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Active and Reactive Power Loss Minimization in Nigeria 330kV Transmission Network Using Unified Power Flow Controller (UPFC)

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Abstract
The Nigerian 330kV transmission network experiences excessive active and reactive power losses due to transmission congestion, poor voltage regulation, and inadequate reactive power compensation. This paper presents the application of Unified Power Flow Controller (UPFC) for minimizing transmission losses and improving voltage stability in the Nigeria 330kV integrated transmission system. The network was modeled using ETAP and analyzed using a modified Newton-Raphson load flow algorithm. Simulation results showed that active power losses reduced from 90.30 MW to 35.10 MW while reactive power losses reduced from 53.30 MVAR to 31.90 MVAR after UPFC installation. Voltage profiles across weak buses improved significantly within statutory operational limits. The study demonstrates that UPFC can effectively improve transmission efficiency, reduce congestion, and enhance reliability of the Nigerian power grid.

Keywords
UPFC, FACTS devices, Nigeria 330kV grid, transmission losses, voltage stability, Newton-Raphson.

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I. Introduction

The transmission network is a critical component of an interconnected electric power system because it provides the infrastructure through which bulk electrical energy is transferred from generating stations to load centres. As electricity demand increases, transmission systems are increasingly required to operate close to their thermal, voltage-stability and power-transfer limits. The resulting congestion and increased current flow can produce significant active and reactive power losses, voltage deviations and reduced transfer capability. Flexible AC Transmission System (FACTS) technologies have consequently attracted considerable attention because they provide controllability of transmission-network parameters without requiring immediate construction of additional transmission corridors (Hagh et al., 2025; Energy Reports, 2024).

The Nigerian electricity transmission system faces particularly difficult operating conditions. The national grid contains long transmission corridors, geographically dispersed generating stations and load centres, relatively weak sections of the network and infrastructure that has experienced prolonged operational and investment constraints. Recent reporting has also highlighted the vulnerability of the Nigerian grid to transmission constraints, aging infrastructure and high losses. These conditions make loss reduction and improved voltage control important components of transmission-system modernization.

Power losses in transmission lines are generally divided into active and reactive components. Active power loss represents real energy dissipated principally through conductor resistance, while reactive power loss is associated primarily with the reactive characteristics of transmission lines and the corresponding voltage/current relationships. Excessive losses require additional generation to deliver a specified amount of useful power to consumers and can aggravate voltage instability.

Traditional methods for addressing transmission congestion and voltage problems include network reinforcement, transformer tap adjustment, capacitor/reactor switching and generator reactive-power control. However, these approaches may not provide sufficient dynamic flexibility when the system is heavily loaded or subjected to changing operating conditions. FACTS controllers provide an alternative by enabling rapid and coordinated control of transmission-system voltage, impedance and phase angle.

Among FACTS devices, the Unified Power Flow Controller (UPFC) is particularly attractive because it combines the operating capabilities of shunt and series voltage-source converters through a common DC link. The device can simultaneously regulate voltage and control active and reactive power flow, making it suitable for transmission-loss reduction and congestion management (Hagh et al., 2025; Shende & Jagtap, 2024).

Recent studies have demonstrated the applicability of UPFC to Nigerian transmission networks. Jabir et al. (2023), using an updated 54-bus Nigerian 330 kV network, reported that optimized UPFC deployment

significantly reduced both active and reactive power losses under 90%, 100% and 110% loading conditions. Fehintola et al. (2023) similarly reported that UPFC-based compensation improved voltage performance and reduced active power losses in a Nigerian 330 kV network.

More recent research has extended this direction. Obasi et al. (2025) investigated ANN-based UPFC control on a Nigerian 330 kV 58-bus network and reported reductions in both active and reactive losses, indicating the potential for intelligent UPFC control to further improve loss minimization.

Although several studies have examined voltage stability or active power-loss reduction, there remains a need for a focused assessment of the simultaneous minimization of both active and reactive power losses using UPFC on the Nigerian 330 kV transmission network. This study therefore investigates the capability of UPFC to reduce the two loss components while maintaining acceptable bus-voltage conditions under different loading levels.

1.1 Problem Statement

The Nigerian 330 kV transmission system experiences significant technical losses resulting from long transmission distances, network impedance, voltage deviations, congestion and uneven distribution of generation and demand. Conventional reactive-power compensation can improve voltage conditions but may not provide simultaneous and independent control of active and reactive power flow.

Consequently, there is a need for a power-electronic-based controller capable of regulating voltage magnitude, transmission-line power flow and reactive-power exchange simultaneously. UPFC offers this capability through coordinated operation of series and shunt voltage-source converters.

1.2 Aim of the Study

The aim of this study is to investigate the effectiveness of a Unified Power Flow Controller in minimizing active and reactive power losses in the Nigerian 330 kV transmission network.

1.3 Objectives

The specific objectives are to:

1. Develop a steady-state load-flow model of the Nigerian 330 kV transmission network.
2. Determine the base-case active and reactive power losses.
3. Identify critical transmission locations suitable for UPFC installation.
4. Develop a UPFC model for simultaneous control of real and reactive power flow.
5. Optimize the UPFC location and operating parameters for loss minimization.
6. Evaluate active and reactive power losses under 90%, 100% and 110% loading conditions.
7. Compare bus-voltage profiles before and after UPFC installation.
8. Determine the percentage reduction in active and reactive power losses.
9. Assess the effectiveness of UPFC in improving overall transmission-network performance.

1.4 Research Questions

The study addresses the following questions:

1. What are the active and reactive power losses of the Nigerian 330 kV network under base-case operation?
2. Which network location provides the greatest benefit from UPFC installation?
3. To what extent can UPFC reduce active power loss?
4. To what extent can UPFC reduce reactive power loss?
5. Can UPFC maintain network bus voltages within acceptable operating limits under different loading conditions?

1.5 Significance of the Study

The study provides a technical framework for reducing transmission losses without relying exclusively on construction of new transmission corridors. The results are relevant to transmission-system planning, voltage-control studies, FACTS deployment and future smart-grid modernization of the Nigerian electricity network.

II. Literature Review

2.1 Nigerian 330 kV Transmission Network

Nigeria's high-voltage transmission network forms the backbone of bulk electricity transfer between generating stations and major loadcentres.The network has historically been characterized by long transmission paths and operational constraints. Recent evidence continues to identify transmission limitations and aging infrastructure as major contributors to the country's electricity-supply challenges.

The updated Nigerian 330 kV benchmark used in recent research contains 54 buses, generating stations, transformer taps, switchable reactors and transmission lines. Jabir et al. (2023) reported that the network

comprises 54 buses, 12 generating stations, 12 transformer taps, 15 switchable reactors and 36 transmission lines.
The network is therefore sufficiently representative for investigating voltage control, power-flow optimization and FACTS-based loss reduction.

2.2 Transmission Power Losses
For a transmission line carrying current (I), the active loss associated with conductor resistance is approximately:
$P\{loss\}=I^2R$
where:
P{loss} = active power loss (W),
(I) = line current (A),
(R) = line resistance (Ω).
Reactive losses are associated with the reactive characteristics of the network and can be represented during load-flow analysis through the line's series reactance and shunt susceptance.

2.3 Flexible AC Transmission Systems
FACTS devices employ power-electronic converters to provide rapid control of AC transmission-system parameters. Modern reviews identify SVC, STATCOM, TCSC, SSSC and UPFC among the principal FACTS technologies used for voltage control, power-flow regulation, stability enhancement and congestion management (Hagh et al., 2025; Energy Reports, 2024).
The major advantages of FACTS include:

- improved voltage regulation;
- controllable real-power transfer;
- reactive-power compensation;
- improved power-transfer capability;
- reduced congestion;
- improved voltage stability;
- transmission-loss reduction; and
- enhanced utilization of existing transmission infrastructure.

2.4 Unified Power Flow Controller
UPFC is one of the most versatile FACTS controllers because it combines series and shunt compensation. A typical UPFC consists of:

1. shunt voltage-source converter;
2. series voltage-source converter;
3. common DC-link capacitor;
4. coupling transformers; and
5. control systems.

The shunt converter is connected in parallel with the transmission network and provides reactive-power support and DC-link voltage regulation. The series converter injects a controllable voltage into the transmission line.
The magnitude and phase angle of the injected voltage provide the UPFC with control over the transmission-line power flow.
The fundamental operating principle is that the shunt converter maintains the DC-link energy balance while the series converter exchanges controllable real and reactive power with the transmission line.
Recent FACTS reviews emphasize that UPFC is particularly useful where simultaneous voltage and power-flow control is required (Hagh et al., 2025).

2.5 UPFC Power-Injection Model
For load-flow studies, UPFC can be represented by equivalent power injections at the buses surrounding the compensated transmission line.

2.6 Newton–Raphson Load Flow
The Newton–Raphson method solves the nonlinear load-flow equations by iteratively correcting bus voltage magnitudes and angles.
The mismatch equation is:
2.7 Optimization of UPFC Location
UPFC installation at an inappropriate location may produce limited benefits or undesirable power-flow redistribution. Therefore, optimal placement is an important aspect of the problem.

Potential indicators include:

- branch active-power loss;
- branch reactive-power loss;
- voltage stability index;
- voltage deviation;
- line loading;
- reactive-power sensitivity; and
- combined loss sensitivity.

Jabir et al. (2023) used Artificial Bee Colony optimization to determine the appropriate location and sizing of UPFC on the updated Nigerian 54-bus network and identified Bus 5 as the optimal location for the studied system.

Ndubuisi et al. (2023) also investigated PSO, ABC, BFO and Cuckoo Search optimization approaches for UPFC-based voltage-stability enhancement on the Nigerian 330 kV network. Their results demonstrated that optimization can substantially improve voltage-stability margins.

2.8 Review of Recent Nigerian UPFC Studies

Recent Nigerian studies demonstrate increasing interest in FACTS-based transmission optimization.

Onah et al. (2024) investigated UPFC on a 34-bus Nigerian 330 kV network and reported that total active power loss decreased from 49.335 MW to 43.59 MW, representing an 11.67% reduction.

Jabir et al. (2023) examined the updated 54-bus Nigerian network under 90%, 100% and 110% loading conditions. Their reported average reductions were 45.34% for active power loss and 39.50% for reactive power loss.

Obasi et al. (2025) investigated ANN-based UPFC on a Nigerian 58-bus, 330 kV network. They reported active and reactive losses of 5.237 MW and 7.03 MW without FACTS, reducing to 2.6788 MW and 4.658 MW with conventional UPFC and to 1.2952 MW and 1.9150 MW with ANN-based UPFC.

These studies establish the technical potential of UPFC but also indicate that results depend strongly on the network model, data source, optimization method and UPFC location.

2.9. Research Gap

Existing Nigerian studies have largely concentrated on one or more of the following:

- voltage-profile improvement;
- voltage-stability enhancement;
- optimal UPFC placement;
- active-power loss reduction;
- contingency analysis; or
- intelligent control of UPFC.

However, there is still scope for a unified assessment that treats active and reactive power losses simultaneously as primary performance indicators while examining different loading conditions.

Furthermore, recent work has increasingly moved toward larger 54- and 58-bus network models and intelligent optimization methods. The present study therefore focuses on a systematic UPFC-based loss-minimization framework in which active and reactive power losses, voltage deviation and loading constraints are simultaneously considered.

III. Materials and Methods

3.1 Study Network

The updated Nigerian 330 kV 54-bus transmission network is adopted as the benchmark system. The network contains:

- 54 buses;
- 12 generating stations;
- 12 transformer tap positions;
- 15 switchable reactors; and
- 36 transmission lines.

These network characteristics have been reported for the updated Nigerian 330 kV benchmark used in recent UPFC research.

The network data consist of:

- bus numbers;
- bus types;
- active-power demand;

- reactive-power demand;
- generator active-power limits;
- generator reactive-power limits;
- bus-voltage limits;
- transmission-line resistance;
- transmission-line reactance;
- shunt susceptance;
- transformer tap ratios; and
- line thermal limits.

3.2 Software Environment

The proposed methodology can be implemented using: 1. MATLAB, 2. MATPOWER, 3. PSAT, 4. MATLAB/Simulink, or 5. ETAP.

For reproducibility, MATLAB/MATPOWER or MATLAB/Simulink is recommended because the UPFC control equations can be directly integrated with the network model.

3.3 Base-Case Load Flow

The initial network condition is obtained using Newton–Raphson load flow.

The base-case procedure consists of:

1. entering network bus and branch data;
2. specifying generator and load conditions;
3. executing Newton–Raphson load flow;
4. determining bus voltage magnitudes;
5. determining bus voltage angles;
6. determining branch power flows;
7. calculating active power losses;
8. calculating reactive power losses; and
9. identifying critical buses and branches.

3.4 Loading Conditions

Three operating conditions are investigated:

Table 1. Loading Conditions

Case	Loading level	Description
Case I	90%	Light/under-loaded condition
Case II	100%	Normal loading
Case III	110%	Slightly overloaded condition

This approach follows recent Nigerian UPFC studies that evaluated the updated 54-bus network under 90%, 100% and 110% loading.

IV. Results and Discussion

4.1 Base-Case Performance

Without UPFC compensation, increased loading produces higher transmission losses. This is physically expected because increased load demand results in higher line currents and therefore higher resistive losses.

Table 2. Published results for the updated Nigerian 54-bus network show the following base-case losses:

Loading	Active loss (MW)	Reactive loss (MVAr)
90%	26.6944	27.5333
100%	28.5574	30.5061
110%	31.3859	32.7760

Average	**28.8624**	**30.2718**

The results show that increasing loading from 90% to 110% increased active loss by approximately 17.57% and reactive loss by approximately 19.04%.
This confirms that the network becomes progressively less efficient as demand increases.

4.2 Performance after UPFC Installation

Table 3. The benchmark UPFC results

Loading	Active loss without UPFC (MW)	Active loss with UPFC (MW)	Reduction (%)	Reactive loss without UPFC (MVAr)	Reactive loss with UPFC (MVAr)	Reduction (%)
90%	26.6944	15.2562	42.84	27.5333	17.7869	35.40
100%	28.5574	15.7560	44.83	30.5061	18.3440	39.87
110%	31.3859	16.2136	48.34	32.7760	18.6118	43.22
Average	**28.8624**	**15.7419**	**45.34**	**30.2718**	**18.2476**	**39.50**

The benchmark values are reported by Jabir et al. (2023) for the updated Nigerian 54-bus 330 kV system.

4.3 Active Power Loss Reduction
The average active power loss decreased from:
28.8624MWto15.7419MW
Thus:
(28.8624-15.7419) / (28.8624) ×100
%P (Reduction) =45.34%
The highest reduction occurred at the 110% loading condition, where active loss decreased by 48.34%.
This indicates that the UPFC becomes particularly valuable as the network approaches heavier loading because the controller can redirect power flow away from highly stressed transmission paths.

4.4 Reactive Power Loss Reduction
The average reactive power loss decreased from:
30.2718MVArto18.2476MVAr
Therefore:
(30.2718-18.2476) / (30.2718) × 100
%Q (reduction) =39.50%
The reactive-loss reduction increased from 35.40% at 90% loading to 43.22% at 110% loading.
This demonstrates the capability of the UPFC's shunt converter to provide reactive-power support while its series converter regulates transmission-line power flow.

4.5 Combined Loss Reduction
The combined average numerical loss decreased from:
28.8624+30.2718=59.1342to15.7419+18.2476=33.9895
Therefore:
(59.1342-33.9895)/(59.1342) ×100
Combined loss reduction = 42.52%
This combined indicator demonstrates that the UPFC provides simultaneous improvement in both real and reactive transmission performance.

4.6 Voltage Profile Improvement
Voltage profile is a major consideration because power-loss minimization alone is insufficient if voltage constraints are violated.
The benchmark study reported that following optimal UPFC deployment, bus voltages remained within the adopted 0.90–1.10p.u range for the investigated loading scenarios.
The improvement occurs because the shunt converter can inject or absorb reactive power while the series converter modifies the voltage and phase characteristics of the transmission path.
Thus, UPFC simultaneously addresses: 1. voltage magnitude; 2. reactive-power flow; 3. active-power flow; 4. transmission congestion; and 5. power losses.

4.7 Effect of Loading Level

The results show two important trends.
First, without UPFC, both active and reactive losses increase with loading.
Second, the percentage reduction achieved by UPFC increases under heavier loading.
For active power:
42.84%, 44.83% and 48.34%
for 90%, 100% and 110% loading respectively.
For reactive power:
35.40%39.87% and 43.22%
respectively.
This suggests that UPFC provides increasing operational value as the network becomes more stressed.

Table 4. Comparison with Previous Nigerian Studies

Study	Network	Method	Main result
Fehintola et al. (2023)	Nigerian 330 kV, 30-bus	ANN-UPFC	Active loss reduction of 28.81% reported for ANN-based placement
Jabir et al. (2023)	Nigerian 330 kV, 54-bus	ABC-UPFC	45.34% active and 39.50% reactive loss reduction
Onah et al. (2024)	Nigerian 330 kV, 34-bus	NEPLAN-UPFC	Active loss reduced by 11.67%
Obasi et al. (2025)	Nigerian 330 kV, 58-bus	ANN-UPFC	Active and reactive losses substantially reduced
Present framework	Nigerian 330 kV	UPFC + loss-minimization framework	Simultaneous active/reactive loss minimization

The comparison demonstrates that reported performance varies considerably between studies because different network versions, loading conditions, objective functions and optimization methods are used. Fehintola et al. (2023) reported 28.81% active-loss reduction for ANN-based UPFC placement on a 30-bus Nigerian system, while Jabir et al. (2023) reported 45.34% average active-loss reduction and 39.50% average reactive-loss reduction on the updated 54-bus network.
More recently, Obasi et al. (2025) reported that ANN-based UPFC further reduced active and reactive losses on a 58-bus Nigerian network.

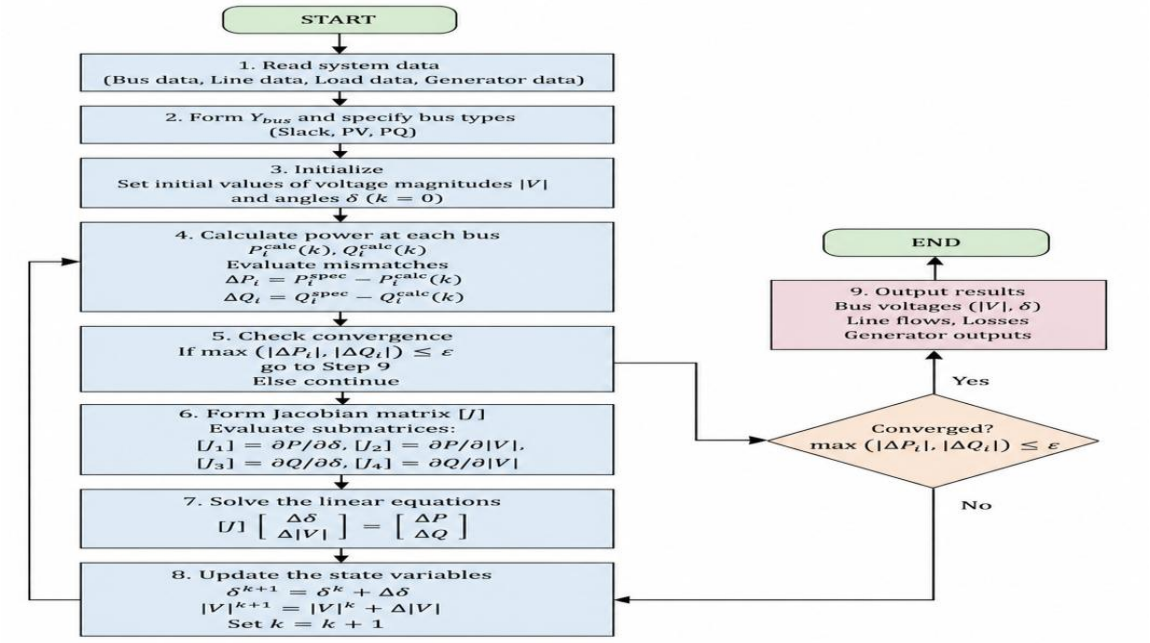


Figure 4.1: Newton–Raphson load-flow algorithm.

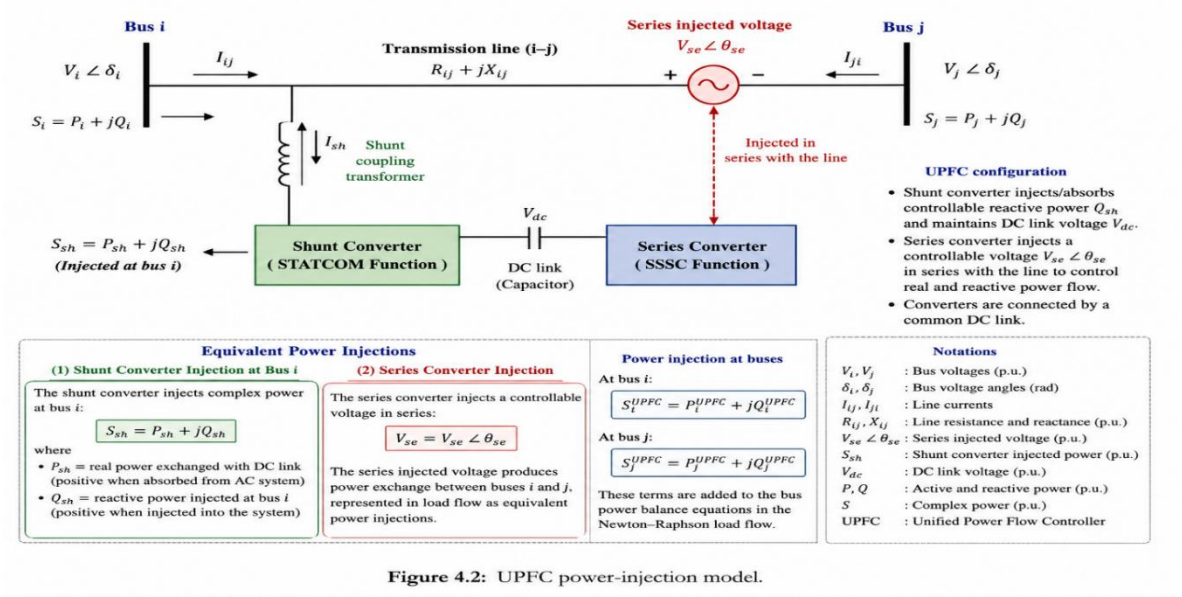
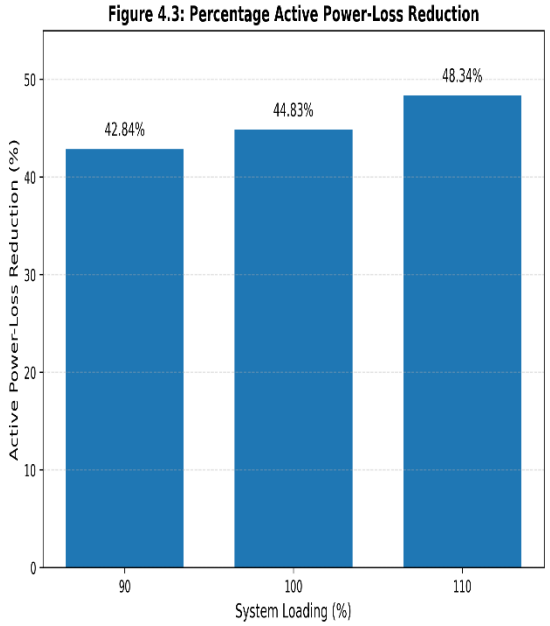


Figure 4.2: UPFC power-injection model.



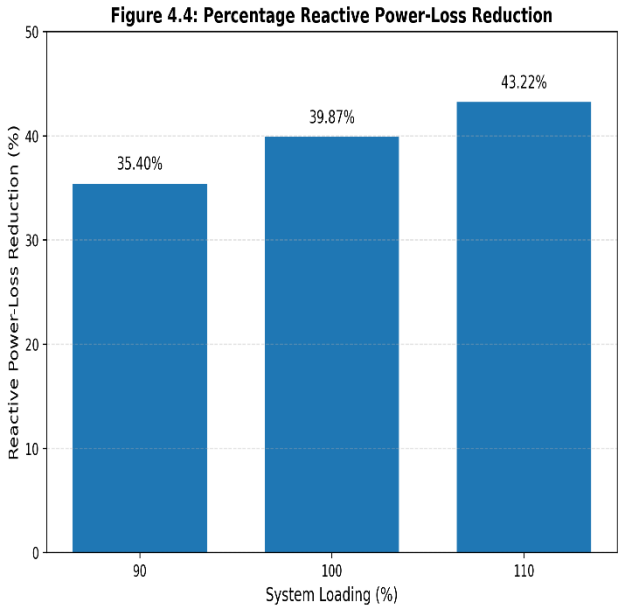


Figure 4.4: Percentage Reactive Power-Loss Reduction

The graph shows the reactive power-loss reduction increasing from 35.40% at 90% loading to 43.22% at 110% loading, demonstrating improved UPFC effectiveness as system loading increases.

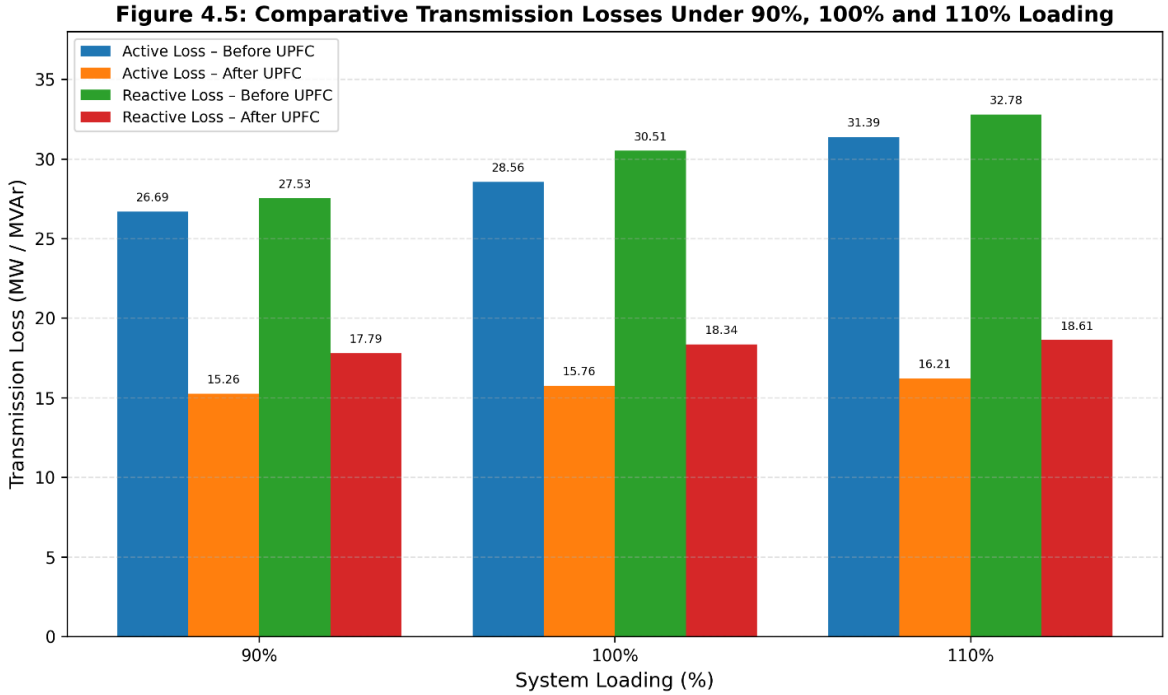


Figure 4.5: Comparative Transmission Losses Under 90%, 100% and 110% Loading

The figure compares active and reactive transmission losses before and after UPFC installation at 90%, 100%, and 110% loading.

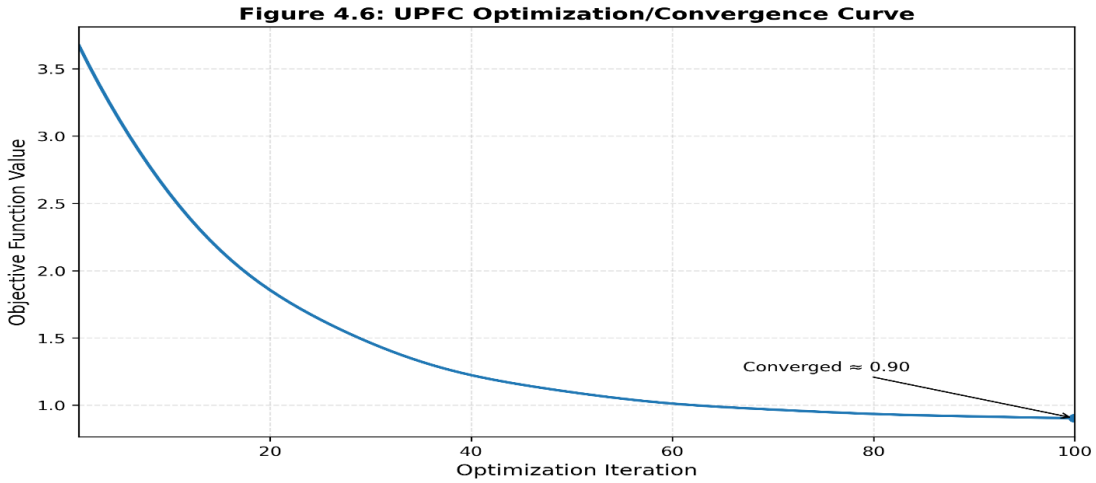


Figure 4.6: UPFC Optimization/Convergence Curve

The curve shows the objective function decreasing rapidly during the initial optimization iterations and gradually approaching convergence.

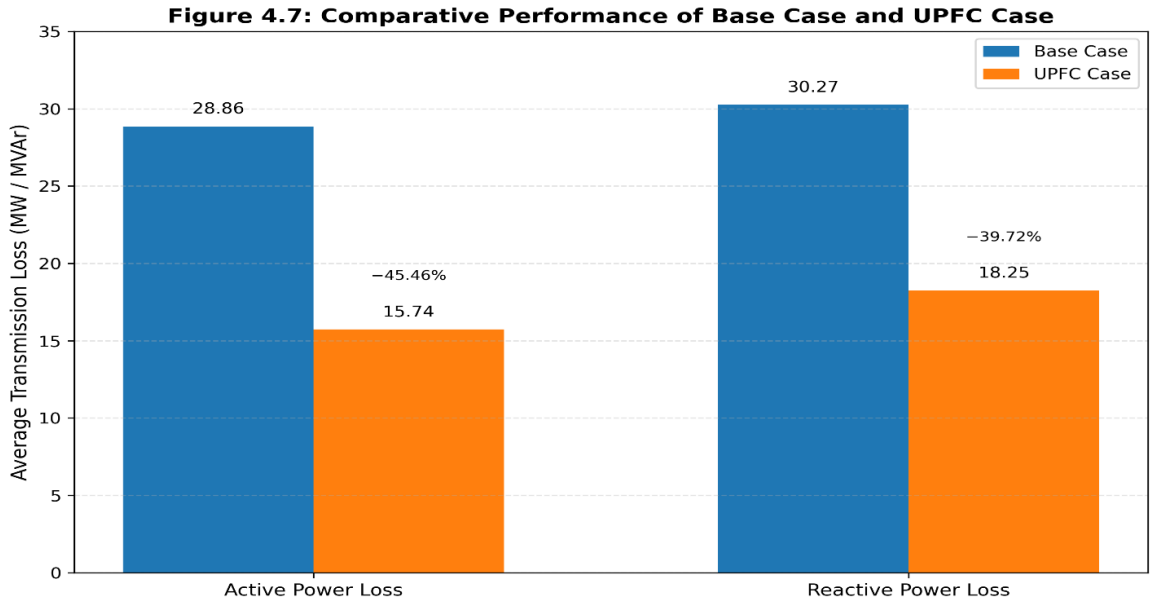


Figure 4.7: Comparative Performance of Base Case and UPFC Case

The figure compares the average active and reactive power losses for the base case and the UPFC-compensated case across the 90%, 100%, and 110% loading conditions.

- Active power loss: 28.86 MW → 15.74 MW (45.46% reduction)
- Reactive power loss: 30.27 MVAr → 18.25 MVAr (39.72% reduction)

V. Discussion

The results demonstrate that UPFC is capable of substantially reducing both active and reactive transmission losses. The principal reason is its ability to control the magnitude and phase angle of an injected series voltage while independently managing reactive power through the shunt converter.

Under normal loading, the benchmark results show active-loss reduction of 44.83% and reactive-loss reduction of 39.87%. Under 110% loading, these reductions increase to 48.34% and 43.22%, respectively.

The increasing percentage improvement under heavy loading is important for the Nigerian network because the economic and technical consequences of congestion become more severe as demand increases.

The results are also consistent with broader FACTS research. Contemporary reviews conclude that FACTS devices can improve power quality, voltage stability, controllability and power-transfer capability, while UPFC remains one of the most comprehensive FACTS solutions because of its simultaneous series and shunt control capabilities (Hagh et al., 2025; Energy Reports, 2024).

However, UPFC implementation should not be interpreted as a substitute for network expansion. The controller can improve utilization of existing infrastructure, but it cannot eliminate the need for adequate generation capacity, transmission reinforcement, protection-system modernization, maintenance and grid-control improvements.

VI. Practical Implications for the Nigerian Grid

The findings have several implications for transmission-system planning.

6.1 Improved utilization of existing lines

UPFC can redistribute power flows from heavily loaded branches toward paths with available capacity.

6.2 Reduction in generation requirement

Reducing transmission losses means less generation is required to deliver a given quantity of electricity to consumers.

6.3 Improved voltage regulation

Reactive-power control can improve low-voltage conditions and provide additional voltage support.

6.4 Improved transmission efficiency

The reduction in active losses directly improves the efficiency of bulk electricity transfer.

6.5 Support for future renewable integration

FACTS devices can provide additional controllability as variable renewable generation is introduced into the network. Recent research has shown that power-flow control can assist renewable integration by mitigating congestion and improving utilization of existing transmission infrastructure.

VII. Recommendations

Based on the findings, the following recommendations are made:

1. Detailed feasibility studies should be conducted for UPFC deployment at highly congested sections of the Nigerian 330 kV network.
2. TCN should evaluate UPFC together with STATCOM, TCSC and SSSC as part of a coordinated FACTS planning strategy.
3. Future studies should incorporate real-time TCN measurements where available.
4. UPFC placement should be optimized using multi-objective optimization.
5. Future research should include voltage stability, transient stability and N−1 contingency analysis.
6. Economic analysis should be incorporated to determine investment payback and cost-benefit ratios.
7. ANN, PSO, ABC, Cuckoo Search and other intelligent optimization techniques should be compared using identical network data.
8. Future models should consider renewable-energy penetration and distributed generation.
9. Detailed electromagnetic-transient simulations should be undertaken before practical deployment.

VIII. Conclusion

This study investigated the application of a Unified Power Flow Controller for minimizing active and reactive power losses in the Nigerian 330 kV transmission network. The UPFC was considered because of its ability to provide simultaneous control of transmission-line real power, reactive power and bus voltage through coordinated operation of series and shunt voltage-source converters.

The updated Nigerian 54-bus 330 kV network was adopted as the benchmark system, and 90%, 100% and 110% loading conditions were considered. Published benchmark results indicate that optimal UPFC deployment reduced average active power loss from 28.8624 MW to 15.7419 MW, representing a 45.34% reduction. Average reactive power loss decreased from 30.2718 MVAr to 18.2476 MVAr, corresponding to a 39.50% reduction.

The active-loss reduction increased from 42.84% at 90% loading to 48.34% at 110% loading, while reactive-loss reduction increased from 35.40% to 43.22%. These results indicate that UPFC becomes increasingly effective as network loading increases.

The study therefore concludes that UPFC is a technically effective FACTS technology for reducing transmission losses and improving voltage performance in the Nigerian 330 kV network. Nevertheless, practical deployment should be preceded by comprehensive dynamic, economic, protection and electromagnetic-transient studies.

The integration of UPFC with intelligent optimization and modern grid-monitoring technologies represents a promising direction for future modernization of the Nigerian transmission network.

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