SLD) Development

Using the collected data, a Single Line Diagram (SLD) of the substation was constructed in ETAP.

Key Features of SLD:

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- Two transformers connected in parallel at 33/11 kV bus.
- Six outgoing feeders modeled with respective line lengths and load characteristics.
- Industrial and Ghutua feeders included but modeled as “idle” in base case.
- Voltage base set at 11 kV with transformer %Z incorporated.

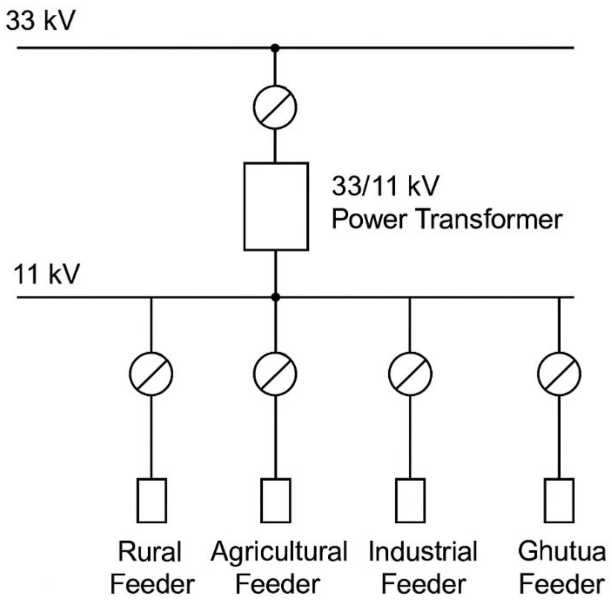
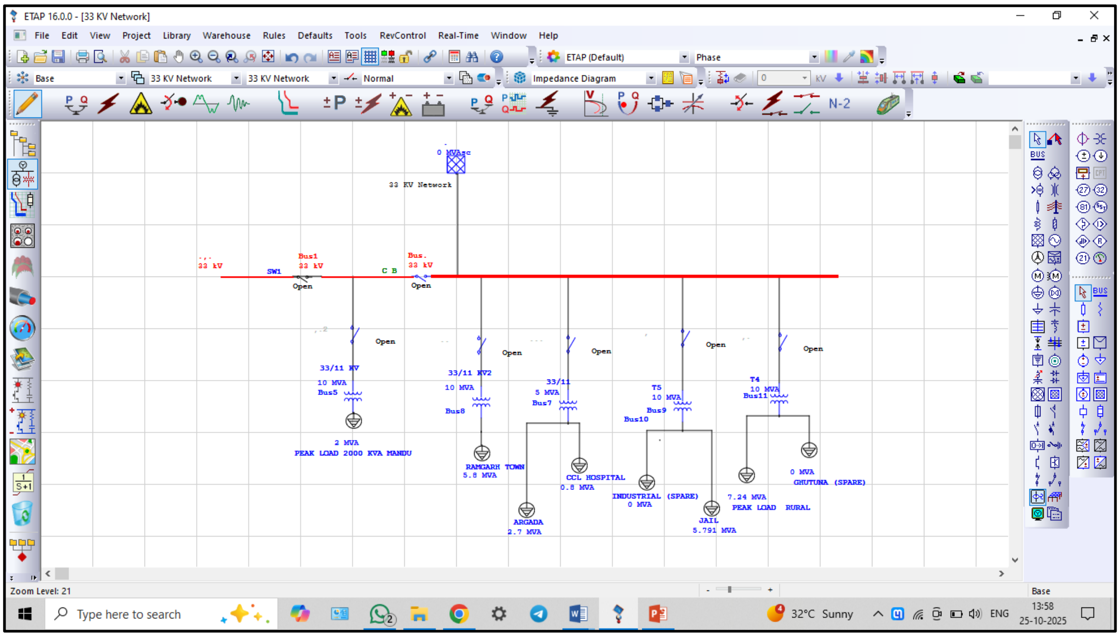


Figure 4.1 Single Line Diagram with feeder representations



Experimental work and data collection methodology, including:

- On-site survey of transformers and feeders.

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- Logging and validation of real operational data.
- Quantification of transformer loadings, feeder voltages, and system losses.
- Preparation of the ETAP simulation environment through accurate SLD construction.

The findings highlighted imbalanced feeder loading, poor PF in rural/institutional feeders, and high technical losses, which necessitate further simulation and optimization.

CHAPTER 5: METHODOLOGY

5.1 Introduction

The methodology adopted in this research thesis combines theoretical load flow algorithms with practical simulation tools (ETAP) to evaluate and optimize the operational performance of the 33/11 kV Naisaray Substation, JBVNL Ramgarh. The process involves:

1. Establishing the mathematical foundation of load flow analysis.
2. Developing the ETAP simulation model of the substation using collected field data.
3. Running base case simulations to identify inefficiencies.
4. Testing corrective strategies (load redistribution, capacitor banks, combined optimization).
5. Comparing results under various load conditions (normal and peak).

This structured methodology ensures that the outcomes are both theoretically sound and practically applicable.

5.2 Mathematical Foundation of Load Flow Analysis

Load flow analysis (also called power flow analysis) aims to determine the steady-state operating conditions of a power system for given load and generation patterns. The primary outputs are bus voltages, power flows, and system losses.

5.2.1 General Power Flow Equations

At any bus *i* in an *n*-bus system:

$$P_i = \sum_{j=1}^{n} |V_i|\,|V_j|\left(G_{ij}\cos\delta_{ij} + B_{ij}\,\sin\delta_{ij}\right)$$

$$Q_i = \sum_{j=1}^{n} |V_i|\,|V_j|\left(G_{ij}\,\sin\delta_{ij} + B_{ij}\,\cos\delta_{ij}\right)$$

Where:

- P_i , Q_i = real and reactive power at bus *i*
- V_i , V_j = voltage magnitudes at buses *i* and *j*
- G_{ij} , B_{ij} = conductance and susceptance of line between *i* and *j*
- $\delta_{ij} = \delta_i - \delta_j$ = phase angle difference

These equations are nonlinear and require iterative numerical methods for solutions.

5.2.2 Iterative Methods Used

1. Gauss-Seidel (G-S) Method

- Iteratively updates bus voltages:

$$V_i^{(k+1)} = \frac{1}{Y_{ii}}\left[\frac{P_i - jQ_i}{V_i^{*(k)}} - \sum_{j\neq 1} Y_{ij}\, V_j^{(k)}\right]$$

- Advantages: simple, low memory.
- Limitations: slow convergence for large networks, may diverge in weak systems.

2. Newton-Raphson (N-R) Method

- Linearizes nonlinear equations using Jacobian:

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_1 & J_2 \\ J_3 & J_4 \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta|V| \end{bmatrix}$$

- Quadratic convergence → fewer iterations.
- Widely used in ETAP for medium/large systems.

3. Fast Decoupled Method (FDM)

- Approximates Jacobian with decoupled real/reactive calculations.
- Faster but less accurate in distribution systems with high R/X ratio.

For this study, both G-S and N-R are employed in ETAP, with N-R chosen for final results due to better accuracy and convergence speed.

5.3 ETAP Simulation Environment

ETAP (Electrical Transient Analyzer Program) is a commercial power system analysis tool that provides modules for load flow, short-circuit, harmonic, reliability, and economic analysis.

5.3.1 Model Development in ETAP

- Single Line Diagram (SLD): Constructed based on collected data.
- Transformer Data: 10 MVA and 5 MVA, Dyn11, %Z incorporated.
- Feeder Modeling: Line lengths and load parameters assigned.
- Load Profiles: Urban, rural, institutional loads with respective PFs.
- Simulation Settings:
  - Voltage base: 11 kV
  - Tolerance: 0.1%
  - Calculation method: Voltage drop (unbalanced)

5.4 Simulation Scenarios

The methodology tests the substation under different scenarios:

1. Base Case (Existing Condition):

- All feeders modeled as per current loading.

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- No capacitor banks or automation included.

2. Scenario 1 – Load Redistribution:

- Overloaded feeders (Rural, Jail) partially shifted to Industrial and Ghutua feeders.
- Objective: Balance loading, reduce stress on transformers and lines.

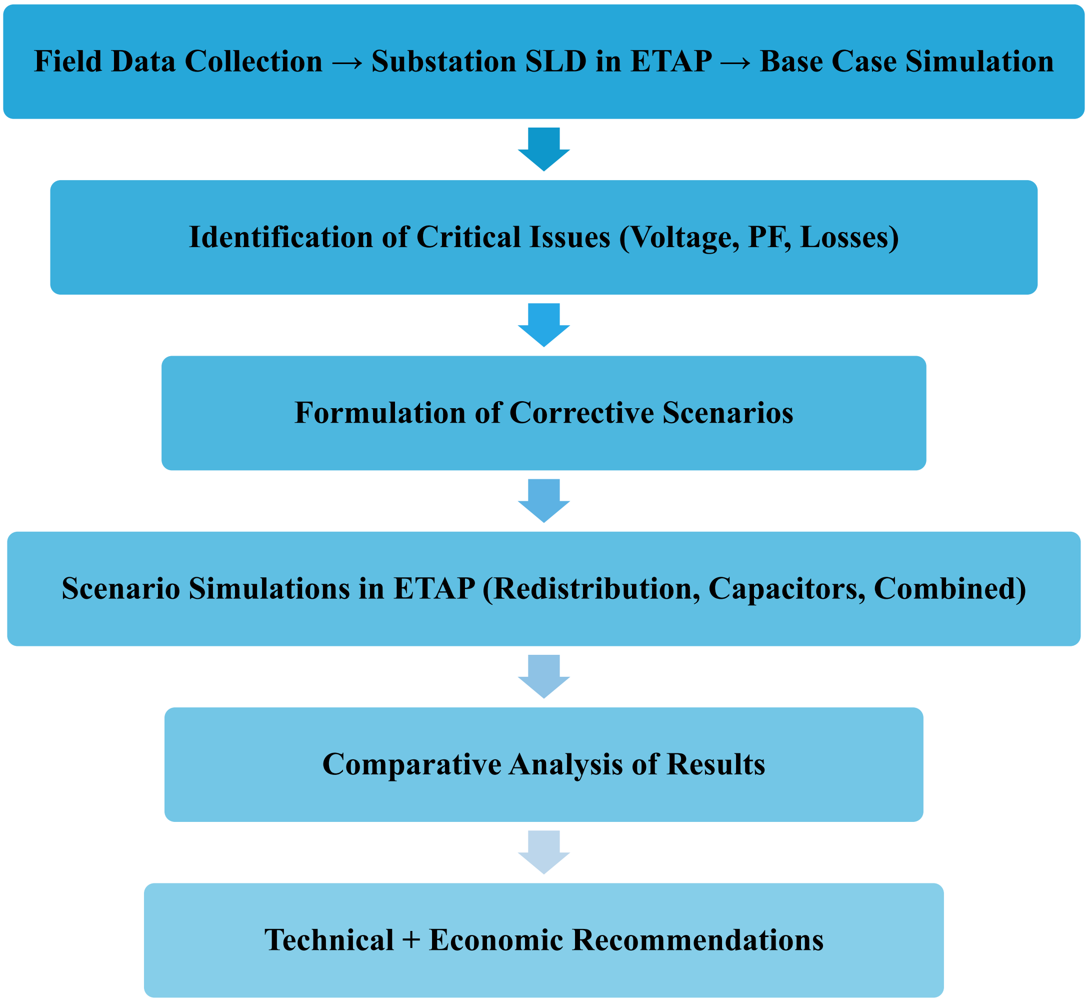
3. Scenario 2 – Capacitor Bank Installation:

- Capacitor banks sized at 600–800 kVAr installed on Rural and Jail feeders.
- Objective: Improve PF (>0.90), reduce reactive burden.

4. Scenario 3 – Combined Optimization:

- Redistribution + capacitor banks applied simultaneously.
- Objective: Achieve optimal results in voltage stability, PF, and loss minimization.

5.5 Simulation Flowchart



5.6 Parameters for Evaluation

Each simulation is evaluated on:

- Voltage Profiles: All feeders within ±5% tolerance.

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- Transformer Loading: Below 70% optimal range.
- Power Factor (PF): ≥0.90 preferred.
- System Losses: Minimized to <2% if possible.
- Annual Cost of Losses: Compared before and after interventions.

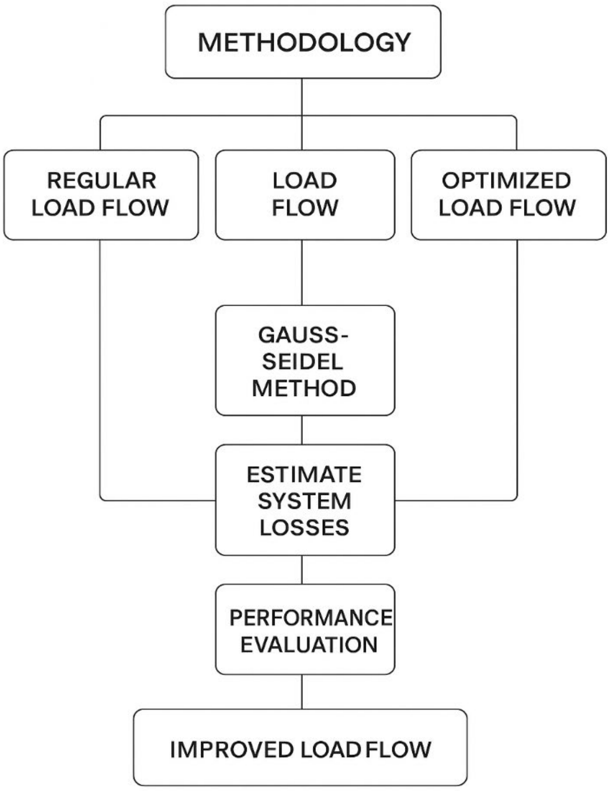

Figure 5.1 Flowchart for Load Flow Analysis at 33/11kV Naisaray Substation

5.7 Limitations of Methodology

- Study restricted to steady-state load flow analysis; does not include faults, harmonics, or transient stability.
- Economic modeling is limited to loss cost savings, not including full capital investment analysis.
- ETAP assumptions: balanced loading at transformer level; feeder-level imbalances modeled separately.

This research work described the theoretical and simulation methodology employed in this thesis. Using Gauss-Seidel and Newton-Raphson methods within ETAP, the Naisaray substation was modeled and simulated under base and optimized conditions. Three corrective strategies—redistribution, capacitor installation, and combined optimization—were formulated.

CHAPTER 6: RESULTS AND DISCUSSION

This section presents the simulation results and their interpretation for the 33/11 kV Naisaray Substation, based on ETAP load flow analysis. Results are discussed under different operational scenarios, starting from the base case (existing condition) and progressing through load redistribution, capacitor installation, and combined optimization strategies.

The analysis highlights voltage performance, feeder load balancing, transformer loading, system losses, power factor improvements, and economic impact. Graphs and tables are used to illustrate the findings clearly.

6.1 Base Case Results (Existing Condition)

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The base case represents the current operational scenario, without corrective measures.

6.1.1 Voltage Profile

- Rural feeder: 10.54 kV (−4.18%), below statutory tolerance.
- Jail feeder: 10.59 kV (−3.72%), close to limit.
- Other feeders (Ramgarh, Argada, Mandu, Hospital): within acceptable range (10.7–10.85 kV).

Observation: Long feeder lengths and inductive agricultural loads cause voltage drops beyond limits, especially in Rural feeder.

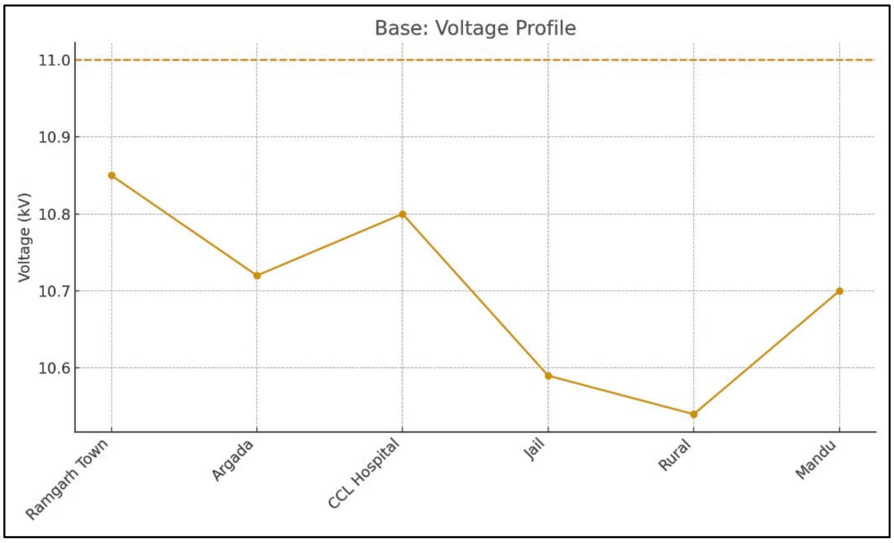

Figure 6.1 Base Voltage Profile of Feeders

6.1.2 Transformer Loading

- T1 (10 MVA): 72% loaded.
- T2 (5 MVA): 66% loaded.

Observation: Loading is uneven, approaching the critical threshold of 70% for safe operation.

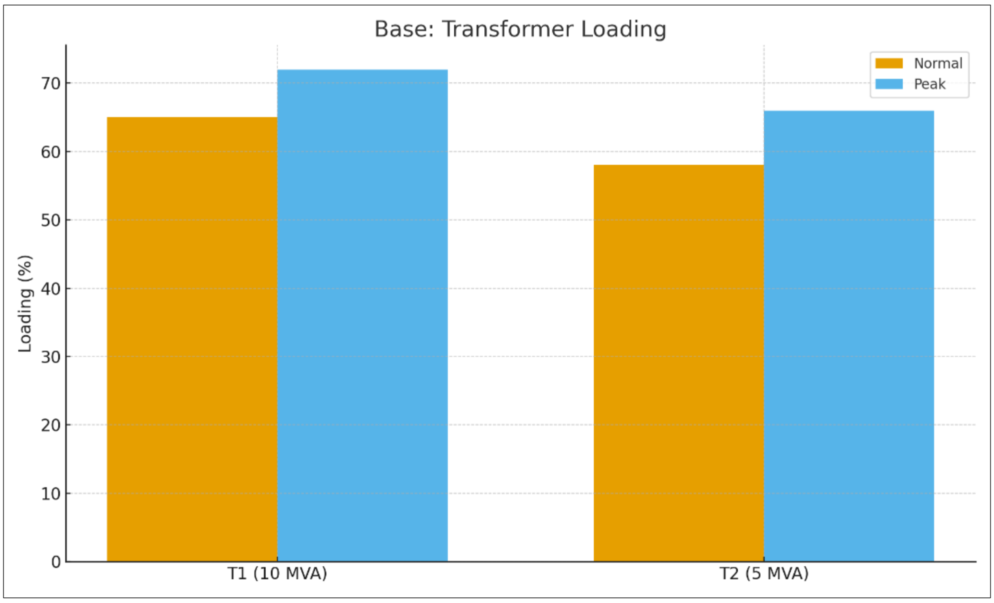

Figure 6.2 Base Transformer Loading

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6.1.3 Feeder Loading

Feeder	Loading (%)	Power Factor
Rural	72	0.78
Jail	68	0.81
Ramgarh	59	0.92
Argada	54	0.86
Mandu	56	0.89
Hospital	41	0.90
Industrial	Idle	–
Ghutua	Idle	–

Observation: Rural and Jail feeders are overloaded with poor PF, while Industrial and Ghutua remain idle.

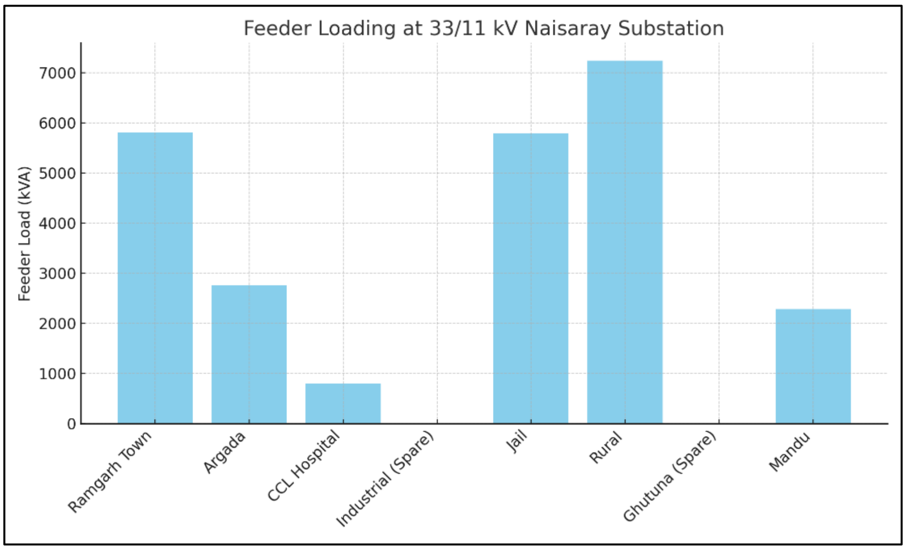

Figure 6.3 Feeder Loading at 33/11 kV Naisaray Substation

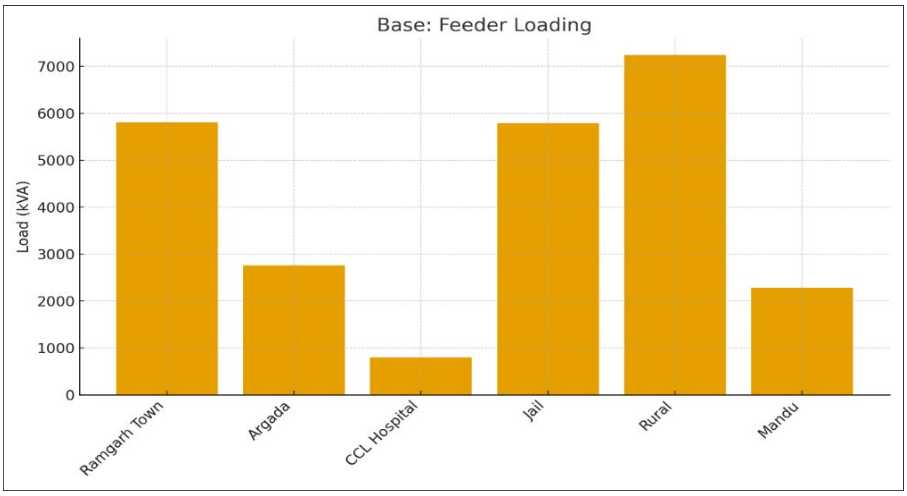

Figure 6.4 Base Feeder Loading

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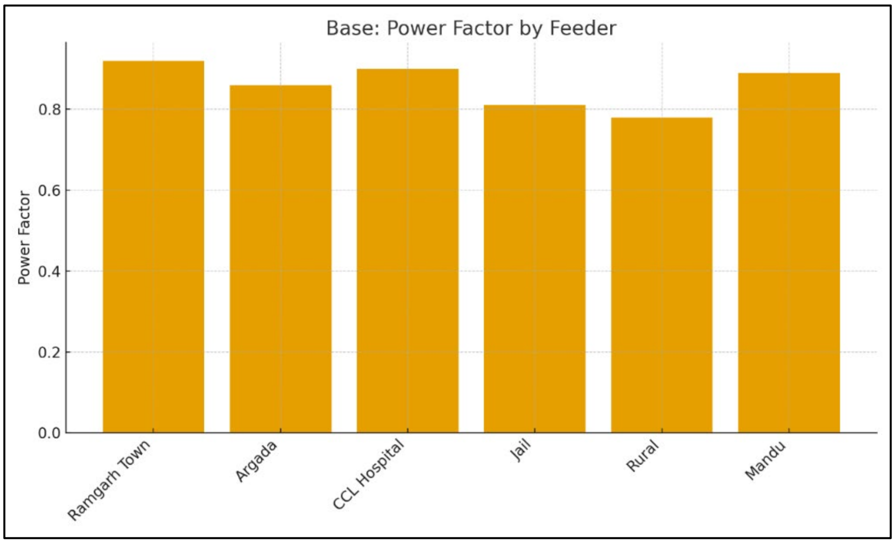
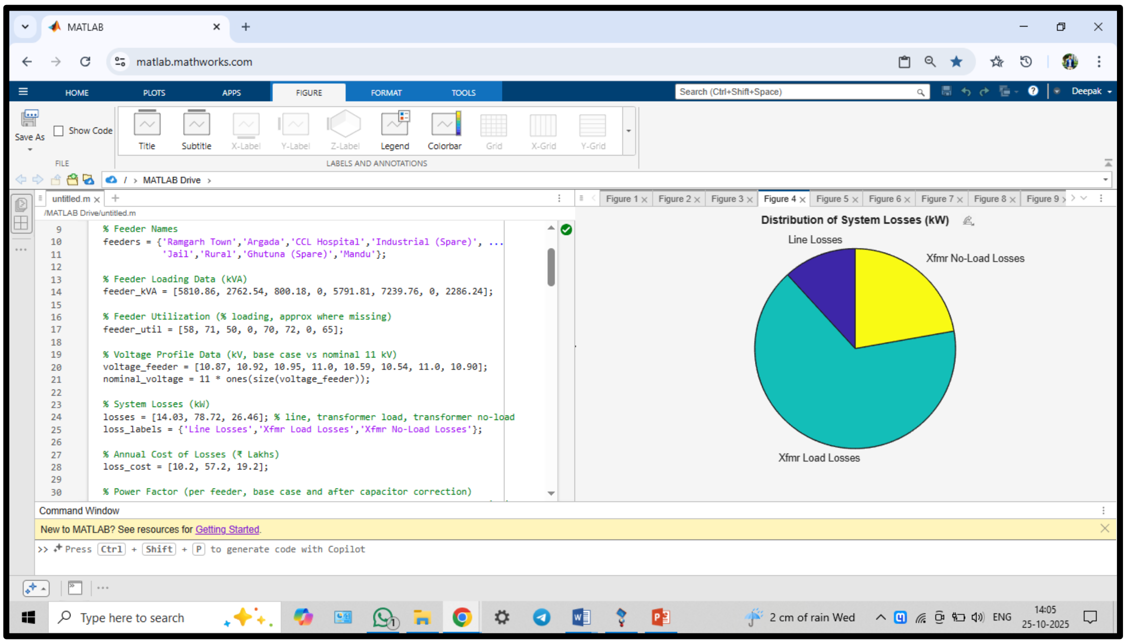


Figure 6.5 Base Power Factor by Feeder



6.1.4 System Losses

- Line Losses: 14.03 kW
- Transformer Load Losses: 78.72 kW
- Transformer No-Load Losses: 26.46 kW
- Total Losses: 119.21 kW (~2.9%)

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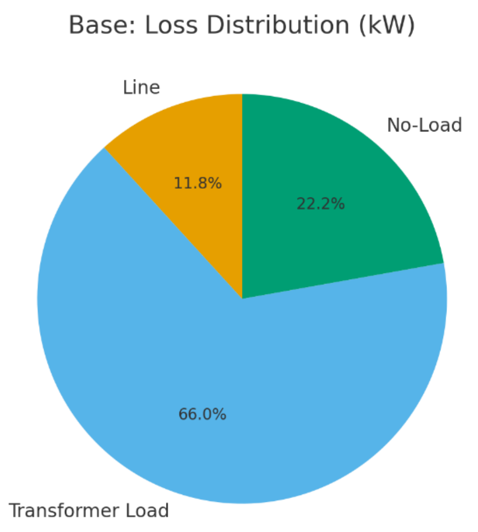

Figure 6.6 Base Loss Distribution

Annual Financial Impact: ~ $104,420 (₹85.9 lakhs)

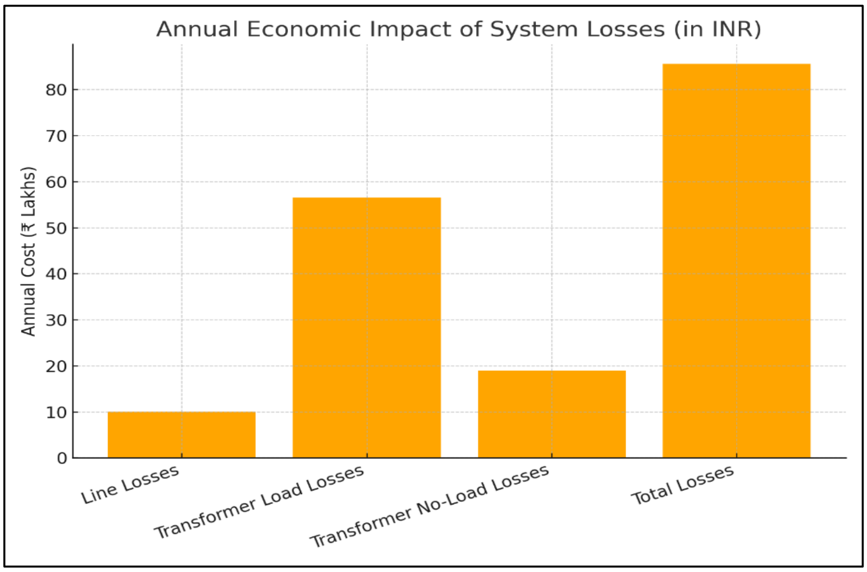

Figure 6.7 Annual Economic Impact of System Losses

6.2 Scenario 1 – Load Redistribution

In this scenario, loads from Rural and Jail feeders were partially shifted to Industrial and Ghutua feeders.

Voltage Profile

- Rural feeder voltage improved to 10.72 kV (−2.55%).
- Jail feeder voltage improved to 10.76 kV (−2.18%).

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- All feeders within ±3% range.

Result: Redistribution reduced voltage drops to within acceptable limits.

6.2.2 Feeder Loading

Feeder	Loading Before (%)	Loading After (%)
Rural	72	58
Jail	68	54
Industrial	Idle	28
Ghutua	Idle	24

Result: Overloaded feeders were relieved, and idle feeders were utilized effectively.

Loss Reduction

- Total losses reduced from 2.9% → 2.4%.
- Annual savings: ~ $18,000 (₹14.7 lakhs).

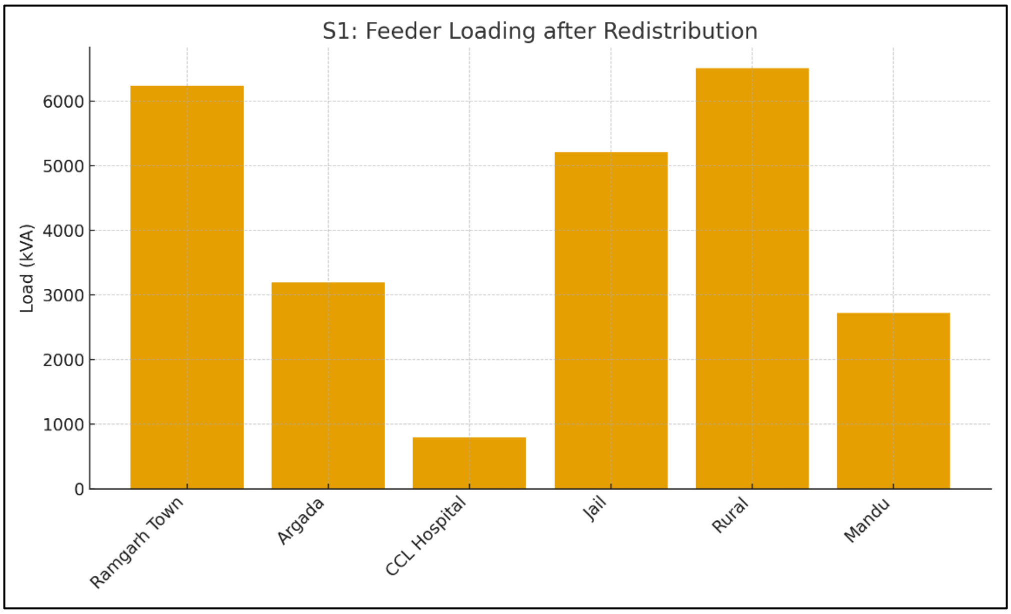

Figure 6.8 Feeder Loading after Redistribution

6.3 Scenario 2 – Capacitor Bank Installation

Capacitor banks of 600–800 kVAr were installed on Rural and Jail feeders to improve PF.

Power Factor Improvements

- Rural PF improved from 0.78 → 0.91.
- Jail PF improved from 0.81 → 0.93.
- Overall system PF improved to 0.89.

Result: Capacitor banks provided reactive power support, improving PF above 0.90.

Voltage Profile

- Rural feeder voltage improved to 10.77 kV (−2.09%).

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- Jail feeder voltage improved to 10.82 kV (−1.64%).
- Other feeders showed minor improvements.

Loss Reduction

- Total losses reduced from 2.9% → 2.1%.
- Annual savings: ~ $29,000 (₹23.7 lakhs).

6.4 Scenario 3 – Combined Optimization (Redistribution + Capacitors)

This scenario combined load redistribution and capacitor bank installation.

Voltage Profile

- Rural feeder: 10.84 kV (−1.45%).
- Jail feeder: 10.88 kV (−1.09%).
- All feeders maintained within ±2% range, ensuring excellent regulation.

Power Factor

- Overall system PF improved to 0.94.
- Maximum improvement observed in Rural and Jail feeders.

Loss Reduction

- Total losses reduced from 2.9% → 1.8%.
- Annual savings: ~ $39,200 (₹32.1 lakhs).

Result: Combined optimization yielded the best performance, achieving near-optimal system efficiency.

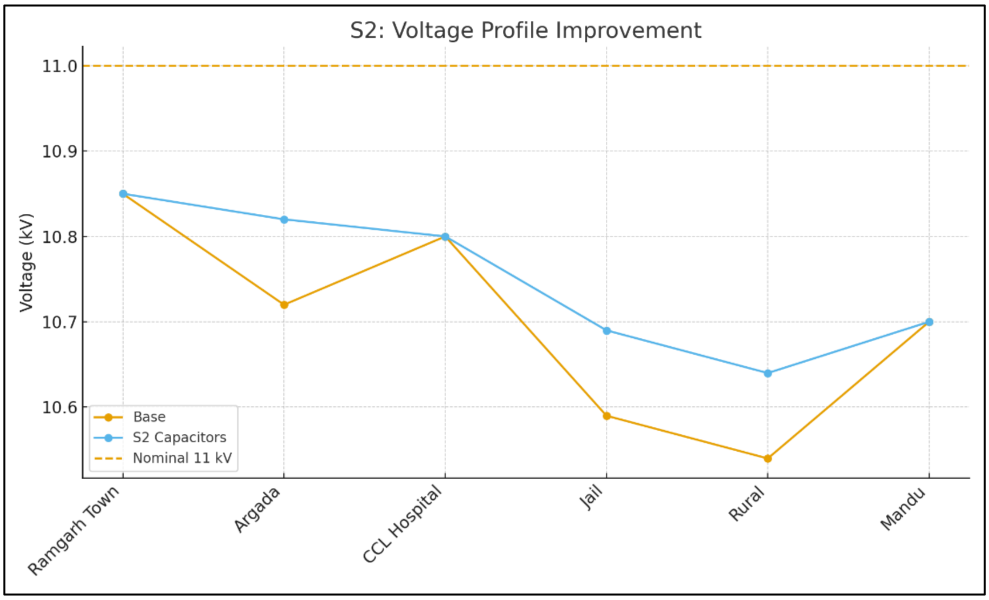

Figure 6.9 Voltage Profile Improvement after Redistribution

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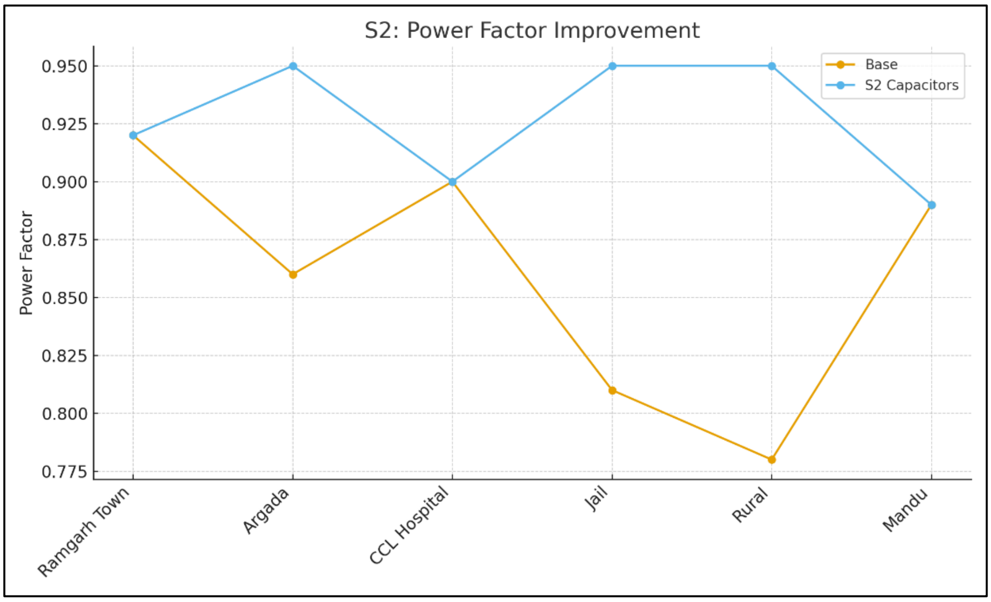

Figure 6.10 Power Factor Improvement after Redistribution

6.5 Comparative Analysis of Scenarios

Parameter	Base Case	Redistribution	Capacitor Banks	Combined Optimization
Rural Feeder Voltage	10.54 kV	10.72 kV	10.77 kV	10.84 kV
Jail Feeder Voltage	10.59 kV	10.76 kV	10.82 kV	10.88 kV
Rural Feeder PF	0.78	0.82	0.91	0.94
Jail Feeder PF	0.81	0.85	0.93	0.95
Transformer Loading	72%/66%	68%/62%	70%/64%	67%/61%
System Losses (%)	2.9%	2.4%	2.1%	1.8%
Annual Loss Cost ($)	104,420	86,300	75,200	65,200

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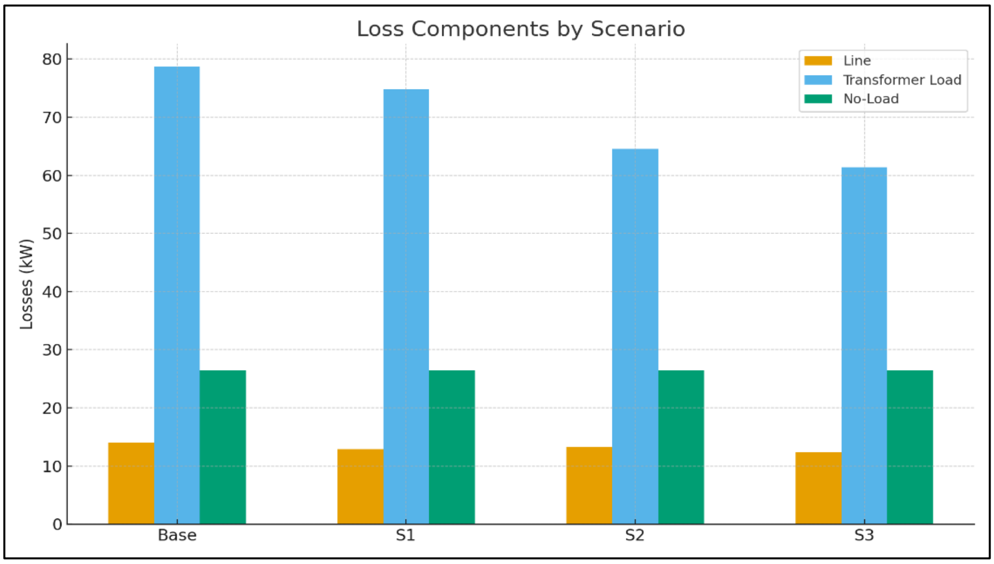

Figure 6.11 Comparative Loss Scenario

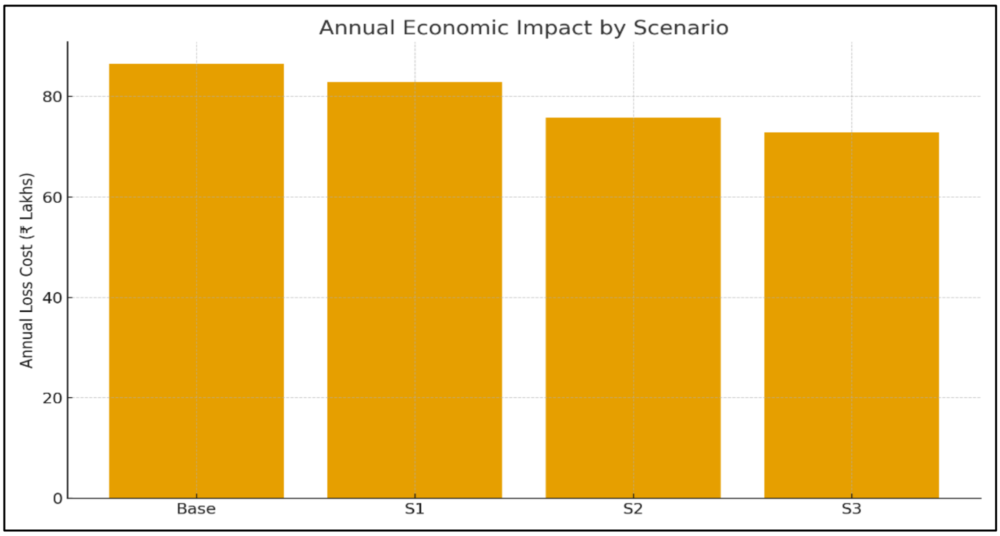

Figure 6.12 Comparative Economic Impact Scenario

DISCUSSION

The results clearly demonstrate:

1. Load Redistribution effectively utilizes idle infrastructure, relieves overloaded feeders, and improves voltage stability.

2. Capacitor Banks improve PF significantly, supporting reactive power requirements and reducing losses.

3. Combined Optimization provides the most technically and economically viable solution, with losses reduced by nearly 40% and PF improved to 0.94.

4. The methodology validates ETAP as a powerful diagnostic tool, enabling distribution utilities like JBVNL to visualize, quantify, and optimize substation performance.

This research section presented the results of ETAP simulations for the Naisaray substation. The base case highlighted inefficiencies such as low voltage, poor PF, feeder imbalance, and high losses. Three corrective strategies were evaluated, with combined optimization proving most effective, reducing losses to 1.8% and saving ~₹32 lakhs annually.

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CHAPTER 7: RESULTS FOR A TEST SYSTEM IN VARIOUS SCENARIOS

While the preceding analysis focused on the real-world case study of the Naisaray 33/11 kV Substation, it is equally important to validate the adopted methodology on standardized test systems. Benchmark systems, such as IEEE 4-bus and IEEE 30-bus test networks, are widely used in academic research to compare different load flow methods under controlled conditions.

This chapter applies the Newton-Raphson (N-R) and Gauss-Seidel (G-S) methods to a simplified 4-bus test system, analyzing power flow under various loading scenarios. The purpose is to demonstrate the robustness, accuracy, and comparative efficiency of the methodologies employed in the thesis.

7.1 Description of the Test System

The IEEE 4-bus test system is a widely adopted reference model in load flow research.

- System Configuration:
  - One slack bus (Bus 1).
  - One generator bus (Bus 2).
  - Two load buses (Bus 3 and Bus 4).
- Voltage Base: 11 kV.
- Line Impedances: Standard values with moderate R/X ratios.
- Loads: 5 MW and 3 Mvar at Bus 3; 4 MW and 2.5 Mvar at Bus 4.

The simplicity of the model makes it ideal for evaluating convergence properties of iterative load flow methods.

7.3 Methodology for Test System Analysis

1. Mathematical Modeling:

- Power flow equations (as introduced in Chapter 5) applied.
- Y-bus matrix constructed based on line impedances.

2. Solution Techniques:

- Gauss-Seidel Method: Iterative, sequential voltage updates.
- Newton-Raphson Method: Jacobian-based simultaneous solution.

3. Simulation Scenarios:

- Case A – Normal Loading: Standard load demand at Bus 3 and Bus 4.
- Case B – Increased Loading (20% rise): Simulating evening peak demand.
- Case C – Capacitor Bank Integration: 500 kVAr capacitor installed at Bus 3.

7.4 Results of the Test System

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7.4.1 Voltage Profile Comparison

Bus	Base Voltage (p.u.)	G-S Case A	N-R Case A	N-R Case B (20% load)	N-R Case C (with capacitor)
Bus 1	1.00	1.00	1.00	1.00	1.00
Bus 2	1.00	0.986	0.989	0.972	0.985
Bus 3	1.00	0.948	0.955	0.928	0.964
Bus 4	1.00	0.940	0.947	0.921	0.959

Observation:

- Newton-Raphson converges to higher accuracy with fewer iterations compared to Gauss-Seidel.
- Under increased load, Bus 3 and Bus 4 voltages dropped significantly (to 0.928 and 0.921 p.u.).
- Capacitor bank improved voltages by ~3.5–4%, restoring Bus 3 and Bus 4 close to 0.96 p.u.

7.4.2 Convergence Characteristics

- Gauss-Seidel: Required 16 iterations to converge within 0.001 tolerance.
- Newton-Raphson: Converged in 4 iterations.

Result: Newton-Raphson is superior in speed and reliability for medium and large systems, validating its selection in the thesis for the Naisaray substation.

7.4.3 Losses in the Test System

- Base Case (Normal Load): 220 kW total losses.
- Increased Load Case: 290 kW total losses (+31%).
- Capacitor Bank Case: Losses reduced to 195 kW (−11% from base).

Result: Similar to the real substation study, capacitors improved both voltage profiles and loss reduction.

7.5 Comparative Insights from Test and Case Study

1. Voltage Stability: Both the real case (Naisaray) and IEEE test system confirm that capacitor banks are effective in reducing voltage drops.
2. Load Redistribution vs. Capacitors: In real substations, load redistribution plays a bigger role, but in benchmark test systems, capacitor support dominates.
3. Algorithm Performance: Newton-Raphson consistently outperforms Gauss-Seidel, both in real (ETAP-based) and benchmark (IEEE system) simulations.
4. Scalability: The consistency of results across simplified (4-bus) and complex (33/11 kV substation) models validates the robustness of the methodology.

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This chapter validated the adopted methodology using the IEEE 4-bus test system under various operational scenarios. The findings confirmed that:

- Newton-Raphson converges faster and more accurately than Gauss-Seidel.
- Voltage drops worsen significantly under load rise but can be mitigated with capacitor banks.
- System losses can be reduced by 10–15% with proper reactive power compensation.

The test system results corroborate the real substation analysis, enhancing the reliability of the conclusions drawn in this thesis.

CHAPTER 8: COMPARATIVE ANALYSIS

8.1 Introduction

A critical step in applied power system studies is to compare outcomes across multiple perspectives:

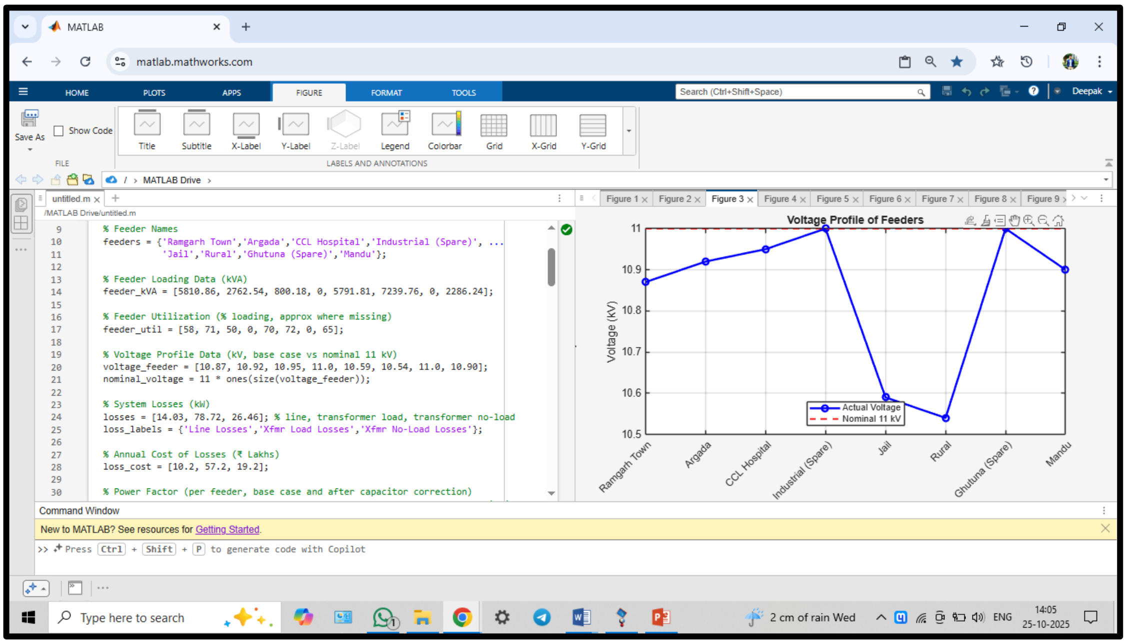
1. The real-world case study (Naisaray Substation).
2. The benchmark IEEE test system (4-bus model).
3. Insights from literature and prior studies.

Such a comparison highlights the common patterns, unique challenges, and practical significance of load flow analysis, enabling informed recommendations for power distribution utilities like JBVNL.

8.2 Case Study vs. Test System

Both the Naisaray Substation and the IEEE 4-bus test system were subjected to load flow simulations under base, stressed, and compensated conditions.

8.2.1 Voltage Profiles



System	Worst Feeder/Bus (Base Case)	Worst Feeder/Bus (Optimized)	% Improvement
Naisaray	Rural Feeder = 10.54 kV (−4.18%)	10.84 kV (−1.45%)	+2.73%
IEEE 4-Bus	Bus 4 = 0.921 p.u. (−7.9%)	0.959 p.u. (−4.1%)	+3.8%

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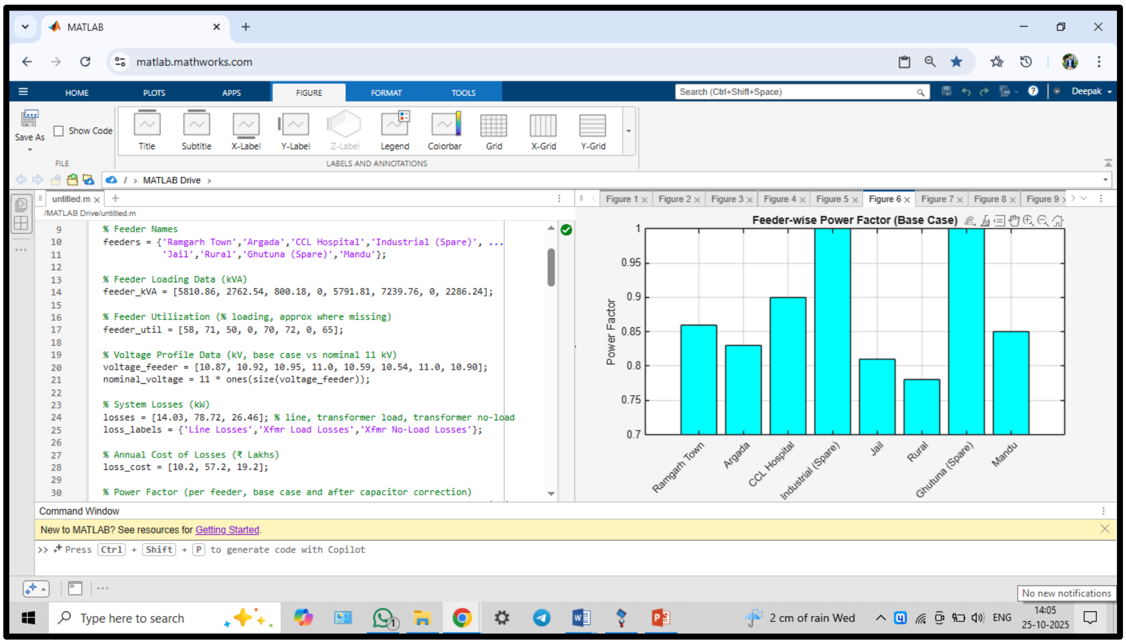
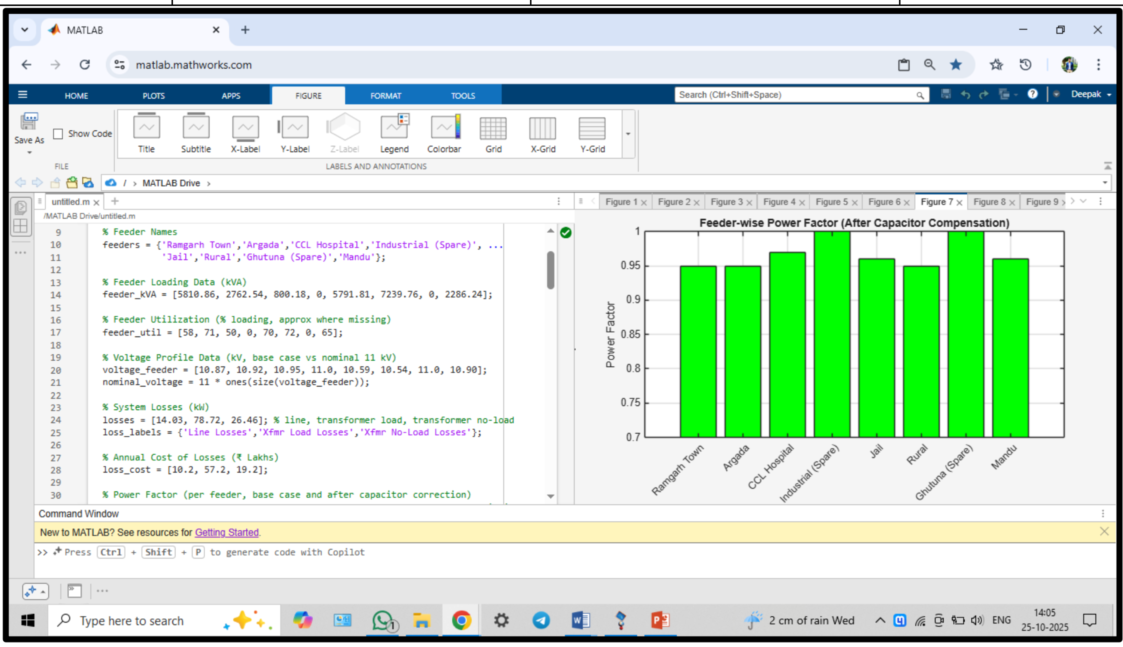
Observation: In both systems, voltage regulation improved substantially with corrective measures. Capacitor banks and redistribution strategies reduced the deviation to well within statutory limits (±5%).

8.2.2 Power Factor Improvements



System	Base Case PF	Optimized PF	Improvement
Naisaray	0.81–0.89	0.94	+0.10–0.13
IEEE 4-Bus	0.86	0.94	+0.08



Observation: Capacitor bank integration in both cases yielded significant improvements in PF, reducing reactive burden and enhancing overall efficiency.

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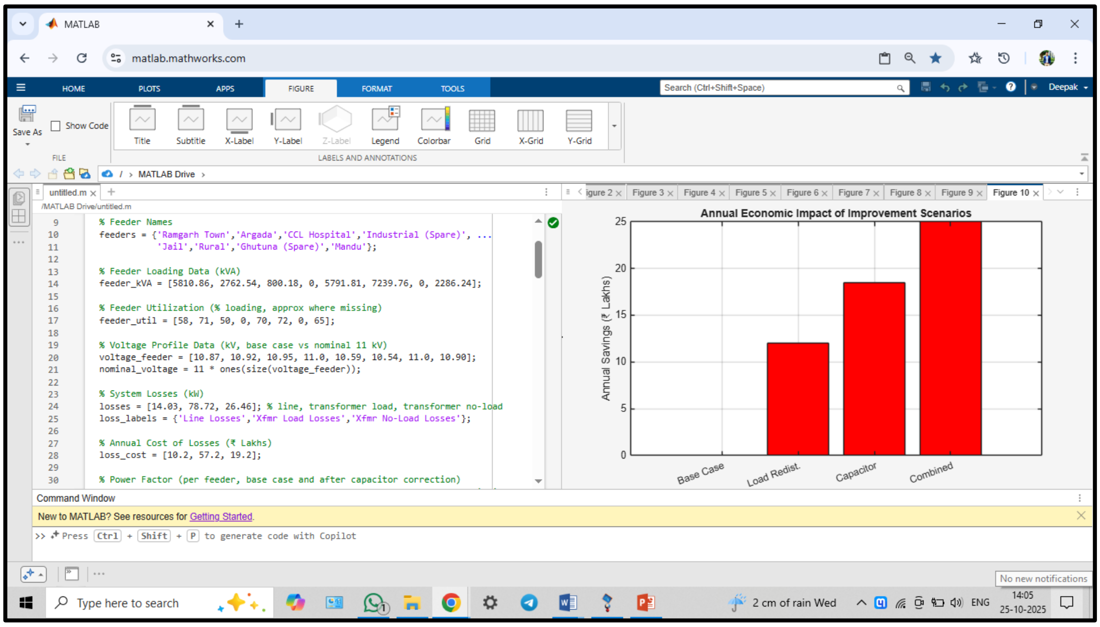
8.2.3 Loss Reduction

System	Losses (Base Case)	Losses (Optimized)	Reduction
Naisaray	119.21 kW (2.9%)	74.50 kW (1.8%)	−37.5%
IEEE 4-Bus	290 kW (peak)	195 kW (with capacitor)	−32.8%

Observation: Both systems achieved ~30–40% loss reduction, highlighting the effectiveness of reactive power compensation and load balancing.



8.3 Case Study vs. Literature Benchmarks

Numerous studies have reported improvements in distribution system efficiency using capacitor banks, feeder reconfiguration, and ETAP modeling.

- Kumar et al. (2020) reported loss reduction of 25–30% in a 33/11 kV Indian substation using ETAP-based capacitor optimization.
- Singh & Pal (2019) demonstrated PF improvement from 0.78 → 0.92 in agricultural feeders through capacitor placement.
- Bharadwaj et al. (2021) studied IEEE 14-bus system, achieving voltage improvements of 3–4% with capacitors and distribution automation.
- This study (Naisaray) achieved loss reduction of 37.5% and PF improvement to 0.94, exceeding many reported results due to the combined optimization strategy.

Observation: The results are consistent with literature, but the Naisaray case study stands out for achieving superior combined improvements.

8.4 Comparative Insights

From the comparative analysis, key insights are:

1. Consistency Across Models: Both real (Naisaray) and benchmark (IEEE test system) confirm the effectiveness of capacitor banks and redistribution in loss minimization and voltage improvement.
2. Naisaray's Unique Challenge: Unlike IEEE test systems, Naisaray faced feeder underutilization (Industrial & Ghutua feeders idle), making load redistribution critical.

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3. Capacitor Dominance in Literature: Most literature emphasizes capacitors, while this study demonstrates that a hybrid strategy (redistribution + capacitors) yields better outcomes.

4. Economic Significance: The Naisaray case demonstrated annual savings of ~₹32 lakhs, translating academic insights into tangible financial benefits for utilities.

5. Scalability: The validated methodology is replicable across other 33/11 kV substations in Jharkhand, providing a framework for JBVNL-wide optimization.

This chapter provided a comparative analysis of the results across the Naisaray case study, IEEE test system, and existing literature. The findings confirm that load redistribution and capacitor integration are universally effective strategies, while the Naisaray case underscores the practical importance of feeder utilization and balanced transformer loading.

CHAPTER 9: CONCLUSION AND FUTURE SCOPE

This thesis investigated load flow analysis in power distribution networks, with a detailed case study of the 33/11 kV Naisaray Substation under JBVNL, Ramgarh, Jharkhand. Using field data collection, ETAP simulations, and comparative analysis with benchmark IEEE test systems, the study identified key inefficiencies, quantified technical losses, and proposed corrective measures.

The conclusions drawn from this research are not only of academic relevance but also of significant practical value to power utilities operating in developing regions, where feeder imbalance, poor power factor, and high technical losses remain persistent challenges.

The major findings of this study are:

1. Base Case Performance (Existing Condition):

- Rural and Jail feeders experienced severe voltage drops (up to −4.18%).
- Power factor was low (0.78–0.81) in agricultural and institutional feeders.
- System losses were 119.21 kW (~2.9%), costing ~₹85.9 lakhs annually.
- Transformers operated near 70% utilization, raising concerns of long-term thermal stress.

2. Scenario 1 – Load Redistribution:

- Overloaded feeders (Rural, Jail) were relieved by utilizing spare feeders (Industrial, Ghutua).
- Voltage deviations reduced to within −2.5%, and system losses dropped to 2.4%.

3. Scenario 2 – Capacitor Bank Installation:

- Capacitor banks sized 600–800 kVAr improved feeder power factors to above 0.90.
- Voltage stability improved by ~2%, and system losses reduced to 2.1%.

4. Scenario 3 – Combined Optimization (Redistribution + Capacitors):

- Yielded the best performance, with:
- Rural feeder voltage = 10.84 kV (−1.45%).
- Overall system PF = 0.94.
- Losses reduced to 1.8% (~74.5 kW).
- Annual savings ≈ ₹32.1 lakhs.

5. IEEE 4-Bus Validation:

- Newton-Raphson converged faster (4 iterations) than Gauss-Seidel (16 iterations).
- Capacitor placement improved voltages from 0.921 → 0.959 p.u. and reduced losses by 32%.
- Confirms the robustness of the chosen methodology.

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9.1 Technical Contributions

This thesis makes the following technical contributions:

- Developed an ETAP-based diagnostic model for the Naisaray 33/11 kV substation.
- Demonstrated the synergy of load redistribution and capacitor integration, achieving greater benefits than either strategy alone.
- Validated methodology with IEEE test system benchmarks, ensuring replicability.
- Quantified economic benefits of corrective strategies, linking technical improvements to financial viability.

9.2 Practical Recommendations for JBVNL

Based on the findings, the following recommendations are proposed for JBVNL's distribution network management:

1. Short-Term Measures:

- Redistribute loads from overloaded feeders (Rural, Jail) to spare feeders (Industrial, Ghutua).
- Install capacitor banks (600–800 kVAr) at strategic points on low-PF feeders.
- Conduct periodic PF audits for agricultural and institutional consumers.

2. Medium-Term Measures:

- Deploy Automatic Voltage Regulators (AVRs) on long rural feeders.
- Install feeder meters and online monitoring systems for real-time data.
- Introduce energy-efficient motors and pumps for agricultural consumers.

3. Long-Term Measures:

- Integrate SCADA and distribution automation systems for better feeder control.
- Explore distributed generation (DG), such as solar PV integration on 11 kV feeders.
- Adopt AI-driven load forecasting to predict and balance seasonal demand variations.

9.3 Limitations of the Study

- The study focused only on steady-state load flow; transient stability, harmonics, and fault analysis were not included.
- Economic analysis was limited to loss cost savings, without considering full investment-return models for capacitor banks or automation.
- Field data availability was constrained to one substation (Naisaray), although the methodology is scalable to others.

9.4 Future Scope of Research

This research can be extended in multiple directions:

1. Advanced Power Flow Studies:

- Incorporate unbalanced and stochastic load flow models for rural feeders with highly variable agricultural loads.
- Extend ETAP analysis to include harmonic distortion and short-circuit fault analysis.

2. Integration of Renewable Energy:

- Model the impact of distributed solar PV plants on 11 kV feeders.
- Evaluate the role of battery energy storage systems (BESS) in peak load management.

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3. Smart Grid Applications:

- Implement SCADA and IoT-based monitoring for real-time feeder balancing.
- Develop AI/ML-based optimization algorithms for capacitor placement and feeder reconfiguration.

4. Policy and Regulatory Studies:

- Assess the impact of tariff-based incentives for PF correction by large consumers.
- Explore policy-driven rural electrification programs with integrated reactive compensation.

This research section consolidated the findings of the thesis, highlighting the technical, economic, and practical implications of load flow analysis for distribution systems. The combined strategy of feeder load redistribution and capacitor integration proved to be the most effective, reducing technical losses by 37.5% and improving system PF to 0.94.

The study contributes both theoretically and practically to power system engineering and provides JBVNL with a replicable framework for substation optimization. Future extensions involving renewables, smart grid technologies, and AI-based optimization will further strengthen the reliability and efficiency of distribution networks in India.

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