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Power Losses in Transformer And Transmission Lines

Professor P.E.Pawar ,Mr.Sumit Patole,Mr.Ramchandra Karennavar, Mr.Pushkar Kulkarni, Mr.viraj Raskar, Mr.Sourabh Bhosale, Mr.Sangram Patil, Mr.Indrajeet Salunkhe, Mr.Rahid Shaikh, Mr.Madgonda Pargond, Mr.Pritum Sutar

General Sciences and Engineering, AITRc, Vita

Abstract- This research comprehensively examines the persistent issue of energy losses in transmission and distribution (T&D) systems, which pose a significant challenge to the efficiency and reliability of electrical power delivery. Losses are broadly divided into technical losses— originating from physical and electrical characteristics of the grid infrastructure—and non- technical losses, which are largely administrative or socio-political in nature. To address these issues, the study introduces a globally adaptable statistical model that predicts loss behaviour based on economic indicators (GDP per capita), socio-political factors (corruption index), geographical characteristics, ambient climate conditions, and the structural organization of the electrical grid. On the technical side, the study evaluates the impact of reactive power on transmission efficiency and explores the effectiveness of capacitor-based compensation methods for loss mitigation. The integration of Phasor Measurement Units (PMUs) and smart metering technologies allows for a more granular and synchronized analysis of power flows, enhancing the real-time detection and classification of loss types, including Joule losses, corona discharge, and insulation leakage. The proposed methodologies offer a holistic and scalable approach to minimizing power losses, improving grid stability, and guiding policy decisions in both developed and developing regions. The findings provide a robust framework for engineers, system operators, and policymakers aiming to modernize electrical infrastructure and promote sustainable energy practices.

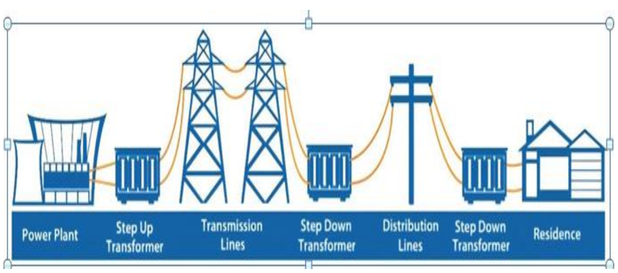
Keywords- Transmission and Distribution Losse,Technical Losses,Non-Technical Losses,Power Grid Efficiency, Reactive Power Compensation

I. INTRODUCTION

Energy transmission and distribution networks serve as the backbone of any nation's power infrastructure, enabling the delivery of electricity from generation plants to end consumers. However, throughout this journey, a substantial portion of the electrical energy is lost due to various technical and operational inefficiencies. These losses are generally categorized into two groups: technical losses and non-technical losses. Technical losses primarily arise from the inherent properties of the electrical components in the system. These include resistive heating (Joule losses), magnetic losses in transformers, dielectric losses, and corona discharge, particularly in high-voltage overhead lines. These losses are typically proportional to the square of the current and are influenced by conductor resistance, system voltage, frequency, line length, and environmental factors such as temperature and humidity. High-voltage transmission systems, such as those operating at 400 kV and above, are particularly susceptible to atmospheric losses due to ionization of the surrounding air in moist or foggy conditions, resulting in corona discharges.

Non-technical losses, on the other hand, arise from human and systemic inefficiencies. These include electricity theft, illegal connections, tampered meters, errors in billing, and administrative mismanagement. Although often underestimated, non-technical losses can significantly distort energy accountability, especially in developing countries where regulatory enforcement may be weak.

Traditional methods used to estimate losses—such as energy audits via SCADA and conventional metering—are limited in scope and often provide inaccurate or delayed readings due to their asynchronous nature. In contrast, Phasor Measurement Units (PMUs) offer time-synchronized, high-resolution data that enable system operators to assess power quality and losses with far greater accuracy. This paper integrates these advanced monitoring techniques with targeted reactive power compensation strategies and predictive modelling to provide a comprehensive solution for minimizing energy losses in T&D systems.



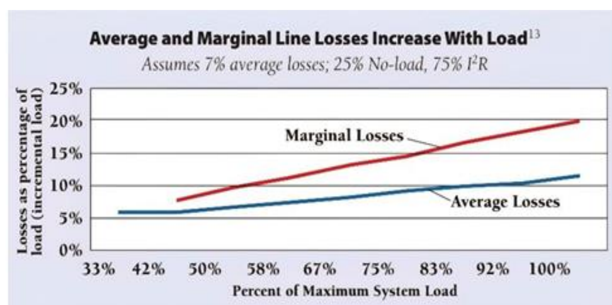
II. LITERATURE REVIEW

Causes of Transmission Losses

The physical structure and electrical behaviour of transmission systems inherently give rise to losses. The most dominant form of loss is resistive heating, known as Joule loss, which results from the current flowing through conductors with finite resistance. Corona loss becomes significant in systems operating at very high voltages, particularly during inclement weather conditions, where the air surrounding the conductor ionizes and causes energy dissipation. Transformer losses are also considerable, divided into no-load losses (caused by constant magnetization of the core) and load losses (caused by current-induced heating in copper windings). Additional phenomena such as skin effect and eddy current losses contribute to inefficiencies, particularly in older infrastructure.

III. ADVANCED MONITORING AND MITIGATION TECHNIQUES

To effectively combat these losses, recent research emphasizes the use of advanced technologies like PMUs and smart meters. These devices provide real-time, synchronized data across the network, enabling accurate identification and segregation of various loss components. SCADA systems are also integrated to offer a complete visualization of grid behaviour. For mitigation, capacitor banks—either series or shunt—are deployed to reduce the reactive power component, which lowers current flow and thus resistive losses. FACTS devices offer more dynamic compensation, adjusting voltage and reactance in response to system load and stability conditions.



Impact Of System Design And Operational Practices

Losses are influenced by the design choices made in grid planning. For instance, using conductors with high thermal and electrical conductivity reduces resistive losses, while increasing transmission voltage lowers current and related losses but at a higher installation cost. Long transmission distances exacerbate line losses and voltage drops, necessitating the use of booster transformers and capacitive support. Operational strategies such as peak load management, load shedding, and load shifting (e.g., ice storage in cooling applications) help in flattening demand curves and minimizing overload-induced losses

IV. CHALLENGES AND EMERGING SOLUTIONS

Despite technological advancements, challenges persist. Measuring losses accurately in real time remains difficult due to non-linear load patterns, environmental variability, and equipment aging. Environmental effects such as rain, fog, and pollution significantly influence corona losses, making them hard to predict. Moreover, in many developing nations, non-technical losses can exceed 30%, often due to systemic issues like corruption, poverty, and regulatory loopholes. Recent innovations include machine learning algorithms trained on historical loss patterns, dynamic line rating systems that adjust capacity based on environmental inputs, and portable FACTS devices for rapid deployment.

V. GAPS AND FUTURE DIRECTIONS

Future research should focus on integrating socio-economic parameters into T&D loss models to reflect real-world conditions more accurately. The adoption of hybrid solutions that combine artificial intelligence with high-fidelity PMU data offers promising avenues for adaptive forecasting and preventive maintenance. Additionally, decentralized compensation and control mechanisms are crucial for renewable-heavy grids, which experience more variable power flows and complex loss dynamics.

Methodology

Data Collection and Advanced Monitoring

The methodology begins with the deployment of PMUs at critical nodes within a 400 kV transmission network. These units capture real-time, synchronized voltage and current phasors, offering microsecond-level accuracy. This data is complemented by information from SCADA systems and advanced smart meters, allowing for a multi-tiered validation mechanism. Weather data such as temperature, humidity, and precipitation is also integrated to assess how environmental changes influence corona and insulation leakage losses. Cross-verification algorithms are used to compare PMU-derived loss profiles with traditional metering outputs, enhancing confidence in the measurements.

Reactive Power Compensation and Loss Mitigation

- Reactive power is a major contributor to transmission losses, as it causes increased current flow without delivering usable energy. **The study proposes:**
- Strategic capacitor placement based on load flow analysis to identify locations with high reactive loads.
- Dynamic compensation, where the capacitive reactance is adjusted in real time to counteract changing load conditions.

- Series compensation in long transmission lines, where capacitors are inserted in series with the line to cancel a portion of its inductance, thereby improving voltage profiles and reducing reactive current flow.
- **Modelling and Loss Allocation**
- A hybrid model combining empirical and statistical methods is developed to quantify and allocate losses. It includes:
- Real-time classification of loss types (resistive, corona, transformer) based on PMU data.
- Use of environmental correction coefficients to account for dynamic weather effects.
- Allocation of losses to specific generators, consumers, and transmission paths using proportional distribution models.
- Machine learning regression models trained on historical operational data to forecast future losses under different scenarios.

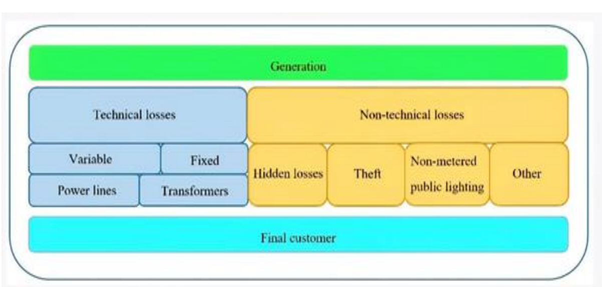
Losses at Each Stage of Electricity Distribution[6]

Component	Estimated Loss as a Percentage of Energy Sold	
	Typical Urban	Typical Rural
Subtransmission Lines	0.1	0.7
Power Transformers	0.1	0.7
Distribution Lines	0.9	2.5
Distribution Transformers No Load	1.2	1.7
Distribution Transformers Load	0.8	0.8
Secondary Lines	0.5	0.9
Total	**3.6**	**7.3**

VI. RESULTS

Component-wise Loss Analysis Analysis of PMU data revealed that resistive (Joule) losses accounted for an average of 78% of the total technical losses across the monitored 400 kV lines. Corona losses contributed around 14% under normal weather, while leakage losses made up the remaining 8%. During adverse weather events—such as rainfall, fog, or high humidity—corona-related losses increased dramatically, comprising as much as 25% of total losses, highlighting the importance of environmental data in loss prediction.

Effectiveness of Compensation The installation of shunt and series capacitor banks at key high-loss locations led to a 10–15% reduction in overall transmission losses. Systems employing dynamic compensation, where capacitor values changed in real time with the load, achieved an additional 6–8% reduction in peak-hour losses. Series capacitors in long- distance transmission routes significantly improved voltage stability and reduced the need for intermediate voltage support, enhancing system reliability and efficiency.



Policy and Operational Impacts Findings suggest that policies promoting the deployment of real-time monitoring technologies and reactive compensation infrastructure can have a transformative impact on grid efficiency. Government and utility stakeholders should also address non-technical losses through stricter enforcement, public engagement, and regulatory reform. Incentives for using AI-based forecasting, upgrading outdated infrastructure, and adopting modular FACTS devices can further enhance grid resilience and performance.

VII. CONCLUSION

This study presents a robust, multi-dimensional approach to diagnosing and mitigating energy losses in transmission and distribution systems. By integrating synchronized PMU data, dynamic reactive power compensation, and predictive statistical modelling, the proposed framework offers significant improvements in both technical performance and decision- making accuracy. The inclusion of environmental and socio-economic variables in the modelling process makes it adaptable to a wide range of global contexts. With the power sector increasingly relying on digital infrastructure and decentralized energy sources, the adoption of intelligent, data-driven methods for loss reduction is not just beneficial—it is essential. These findings serve as a valuable resource for energy planners, policymakers, and utility companies committed to building a more efficient and resilient electric grid.

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