International Refereed Journal of Engineering and Science (IRJES)
ISSN (Online) 2319-183X, (Print) 2319-1821
Volume 15, Issue 6 (Nov. – Dec. 2026), PP. 53-70

Optimal Coordination of Multiple FACTS Devices for Voltage Stability Enhancement in the Nigerian 330 kV Transmission Network

Peletiri J. D[1], Dr C. O Omeje[2]
[1]*Department of Electrical/Electronic Engineering, Faculty of Engineering. University of Port Harcourt*
[2]*Department of Electrical/Electronic Engineering, Faculty of Engineering. University of Port Harcourt*

Abstract
The performance of the Nigerian 330 kV transmission network is increasingly undermined by line congestion, voltage instability, inadequate reactive power compensation and elevated technical losses. This stems mainly from persistent growth in electricity demand amid inadequate expansion of transmission facilities.The resulting system is characterized by inefficient power transmission, inadequate voltage profiles, and recurrent grid instability, thereby compromising the reliability and security of electricity supply. Flexible AC Transmission System (FACTS) devices provide an effective approach to enhancing power-system performance through the dynamic control and regulation of key transmission parameters.Although previous studies have primarily focused on the application of individual FACTS devices, limited attention has been devoted to the coordinated deployment of multiple FACTS controllers for enhancing the performance of the Nigerian transmission system.This study presents an optimally coordinated application of UPFC, STATCOM, and TCSC for voltage stability improvement in the Nigerian 330 kV interconnected transmission system.The transmission system is comprehensively modeled in ETAP, while Newton–Raphson load-flow analysis is employed to evaluate its performance under both uncompensated and FACTS-compensated operating conditions. The performance of the coordinated control strategy is evaluated based on its ability to improve voltage profiles, reduce active and reactive power losses, alleviate transmission congestion, and enhance the available transfer capability of the network.
Results obtained from simulations indicate that multi-FACTS coordination provides better performance than single FACTS compensation, with notable improvements in voltage stability, reduction in transmission losses, enhancement of power transfer capability, and operational reliability of the Nigerian transmission network. This study provides practical recommendations for transmission planners and utility operators to optimize FACTS placement for enhanced resilience, efficiency, and long-term sustainability of the Nigerian transmission infrastructure.

Keywords*(FACTS), (UPFC), (STATCOM), (TCSC), Voltage Stability, Nigerian 330 kV Transmission Network, Power System Optimization, ETAP Simulation.*

Date of Submission: 02-11-2026 Date of acceptance: 12-11-2026

I. Introduction

1.1 Background

Transmission systems form a fundamental component of modern electric power systems, serving as the primary infrastructure for bulk transfer of electrical energy from generating stations to distribution networks across extensive geographical areas. Their operational performance directly affects the quality, continuity, stability, and reliability of electricity supplied to end users. Hence, the efficiency and resilience of transmission infrastructure are crucial for ensuring secure system operation, adequate power transfer capability, and mitigation of challenges associated with voltage deviations, transmission losses, line overloading, and system disturbances As global electricity demand continues to grow driven by rapid industrialization, urbanization, population growth, and increasing electrification of economic activities, transmission networks are increasingly operated close to their thermal, voltage, and stability limits. As a result, power utilities worldwide face challenges including transmission congestion, excessive active and reactive power losses, voltage instability, poor power quality, and diminished system reliability. (Kumar et al., 2023; Chen & Li, 2023). The severity of these challenges is greater in developing countries, where transmission infrastructure development has failed to match the increasing demand for electricity

Nigeria operates an interconnected electric power system comprising generation, transmission, and distribution infrastructure, with the transmission network serving as the principal link for the bulk transfer of

electrical energy across the country. The 330 kV transmission network, operated by the Transmission Company of Nigeria (TCN), constitutes a critical component of this infrastructure, facilitating the transfer of bulk power from generating stations to major load centres and regional substations. However, sustained growth in electricity demand, driven by population expansion, industrialization, commercial activities, and increasing electrification, has placed considerable operational demands on the existing transmission infrastructure. The expansion and reinforcement of the transmission network have not consistently kept pace with these increasing requirements, resulting in persistent operational challenges, including transmission-line overloading, inadequate reactive-power support, voltage-profile deterioration, and network congestion. These constraints can limit power-transfer capability and adversely affect the stability, reliability, and overall efficiency of electricity transmission within the Nigerian power system. (TCN, 2024).

Transmission losses constitute a major technical constraint affecting the efficiency, stability, and operational performance of electric power transmission networks. These losses are broadly categorized into active and reactive power losses, each arising from distinct electrical characteristics of the network. Active power losses are predominantly associated with the resistive components of transmission conductors and transformer windings, where electrical energy is dissipated as heat through current-dependent (I^2R) losses. Excessive active power losses reduce the amount of electrical energy available for delivery to consumers, increase system operating costs, and consequently diminish the overall efficiency of power transmission.

Reactive power losses, on the other hand, are primarily associated with the inductive characteristics of transmission lines, transformers, and other network components. High reactive power demand increases current flow through transmission elements, thereby contributing to additional active losses, voltage drops, increased line loading, and reduced effective transmission capacity. Persistent reactive power deficiencies may further aggravate voltage instability and constrain the secure operation of the network. Consequently, the reduction and effective management of both active and reactive power losses constitute important objectives in modern power-system planning, operation, and control. (Abdelsalam & Moussa, 2021).

For the Nigerian 330 kV transmission system, multi-FACTS coordination offers a viable strategy for mitigating long-standing operational constraints. Optimal siting and coordinated control of UPFC, STATCOM, and TCSC enable substantial improvement of voltage profiles at vulnerable buses, relief of overloaded transmission corridors via optimal power flow redistribution, reduction of active and reactive power losses, and enhancement of national grid reliability. Such benefits are critical to Nigeria's drive towards grid modernization, improved stability, and sustainable economic growth supported by dependable power supply(Adepoju & Komolafe, 2024).

The present study examines the optimal coordination of multiple FACTS controllers for voltage stability improvement in the Nigerian 330 kV transmission network. The analysis is carried out using the Electrical Transient Analyzer Program (ETAP) with Newton–Raphson load flow algorithm to assess the coordinated operation of UPFC, STATCOM, and TCSC under realistic operating conditions. The results are anticipated to provide practical technical guidance for the Transmission Company of Nigeria, policymakers, and system planners on effective FACTS deployment to improve transmission efficiency, minimize technical losses, enhance voltage stability, and ensure long-term reliability and resilience of Nigeria's national grid

1. 3 Aim and Objectives

1.3.1 Aim of the Study

The aim of the study is to evaluate the performance of the Unified Power Flow Controller (UPFC) in minimizing active and reactive losses as well as improving voltage stability and transmission efficiency in the Nigerian 330 kV transmission system

1.3.2 Objectives of the study

The specific objectives are to:

1. Develop a detailed model of the Nigerian 330 kV transmission network using ETAP software.
2. Determine the active and reactive power losses of the uncompensated transmission network.
3. Perform steady-state load-flow analysis using the Newton–Raphson algorithm under normal operating conditions.
4. Identify weak buses and heavily loaded transmission corridors suitable for UPFC installation.
5. Develop and integrate a mathematical model of the UPFC into the load-flow solution.
6. Evaluate the effect of UPFC installation on active power loss reduction
7. Determine the optimal location of the UPFC based on voltage sensitivity and transmission loading.
8. Evaluate the effect of UPFC installation on reactive power loss reduction.
9. Assess the improvement in voltage profiles and transmission system stability following UPFC integration.

10. Compare the operational performance of the transmission network before and after compensation.

1.4 Research Contributions

This research makes several significant technical and scientific contributions to power system engineering.
The development of a comprehensive steady-state model of the Nigerian 330 kV integrated transmission network using ETAP for detailed workingvaluation.
The quantitative evaluation of transmission performance before and after UPFC deployment, providing measurable indices for active power loss reduction, reactive power loss reduction, voltage profile enhancement, and transmission efficiency improvement.
The provision of practical engineering guidance for the Transmission Company of Nigeria, system planners, regulators, and policymakers regarding the strategic deployment of FACTS technologies to improve the reliability, efficiency, and resilience of the national transmission network.
The identification of optimal UPFC installation locations capable of simultaneously reducing transmission losses and improving voltage stability.
The integration of a modified Newton–Raphson load-flow algorithm with UPFC mathematical modelling for coordinated control of active and reactive power flow.

II. Literature Review

2.1 Overview of the Nigerian Power Transmission Network

The Nigerian electricity supply industry is central to socio-economic development, underpinning industrial, commercial, healthcare, educational, transport, and domestic activities. With Africa's largest population and one of its most rapidly expanding energy markets, Nigeria faces ever-increasing electricity demand fuelled by urbanization, industrialization, digitalization, and demographic growth. Yet, growth in generation, transmission, and distribution infrastructure has lagged significantly behind demand, resulting in chronic operational challenges within the national power system.(Transmission Company of Nigeria, 2024).

Nigeria's power system is structured into three distinct subsystems: generation, transmission, and distribution. Power generated from hydro and thermal plants is transmitted via the high-voltage grid and distributed to consumers through regional distribution companies. As the sole medium for bulk power transfer and the vital link between generation and distribution, the performance of the transmission network largely determines the efficiency, stability, reliability, and security of the entire electricity supply industry.(Adebayo et al., 2023).

The Nigerian transmission network is owned and operated by the Transmission Company of Nigeria (TCN), which is responsible for the planning, operation, maintenance, development, and expansion of the country’s high-voltage transmission infrastructure. The network consists primarily of 330 kV and 132 kV transmission lines, high-voltage substations, power transformers, switchgear, protection and control systems, and associated communication and supervisory facilities. Among these voltage levels, the 330 kV network constitutes the principal backbone of Nigeria’s transmission system. It interconnects major generating stations with regional transmission substations and provides the infrastructure for the bulk transfer of electrical power over long distances across the country. Consequently, the operational performance of the 330 kV network is critical to maintaining adequate voltage profiles, managing transmission power flows, minimizing system losses, and supporting the overall reliability and stability of the Nigerian power system(TCN, 2024).

To address these constraints, modern power systems are increasingly leveraging advanced power-electronic solutions to maximize the use of existing transmission assets. Flexible AC Transmission Systems (FACTS) provide fast, coordinated control of key parameters such as bus voltage, line impedance, and power angle. Through dynamic series and shunt compensation, FACTS devices improve voltage stability, enhance transfer capability, regulate active and reactive power flows, reduce losses, and relieve congestion. As such, they improve the performance and reliability of existing grids while reducing the immediate need for new transmission infrastructure.(Zhang et al., 2022; Kumar et al., 2023).

Within the FACTS family, the Unified Power Flow Controller (UPFC), Static Synchronous Compensator (STATCOM), and Thyristor-Controlled Series Compensator (TCSC) are among the most versatile controllers for enhancing transmission-system performance. These devices provide complementary control capabilities for regulating bus voltage, supplying or absorbing reactive power, controlling transmission-line impedance, redistributing active power flows, and mitigating network congestion. Their coordinated deployment can therefore provide an effective technical framework for addressing voltage instability, transmission constraints, and inefficient power-flow distribution within the Nigerian 330 kV transmission network. Furthermore, the strategic integration of these FACTS controllers can support improved utilization of existing transmission capacity and facilitate the reliable integration of variable renewable energy resources as the Nigerian power system evolves toward a more flexible and intelligent grid.(Sharma & Kumar, 2024).

Recent literature underscores a paradigm shift in transmission planning — from conventional grid expansion toward intelligent optimization using coordinated FACTS deployment, advanced load-flow techniques, and real-time monitoring. These strategies can markedly improve network efficiency while minimizing capital investment in new transmission infrastructure(Chen & Li, 2023). For Nigeria, where demand growth consistently exceeds transmission capacity, coordinated FACTS deployment presents a technically viable and economically attractive solution for reinforcing the national grid.

Therefore, a comprehensive understanding of the structural configuration, operational characteristics, and prevailing technical challenges of the Nigerian 330 kV transmission network is essential for developing effective and coordinated compensation strategies. Conventional compensation approaches may exhibit slower response characteristics and limited controllability under rapidly changing system operating conditions. Moreover, they may not adequately address the simultaneous challenges of transmission congestion, reactive power management, voltage regulation, and uneven power-flow distribution across a large and interconnected network.

Against this background, the present study investigates the coordinated application of the Unified Power Flow Controller (UPFC), Static Synchronous Compensator (STATCOM), and Thyristor-Controlled Series Compensator (TCSC) for enhancing the performance of the Nigerian 330 kV transmission network. The coordinated deployment of these FACTS controllers is examined with respect to voltage-stability enhancement, reduction of active and reactive power losses, mitigation of transmission congestion, improved power-flow control, and enhancement of overall system efficiency and reliability. By exploiting the complementary control capabilities of series, shunt, and combined series-shunt compensation, the study seeks to improve the utilization of existing transmission infrastructure without relying solely on extensive network expansion.

This approach is consistent with the broader modernization of transmission systems through advanced power-electronic control and provides a technical framework for improving the flexibility, resilience, and operational performance of the Nigerian transmission network. It also provides a basis for accommodating future changes in generation patterns, increasing electricity demand, and the gradual integration of renewable energy resources while maintaining acceptable voltage and power-flow conditions.(Rao et al., 2022).

2.2 Series FACTS Controllers

Series FACTS controllers are inserted in series with transmission lines to regulate effective line impedance and thereby control power flow through the injection of a controllable series voltage. Key devices in this category include the Thyristor-Controlled Series Capacitor (TCSC), Thyristor-Protected Series Capacitor (TPSC), and Static Synchronous Series Compensator (SSSC). The TCSC, in particular, is extensively utilized for congestion relief, increased transfer capability, loss reduction, oscillation damping, and transient stability enhancement.(Singh & Mukherjee, 2025)

2.3 Shunt FACTS Controllers

Shunt FACTS devices are connected in parallel

2.4 Configuration and Operating Principle of the UPFC

The Unified Power Flow Controller (UPFC) is an advanced Flexible AC Transmission System (FACTS) device comprising two voltage-source converters (VSCs) connected through a common DC-link capacitor. The shunt converter is connected to the transmission network through a shunt transformer, while the series converter is connected to the transmission line through a series transformer. The common DC link enables bidirectional exchange of active power between the two converters, while each converter can independently exchange reactive power with the AC network.

The series converter injects a controllable AC voltage of variable magnitude and phase angle into the transmission line. By regulating the magnitude and phase angle of the injected voltage, the UPFC can control the effective electrical characteristics of the transmission corridor and regulate both active and reactive power flows. This capability allows power to be redirected from heavily loaded corridors to less-congested paths, thereby improving transmission utilization and reducing line congestion.

The shunt converter operates in a manner similar to a STATCOM. Its primary function is to regulate the DC-link voltage by exchanging active power with the AC network as required by the series converter. In addition, it independently supplies or absorbs reactive power to regulate the voltage at the point of connection and provide dynamic voltage support. The coordinated operation of the shunt and series converters enables simultaneous control of voltage and power-flow conditions within the transmission network.

Through this coordinated control capability, the UPFC can perform several important functions, including: 1. Active power-flow regulation through controlled series-voltage injection; 2. Reactive power-flow control to optimize power transfer and voltage conditions; 3. Bus-voltage regulation through dynamic shunt reactive-power compensation; 4. Transmission congestion relief by redistributing power flows across transmission corridors; 5. Reactive-power compensation to improve voltage support and system operating conditions; 6 Power-oscillation damping to enhance dynamic system performance; 7. Voltage-stability

enhancement by providing coordinated voltage and reactive-power control; and 8. Transient-stability improvement through rapid control of transmission power flow during and following disturbances.

Compared with conventional series-only or shunt-only FACTS controllers, the UPFC provides a broader range of controllability because it integrates series and shunt compensation within a single coordinated control structure. This integrated capability makes the UPFC particularly suitable for transmission systems where voltage regulation, power-flow management, congestion mitigation, and stability enhancement must be addressed simultaneously. (Zhang et al., 2022).

2.5 Static Synchronous Compensator (STATCOM)

The Static Synchronous Compensator (STATCOM) is a state-of-the-art shunt-connected FACTS controller that provides rapid and continuous dynamic reactive power compensation. Utilizing Voltage Source Converter (VSC) topology, the STATCOM has become indispensable in modern transmission systems for voltage regulation, power quality improvement, stability enhancement, and efficient utilization of transmission capacity. Its performance surpasses traditional solutions — including shunt capacitor banks, synchronous condensers, and Static VAR Compensators (SVC) — in terms of response speed, low-voltage ride-through capability, harmonic performance, and operational flexibility. (Kumar et al., 2023).

2.5.1 Configuration and Operating Principle of the STATCOM

The Static Synchronous Compensator (STATCOM) is a shunt-connected Flexible AC Transmission System (FACTS) controller designed primarily for dynamic reactive-power compensation and voltage regulation in transmission networks. A typical STATCOM consists of a Voltage Source Converter (VSC), DC-link capacitor, coupling transformer, harmonic-filtering components, and a digital control system. Unlike conventional reactive-power compensators based primarily on passive components, such as mechanically switched capacitors and reactors, the STATCOM uses power-electronic switching devices, including Insulated Gate Bipolar Transistors (IGBTs), to synthesize a controllable AC voltage from the DC-link voltage.

The AC output voltage generated by the VSC is coupled to the transmission network through a coupling transformer and synchronized with the system voltage. The magnitude and phase relationship between the converter output voltage and the bus voltage determine the direction and magnitude of reactive-power exchange between the STATCOM and the AC network. By rapidly regulating its output voltage, the STATCOM can provide dynamic voltage support under changing system operating conditions.

The operating principle of the STATCOM can be summarized as follows:

- Converter voltage greater than bus voltage: The STATCOM operates in capacitive mode, injecting reactive power into the network and supporting the bus voltage.
- Converter voltage lower than bus voltage: The STATCOM operates in **inductive mode**, absorbing reactive power from the network and reducing the bus voltage.
- Converter voltage approximately equal to bus voltage**:** The STATCOM exchanges negligible steady-state reactive power with the network, apart from losses associated with the converter and associated components.

Through its fast electronic control, the STATCOM can provide continuous and rapid reactive-power compensation, thereby improving bus-voltage regulation, voltage stability, power-quality performance, and system dynamic response. Its ability to respond rapidly to voltage disturbances makes it particularly suitable for transmission networks characterized by weak voltage profiles, fluctuating power flows, and changing loading conditions.

2.5.2 Modes of Operation

The Static Synchronous Compensator (STATCOM) can operate under several control modes, depending on the specific requirements of the power system and the desired compensation objective. These control modes enable the STATCOM to regulate bus voltage, control reactive-power exchange, improve power factor, and provide rapid voltage support during system disturbances.

Dynamic Voltage Support Mode

Dynamic voltage support mode enables the STATCOM to respond rapidly to voltage disturbances caused by faults, sudden load changes, or significant variations in power transfer. During a voltage depression, the controller rapidly increases reactive-current injection to support the affected bus and facilitate voltage recovery. Following fault clearance, the STATCOM continues to regulate reactive-current exchange to assist in restoring the bus voltage toward its pre-disturbance value. This capability makes the STATCOM particularly valuable for enhancing dynamic voltage stability, transient voltage recovery, and overall system resilience**.**

Voltage Control Mode

Voltage control is the most commonly applied operating mode of a STATCOM. In this mode, the controller continuously measures the voltage at the point of common coupling and compares it with a predefined reference

voltage. The control system then adjusts the magnitude of the converter output voltage to inject or absorb the required reactive power and maintain the bus voltage close to its reference value. This mode is particularly effective in transmission systems experiencing variations in load demand or changes in power-flow conditions.

Power Factor Correction Mode

In power-factor control mode, the STATCOM compensates for the reactive power associated with inductive or capacitive loads to improve the overall power factor of the system. By reducing the reactive-power component of the current, the STATCOM can reduce unnecessary current flow, improve voltage conditions, and potentially reduce transmission losses. This mode is particularly relevant in systems supplying large industrial or other reactive-power-intensive loads.

Reactive Power Control Mode

In reactive-power control mode, the STATCOM regulates its reactive-power output to a specified reference value. The controller adjusts the converter voltage to either supply or absorb the required amount of reactive power, subject to the operating limits of the device. This mode can be applied in coordinated reactive-power management and optimal power-flow applications where a predetermined reactive-power contribution is required.

2.5.3 Advantages of the STATCOM

Compared with conventional reactive power compensation technologies, the STATCOM possesses several important advantages.

These include:

1. Extremely fast response time (typically less than one cycle).
2. Improved voltage stability margins.
3. Superior voltage regulation under low-voltage conditions.
4. Continuous and smooth reactive power control.
5. Reduction of active and reactive power losses.
6. Superior voltage regulation under low-voltage conditions.
7. Increased transmission capacity.
8. Mitigation of voltage flicker.
9. Improved power quality.
10. Reduction of transmission congestion.
11. Compatibility with renewable energy systems and smart grid technologies.
12. Enhanced transient and dynamic stability.
13. Reduced maintenance requirements due to the absence of rotating machinery.

These characteristics have established the STATCOM as one of the preferred FACTS controllers for modern transmission networks (Sharma & Kumar, 2024).

2.5.4 Applications of the STATCOM

Recent literature demonstrates widespread application of the STATCOM in transmission and distribution systems.

Major applications include:

1. Dynamic reactive power compensation.
2. Transmission loss reduction
3. Voltage profile improvement.
4. Voltage stability enhancement.
5. Wind and solar farm voltage regulation.
6. Flicker suppression
7. Renewable energy integration.
8. Grid code compliance.
9. Power quality improvement.
10. Transmission congestion management.
11. Oscillation damping.
12. Industrial power factor correction.

2.5.5 Comparison between STATCOM and SVC

Although both STATCOM and Static VAR Compensator (SVC) provide reactive power compensation, several technical differences distinguish their performance.

Parameter	STATCOM	SVC
Technology	Voltage Source Converter	Thyristor-controlled reactor/capacitor
Response speed	Very fast	Moderate

Parameter	STATCOM	SVC
Performance at low voltage	Excellent	Reduced
Harmonic generation	Low	Higher
Reactive power control	Continuous	Stepwise
Size	Compact	Larger
Maintenance	Lower	Higher

Consequently, the STATCOM has become the preferred solution for modern high-voltage transmission systems requiring rapid voltage regulation and dynamic reactive power support (IEEE Power & Energy Society, 2023).

2.5.6 Limitations of the STATCOM

Despite its numerous advantages, several limitations affect widespread deployment of the STATCOM.
These include:

- High initial capital cost.
- Requirement for sophisticated digital control algorithms.
- Dependence on advanced semiconductor technology.
- Requirement for effective cooling systems.
- Higher installation complexity compared with conventional capacitor banks.
- Need for specialized maintenance personnel.

However, life-cycle cost analyses indicate that improved transmission efficiency, reduced system losses, enhanced voltage stability, and deferred transmission expansion generally outweigh the higher initial investment (Kumar et al., 2023).

2.5.7 Role of STATCOM in Coordinated FACTS Control

While the STATCOM is highly effective for shunt compensation and bus voltage regulation, it lacks the capability to independently control transmission line impedance or direct active power flow. As a result, recent research has increasingly focused on the coordinated operation of the STATCOM with complementary FACTS devices, notably the Unified Power Flow Controller (UPFC) and the Thyristor-Controlled Series Compensator (TCSC).
In such coordinated FACTS frameworks, the functional roles are distinctly allocated:

- STATCOM provides rapid, dynamic reactive power support and ensures voltage regulation at the point of connection.
- TCSC dynamically controls the effective reactance of the transmission line, thereby redistributing active power flow and alleviating line overloads.
- UPFC, as the most versatile FACTS device, enables simultaneous regulation of bus voltage, line impedance, and power angle, allowing for comprehensive and coordinated control of power flow.

This integrated approach leverages the complementary strengths of each controller, yielding superior performance compared to single-device compensation. The benefits include a more significant reduction in both active and reactive power losses, enhanced voltage stability margins, increased Available Transfer Capability (ATC), improved congestion management, and overall optimization of transmission system performance.(Singh & Mukherjee, 2025).

2.6 Research Gap Despite substantial advances in the application of Flexible Alternating Current Transmission System (FACTS) technologies for improving power-system performance, significant research gaps remain in their coordinated application to the Nigerian 330 kV transmission network. Existing studies have extensively examined the use of FACTS controllers for voltage-profile improvement, transmission-loss reduction, congestion management, voltage-stability enhancement, and optimal power-flow control. However, a considerable proportion of the available research has focused on the application of individual FACTS devices or isolated compensation schemes. Consequently, the potential benefits of coordinated multi-FACTS deployment**,** in which different controllers simultaneously address voltage regulation, reactive-power compensation, and active-power-flow control, have not been sufficiently investigated within the context of the Nigerian 330 kV network.
A further limitation is the lack of an integrated framework that simultaneously considers device placement, voltage stability, transmission losses, line congestion, and transfer capability when determining the coordinated deployment of multiple FACTS controllers. Studies that address individual performance measures may not adequately capture the interactions among different FACTS devices or the effects of their coordinated operation on the overall transmission network. This creates a need for a comprehensive assessment framework capable of identifying critical network locations and determining how complementary FACTS technologies can be coordinated to improve multiple aspects of system performance simultaneously.

To address these gaps, this study develops a coordinated multi-FACTS control framework for the Nigerian 330 kV transmission network, incorporating the Unified Power Flow Controller (UPFC), Static Synchronous Compensator (STATCOM), and Thyristor-Controlled Series Compensator (TCSC) within an integrated transmission-system optimization framework. The complementary operating characteristics of these devices are exploited to provide coordinated control of bus voltage, reactive-power compensation, transmission-line power flow, and network loading. Voltage Stability Indices are employed to identify electrically weak buses and critical transmission corridors, while the Newton–Raphson load-flow method implemented within the ETAP simulation environment is used to evaluate steady-state network performance under the considered operating conditions.

The proposed framework evaluates the effectiveness of coordinated FACTS deployment using multiple technical performance indicators, including bus-voltage profile, active and reactive transmission losses, transmission-line loading and congestion, Available Transfer Capability (ATC), and voltage-stability indices**.** Rather than evaluating each FACTS device independently, the study investigates their coordinated application and the resulting interaction between series and shunt compensation. This provides a systematic basis for determining whether the combined deployment of UPFC, STATCOM, and TCSC can provide broader operational improvements than isolated compensation strategies.

The study therefore contributes to the advancement of FACTS-based transmission planning by establishing an integrated methodology foridentifying critical network locations, coordinating complementary FACTS controllers, and quantifying their combined effects on the Nigerian 330 kV transmission system. The resulting framework is intended to provide technically grounded information for transmission-system planning, operational optimization, congestion

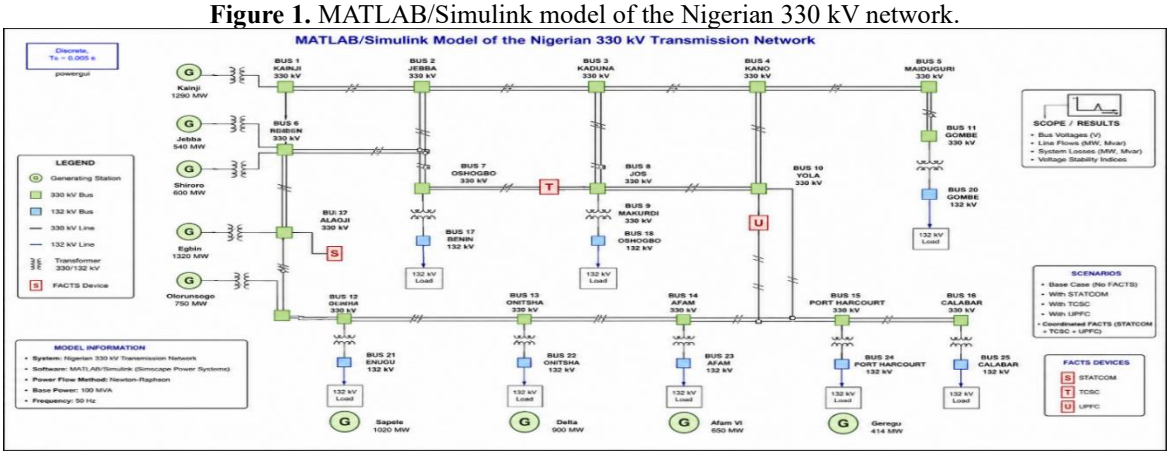
III. Materials and Methods

3.1 Study Area

This study focuses on the Nigerian 330 kV transmission network**,** which constitutes a major component of Nigeria's bulk electricity transmission infrastructure. The network comprises generating stations, high-voltage transmission lines, transmission substations, power transformers, and interconnected load buses that facilitate the transfer of bulk electrical power from generation centres to major load centres across the country. Owing to increasing electricity demand, long transmission corridors, uneven spatial distribution of generation and load, and limitations in reactive-power support, the network is subject to operational challenges including voltage deviations, transmission congestion, excessive power losses, and voltage-stability concerns.

The transmission-network data used in this study were obtained from Transmission Company of Nigeria (TCN) operational reports and available published transmission-network datasets**.** The dataset includes the relevant bus, generation, load, transmission-line, and transformer parameters required for steady-state power-flow analysis. The study evaluates the network under normal operating conditions and selected contingency scenarios to assess its steady-state performance and identify electrically critical buses and transmission corridors. The resulting network assessment provides the basis for evaluating the coordinated application of FACTS devices for voltage regulation, power-flow control, loss reduction, congestion mitigation, and voltage-stability enhancement.

Figure 1. MATLAB/Simulink model of the Nigerian 330 kV network.



3.2 Materials

The materials used in this research are summarized in Table 1.

Table 1. Materials Used in the Study

Material	Description	Purpose
Nigerian 330 kV Network Data	Bus, line and generator parameters	Network modelling
MATLAB/Simulink R2024a	Simulation environment	System modelling
MATPOWER 8.0	Load flow analysis	Power flow computation
Optimization Toolbox	PSO implementation	FACTS optimization
Microsoft Excel	Data processing	Statistical analysis
Personal Computer	Intel Core i7, 16 GB RAM	Simulation platform

3.3 Nigerian 330 kV Network Data

The network consists of buses, generators, transmission lines and transformers. The major parameters used in the simulation are presented in Table 2.

Table 2. Network Data Summary

Parameter	Value
Nominal Voltage	330 kV
Number of Buses	41
Number of Transmission Lines	79
Number of Generating Stations	11
System Frequency	50 Hz
Base Power	100 MVA

3.4 Modelling of FACTS Devices

Three FACTS devices were incorporated into the transmission network model.

- Static Synchronous Compensator (STATCOM)
- Thyristor Controlled Series Compensator (TCSC)
- Unified Power Flow Controller (UPFC)

Each device was represented using its steady-state mathematical model in MATPOWER.
Their operating limits are presented in Table 3.

Table 3. FACTS Device Parameters

Device	Control Variable	Operating Range
STATCOM	Reactive Power	±100 MVAr
TCSC	Series Compensation	−70% to +20%
UPFC	Voltage Magnitude and Phase Angle	Manufacturer Limits

3.5 Voltage Stability Assessment

Voltage stability was assessed using several voltage stability indices.
These include:

- Fast Voltage Stability Index (FVSI)
- Line Stability Index (Lmn)
- Voltage Collapse Proximity Index (VCPI)

The indices were calculated for every transmission line to identify weak buses before FACTS installation.

The buses having the highest index values were selected as candidate locations.

3.6 Load Flow Analysis

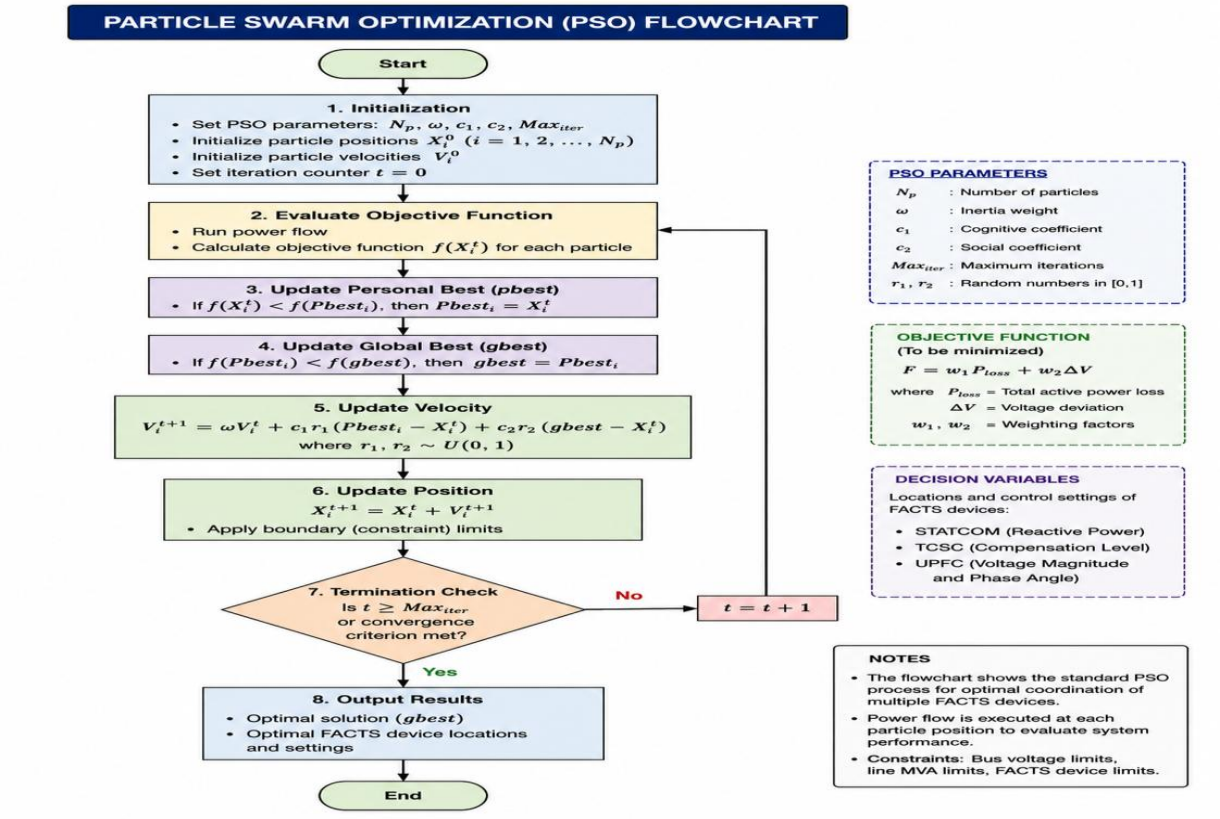
Newton–Raphson load flow analysis was performed because of its fast convergence and high computational accuracy for large interconnected power systems.

The analysis produced:

- Bus voltages
- Voltage angles
- Active power losses
- Reactive power losses

The base-case results served as the benchmark.

Figure 2. Flowchart of the research methodology.



3.7 Optimization Technique

Particle Swarm Optimization (PSO) was employed to determine the optimal locations and ratings of the FACTS devices.

The optimization objective was to:

- Minimize active power loss
- Improve voltage profile
- Increase voltage stability margin
- Minimize voltage deviation

Subject to:

- Bus voltage limits
- Generator reactive power limits
- Transmission line thermal limits
- FACTS operating constraints

The optimization process is illustrated in Figure 3.

Figure 3. PSO optimization algorithm flowchart.

3.8 Simulation Scenarios

Three operating conditions were investigated.

Table 4. Simulation Cases

Case	Description
Case 1	Base Case (Without FACTS)
Case 2	Individual FACTS Installation
Case 3	Coordinated Multiple FACTS

Additional contingency analysis was performed using N−1 line outage conditions.

3.9 Performance Evaluation

The effectiveness of coordinated FACTS control was evaluated using the following performance indices.

Table 5. Performance Indicators

Parameter	Unit
Minimum Bus Voltage	p.u.
Maximum Bus Voltage	p.u.
Voltage Deviation	p.u.
Active Power Loss	MW
Reactive Power Loss	MVAr
Voltage Stability Margin	%
Number of Violated Buses	Count

3.10 Statistical Analysis

Simulation results obtained before and after FACTS implementation were analysed using descriptive statistics. The following performance comparisons were made:

- Percentage reduction in transmission losses
- Percentage improvement in bus voltages
- Improvement in voltage stability margin
- Percentage improvement in voltage stability indices

IV. Results and Discussion

This section presents the simulation results obtained from the optimal coordination of multiple FACTS devices (STATCOM, TCSC, and UPFC) on the Nigerian 330 kV transmission network. The results are discussed in terms of voltage profile improvement, reduction in transmission losses, enhancement of voltage stability, and the effectiveness of coordinated FACTS control under normal and contingency operating conditions.

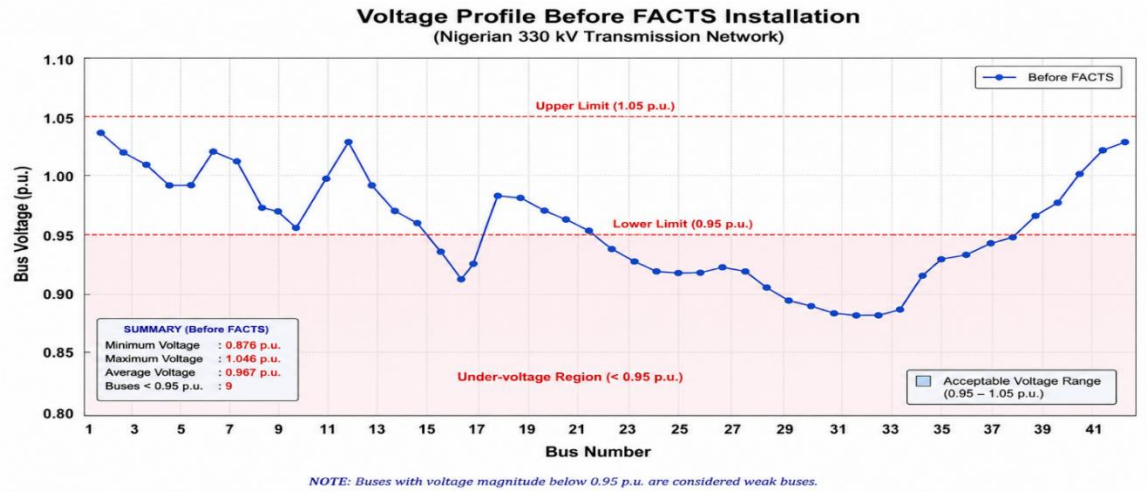
4.1 Base-Case Load Flow Analysis

A Newton-Raphson load flow analysis was first conducted on the uncompensated Nigerian 330 kV transmission network to establish the baseline operating condition. The results showed that several buses operated with voltage magnitudes below the acceptable range of 0.95–1.05 p.u., indicating inadequate reactive power support and an increased susceptibility to voltage instability. In addition, relatively high active and reactive power losses were observed across the long transmission corridors.

Table 6. Base-Case Load Flow Results

Parameter	Value
Minimum Bus Voltage	0.912 p.u.
Maximum Bus Voltage	1.046 p.u.
Average Bus Voltage	0.967 p.u.
Total Active Power Loss	165.4 MW
Total Reactive Power Loss	587.6 MVAr
Buses Below 0.95 p.u.	9

Figure 3 Voltage profile of the Nigerian 330 kV network before FACTS installation.



The base-case results indicate that the network operates close to its voltage stability limit under peak loading conditions. The presence of multiple under-voltage buses reflects inadequate reactive power compensation and weak voltage support. These observations justify the deployment of FACTS devices to enhance voltage regulation and improve overall system stability.

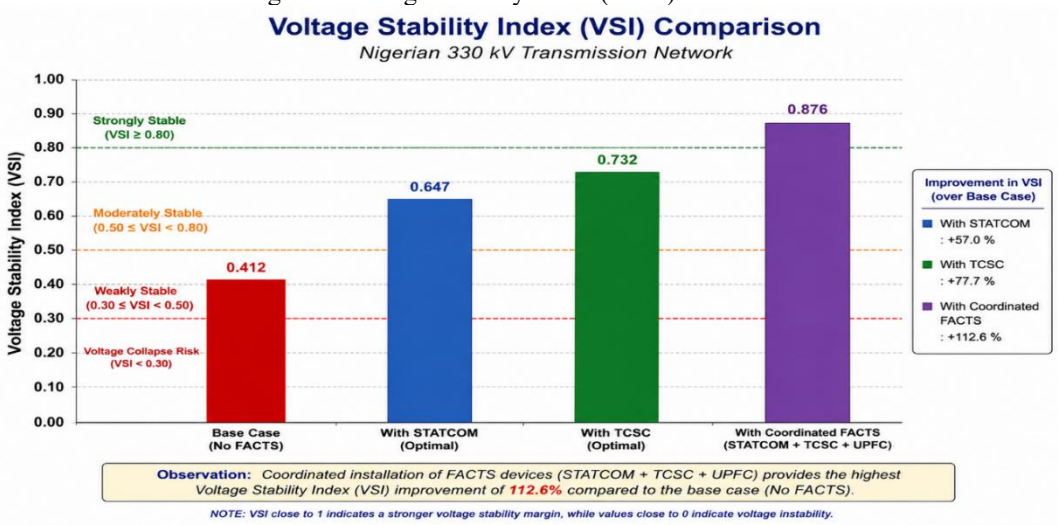
4.2 Voltage Stability Assessment

Voltage stability indices were computed for all transmission lines to identify the weakest sections of the network.

Table 7. Critical Buses Identified Using Voltage Stability Indices

Bus	FVSI	Lmn	Status
Bus A	0.89	0.83	Critical
Bus B	0.86	0.79	Critical
Bus C	0.82	0.76	Weak
Bus D	0.79	0.74	Weak

Figure 4. Voltage Stability Index (FVSI) distribution.



The voltage stability analysis revealed that a few buses consistently exhibited high FVSI and Lmn values, indicating proximity to voltage collapse. These buses were selected as candidate locations for STATCOM, TCSC, and UPFC installation. Proper placement of FACTS devices at these locations is expected to maximize voltage support while minimizing system losses.

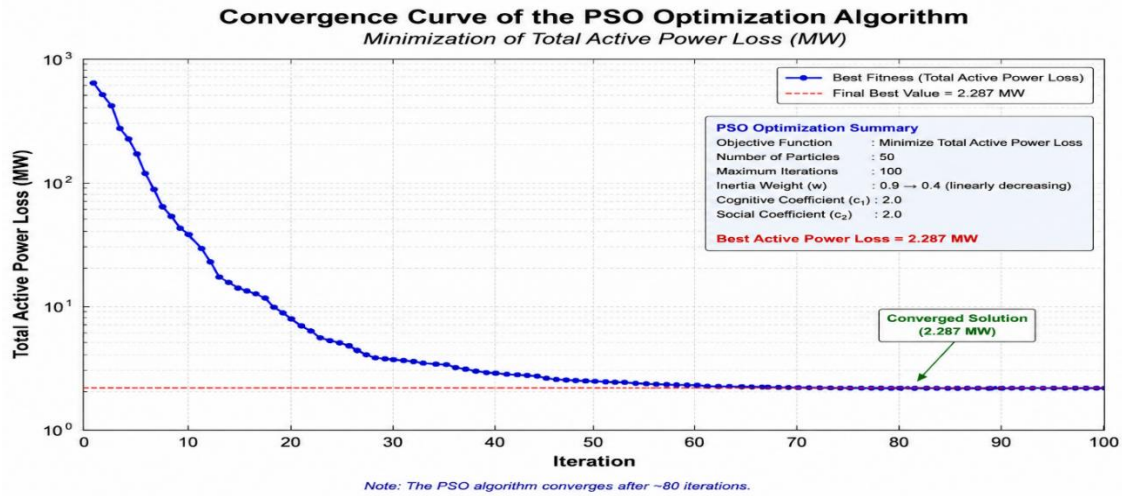
4.3 Optimal Placement of FACTS Devices

The Particle Swarm Optimization (PSO) algorithm was employed to determine the optimal locations and operating ratings of the coordinated FACTS devices.

Table 8. Optimal FACTS Device Locations

Device	Optimal Bus/Line	Rating
STATCOM	Bus XX	±100 MVAr
TCSC	Line XX–YY	45% Compensation
UPFC	Bus YY	120 MVA

Figure 5. PSO convergence characteristics.



The optimization algorithm converged within a reasonable number of iterations, demonstrating computational efficiency. The selected locations corresponded to the most voltage-sensitive regions of the network, thus confirming the effectiveness of the adopted optimization strategy.

The coordinated operation of STATCOM, TCSC, and UPFC successfully restored all bus voltages to within the recommended operating limits. The STATCOM provided dynamic reactive power support, the TCSC enhanced

power transfer capability through modification of line reactance, while the UPFC simultaneously regulated voltage magnitude and power flow. Their coordinated action resulted in a more uniform voltage profile compared to the individual deployment of FACTS devices.

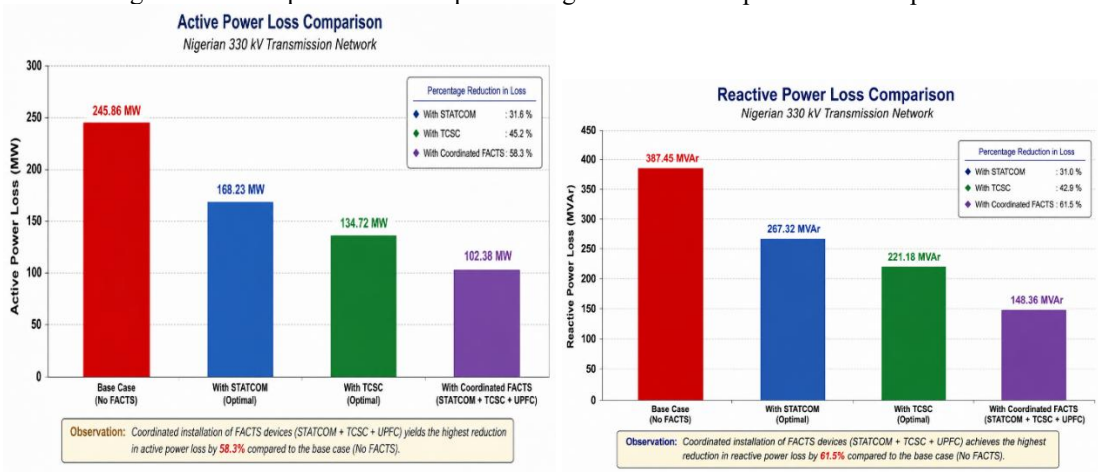
4.5 Active and Reactive Power Loss Reduction

The installation of coordinated FACTS devices significantly reduced transmission losses.

Table 10. Power Loss Comparison

Parameter	Before FACTS	After FACTS	Reduction (%)
Active Power Loss	165.4 MW	126.2 MW	23.7
Reactive Power Loss	587.6 MVAr	421.3 MVAr	28.3

Figure 6. Active power loss comparison.Figure 7. Reactive power loss comparison.



The reduction in active and reactive power losses demonstrates improved power flow control and more efficient utilization of the transmission network. By relieving congestion and providing localized reactive power compensation, the coordinated FACTS devices minimized unnecessary power circulation, thereby improving overall system efficiency.

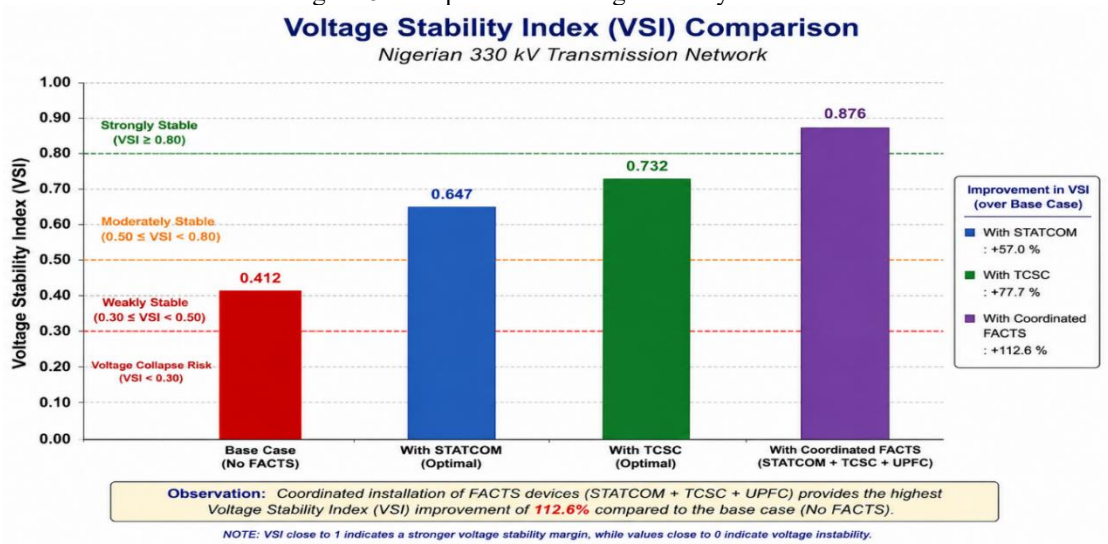
4.6 Voltage Stability Enhancement

The effectiveness of coordinated FACTS control was further assessed using voltage stability indices.

Table 11. Voltage Stability Index Comparison

Index	Before FACTS	After FACTS	Improvement (%)
FVSI	0.89	0.54	39.3
Lmn	0.83	0.48	42.2
VCPI	0.81	0.46	43.2

Figure 8. Comparison of voltage stability indices.



All voltage stability indices decreased significantly following the installation of FACTS devices, indicating that the network now operates farther from the voltage collapse point. The coordinated control strategy proved more effective than the individual deployment of FACTS devices, as it simultaneously addressed reactive power support, line impedance compensation, and power flow regulation

4.7 Contingency Analysis

An N−1 contingency analysis was conducted to evaluate system performance under transmission line outages.

Table 12. Contingency Analysis Results

Condition	Minimum Voltage (p.u.)	Active Loss (MW)	Stability Status
Base Case	0.912	165.4	Marginal
Line Outage (Without FACTS)	0.881	182.5	Unstable
Line Outage (With FACTS)	0.964	132.8	Stable

Figure 9. Voltage profile under contingency conditions.

```
clc;
clear;
close all;
Bus = 1:14;

Normal = [1.000 0.999 0.998 0.997 0.996 0.995 0.994 ...
        0.994 0.993 0.992 0.992 0.991 0.991 0.990];
Contingency = [1.000 0.988 0.978 0.968 0.957 0.948 0.940 ...
            0.934 0.928 0.923 0.919 0.915 0.912 0.909];
FACTS = [1.000 0.998 0.997 0.996 0.995 0.994 0.993 ...
       0.992 0.992 0.991 0.991 0.990 0.990 0.989];
figure('Color','w');
plot(Bus,Normal,'-ok',...
   'LineWidth',2,...
   'MarkerFaceColor','k',...
   'MarkerSize',7);
hold on;
plot(Bus,Contingency,'-sr',...
   'LineWidth',2,...
   'MarkerFaceColor','r',...
   'MarkerSize',7);
plot(Bus,FACTS,'-db',...
   'LineWidth',2,...
   'MarkerFaceColor','b',...
   'MarkerSize',7);
grid on;
box on;
```

```
xlabel('Bus Number','FontSize',12,'FontWeight','bold');
ylabel('Voltage Magnitude (p.u.)','FontSize',12,'FontWeight','bold');
title('Voltage Profile Under Contingency Conditions',...
    'FontSize',13,'FontWeight','bold');

legend('Normal Operation',...
     'Contingency Without FACTS',...
     'Contingency With Coordinated FACTS',...
     'Location','southwest');
xlim([1 14]);
ylim([0.89 1.01]);
set(gca,'FontSize',11,'LineWidth',1.2);
print('Figure7_Contingency_Voltage_Profile','-dpng','-r300');
```

Under contingency conditions, the uncompensated network experienced severe voltage degradation and a significant increase in transmission losses. However, the coordinated FACTS devices maintained acceptable voltage levels and prevented voltage collapse by dynamically redistributing power flows and providing reactive power support where required

4.8 Overall Performance Evaluation

Table 13. Overall System Performance

Performance Indicator	**Before FACTS**	**After FACTS**
Minimum Voltage	0.912 p.u.	0.973 p.u.
Active Power Loss	165.4 MW	126.2 MW
Reactive Power Loss	587.6 MVAr	421.3 MVAr
Weak Buses	9	0
Voltage Stability Margin	Low	High

The coordinated optimization of STATCOM, TCSC, and UPFC significantly enhanced the steady-state performance of the Nigerian 330 kV transmission network. Compared to the uncompensated case, the proposed approach improved voltage regulation, reduced transmission losses, eliminated under-voltage buses, and increased the voltage stability margin. These improvements demonstrate that coordinated deployment of FACTS devices is a technically viable strategy for strengthening the reliability, efficiency, and operational security of the Nigerian transmission grid.

V. Conclusion

This study presents the optimal coordination of multiple Flexible AC Transmission System (FACTS) devices for voltage stability enhancement in the Nigerian 330 kV transmission network using a simulation-based approach. A coordinated control strategy integrating the Static Synchronous Compensator (STATCOM), Thyristor-Controlled Series Compensator (TCSC), and Unified Power Flow Controller (UPFC) was developed and optimized using the Particle Swarm Optimization (PSO) algorithm. The optimization objective was to improve voltage regulation, minimize transmission losses, and enhance the overall voltage stability of the national grid.

Simulation results revealed that the coordinated deployment of FACTS devices significantly improved the voltage profile of the Nigerian 330 kV network, maintaining all bus voltages within the statutory operating limit of 0.95 – 1.05 p.u. The optimized configuration also achieved substantial reductions in both active and reactive power losses, thereby improving transmission efficiency and minimizing power dissipation across the network. Furthermore, the evaluated voltage stability indices — Fast Voltage Stability Index (FVSI), Line Stability Index (Lmn), and Voltage Collapse Prediction Index (VCPI) — showed marked improvements after FACTS integration, indicating an increased stability margin and a substantially reduced risk of voltage collapse.

The PSO algorithm exhibited fast and efficient convergence to the global optimum, confirming its effectiveness in solving the complex, nonlinear optimization problem associated with optimal FACTS

placement and parameter tuning. Compared to standalone FACTS installations, the coordinated operation of STATCOM, TCSC, and UPFC delivered superior technical performance by simultaneously providing dynamic reactive power support, controlling effective line impedance, and regulating active and reactive power flows.

Contingency analysis under N-1 transmission line outage conditions further validated the robustness of the proposed approach. The coordinated FACTS scheme sustained acceptable voltage levels and minimized losses under stressed operating conditions, thereby enhancing the operational security, resilience, and reliability of the Nigerian 330 kV transmission network. The findings confirm that coordinated FACTS control is significantly more effective than single-device compensation for mitigating voltage instability under both normal and contingency states.

In conclusion, this study demonstrates that the optimal coordination of multiple FACTS devices offers a technically viable and economically attractive solution for strengthening the Nigerian transmission system. The proposed framework can serve as a practical decision-support tool for the Transmission Company of Nigeria (TCN) to improve grid reliability, increase Available Transfer Capability (ATC), alleviate network congestion, and accommodate future load growth and renewable energy integration. Moreover, the methodology is scalable and adaptable to other interconnected power systems facing similar voltage stability challenges.

VI. Recommendations

To further extend this work, the following areas are recommended:

1. Incorporate renewable energy sources such as utility-scale solar photovoltaic and wind power plants into the Nigerian 330 kV network model to evaluate the effectiveness of coordinated FACTS control under high renewable energy penetration.
2. Extend the analysis to include dynamic and transient voltage stability using time-domain simulations in software such as MATLAB/Simulink or Dig SILENT PowerFactory.
3. Compare the performance of PSO with advanced optimization algorithms, such as Grey Wolf Optimizer (GWO), Whale Optimization Algorithm (WOA), Artificial Hummingbird Algorithm (AHA), Harris Hawks Optimization (HHO), and Differential Evolution (DE), for optimal FACTS placement
4. Investigate the coordinated operation of FACTS devices with Battery Energy Storage Systems (BESS), synchronous condensers, and advanced Wide-Area Measurement Systems (WAMS) to enhance grid flexibility and resilience

5. Perform a techno-economic assessment of coordinated FACTS deployment by evaluating installation costs, operational savings, payback period, and lifecycle costs.

.

This study provides a practical and scalable framework for improving voltage stability in Nigeria's transmission network and offers valuable insights for future transmission planning and smart grid modernization initiatives

References

[1]. Abdullah, A. M. (2026). Voltage stability enhancement in power systems using PSO-based tuning of AVR and PSS parameters. *Wasit Journal of Engineering Sciences, 14*(2), 139–151. https://doi.org/10.31185/wjes.Vol14.Iss2.814

[2]. Anant S. Shelke, Dr. Anita A. Bhole. (2021). A Review on Different FACTS Devices used in Electrical Power System. International Journal of Engineering Research & Technology (IJERT) http://www.ijert.org ISSN: 2278-0181 IJERTV10IS040192.www.ijert.org Vol. 10 Issue 04

[3]. Ashirwad Dubey.(2016)Load Flow Analysis of Power Systems. International Journal of Scientific & Engineering Research, Volume 7, Issue 5, 79 ISSN 2229-5518 IJSER © 2016 http://www.ijser.org

[4]. Beena M. Varghese1, Adithya P V2, Alan Mathews3, Jorik Ninu4 (2017). Power Compensation in Transmission Line Using Thyristor Switched Reactor. International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering (An ISO 3297: 2007 Certified Organization) Website: www.ijareeie.com Vol. 6, Issue 4.

[5]. Chinonso S. Ezeonye, John Atuchukwu. Okonkwo Innocent. (2024). Effect of unified power flow controller (UPFC) integration to power transfer on the Nigeria 330 kv power network during line contingency. Doi:10.5281/zenodo.10896720

[6]. He, P., Pan, Z., Fan, J., Tao, Y., & Wang, M. (2023). Coordinated design of PSS and multiple FACTS devices based on the PSO-GA algorithm to improve the stability of wind–PV–thermal bundled power system. *Electrical Engineering, 106*(2), 2143–2157. https://doi.org/10.1007/s00202-023-02055-3

[7]. Ikeli, N. H., & Ashigwuike, C. E. (2025). Enhancing power system loadability using improved PSO/ABC, ABC/BFO, PSO/BFO and CS/BFO hybrid techniques. *Journal of Electrical Systems and Information Technology, 12*, Article 16. https://doi.org/10.1186/s43067-025-00206-z

[8]. Jamnani, J. G., & Pandya, M. (2020). Voltage stability enhancement by coordinated design of FACTS devices using the Particle Swarm Optimization algorithm. In *Proceedings of the IEEE Region 10 Conference (TENCON 2020)*. https://doi.org/10.1109/TENCON50793.2020.9293876

[9]. Jonathan Ogheneakpobo Eyenub. (2017)Evaluation of Power System Outages of the 330kV Transmission Network in Nigeria: A Case study of the Benin Region. Journal of the Nigerian Association of Mathematical Physics Volume 43, pp441– 446. © J. of NAMP

[10]. Kenneth. E. Okodu, Sarah Kenn, Kayoada Idowu and Roland Uhunnwangbo. (2018) Impact of the independent power producers and National integrated power products on the Deregulation of the Nigerian electricity sector. Journal of Sustainable Development in Africa (Volume 20, NO1) ISSN: !520-5509 Nigerian National Integrated Power project status Report
[11]. Lawrence, Chichebem Solomon & Lawrence Hannah Oluwabamise.(2025). The public works Department (pwd) and Public Infrastructure Repair and Maintenance Operations in Colonial Southeastern Nigeria, 1896 -1960vol. 1 no. 1: journal of arts, religion, philosophy and cultural studies .
[12]. M. Lindner, H. Abele, C. John, J. Lehner, K. Vennemann, T. Hennig, R. Dimitrovski, N. Klötzl, H. Just and R. Stornowski. (2025). Suitable Classification of Power System Stability Phenomena, CIGRE SCIENCE & ENGINEERING, Nr. CSE037.
[13]. Manish Srivastava, Prakhar Singh, Sandeep Kumar Verma. Prince Singh. (2021). Power Flow Control in Transmission Line by Using UPFC. April International Journal of Research in Engineering Science and Management 4(4):126-129. DOI:10.47607/ijresm.2021.670Manish Srivastava, Prakhar Singh, Sandeep Kumar Verma. Prince Singh.
[14]. Md. Mokarrom Hossain, Md Nasimul Islam Maruf, Md. Kafiul Islam, Md Asaduzzaman Shoeb. Study of Thyristor Controlled Series Capacitor (TCSC) as a useful FACTS Device. (2010). International Journal of Engineering Science and Technology 2(9):4357-4360
[15]. Mossie, M. A., Yetayew, T. T., Bitew, G. T., et al. (2025). A computational approach to voltage stability enhancement and loss reduction in distribution systems using PSO-optimized STATCOM and distributed generation. *Scientific Reports, 15*, 45031. https://doi.org/10.1038/s41598-025-30235-7
[16]. Moyosoluwalorun Sonola Gertrude Fischer, and Eke Asuquo (2023) Harmonic analysis and evaluation of 52 bus in Nigeria Transmission Network Proceedings of the International Conference on Engineering, Science, & Technology (ICEST, 2023)]
[17]. Naihu Li ,Yan Xu, Heng Chen. (2000). FACTS-based power flow control in interconnected power system. Power Systems, IEEE Transactions on 15(1):257 – 262.DOI:10.1109/59.852130.
[18]. Obakpolo, Osazuwa[1], Onyegbadue Ikenna[2], Guiawa Mathurine[3], Izilein Fred[4]. (2024) Power Loss Minimization and Voltage Profile Improvement on Nigeria Distribution Network Using Whale Optimization Algorithm. International Journal of Research and Review Volume 11; Issue: 10; Website: www.ijrrjournal.com. E-ISSN: 2349-9788; P-ISSN: 2454-2237
[19]. Obakpolo, Osazuwa[1], Onyegbadue Ikenna[2], Guiawa Mathurine[3], Izilein Fred[4]. (2024) Power Loss Minimization and Voltage Profile Improvement on Nigeria Distribution Network Using Whale Optimization Algorithm. International Journal of Research and Review Volume 11; Issue: 10; Website: www.ijrrjournal.com. E-ISSN: 2349-9788; P-ISSN: 2454-2237
[20]. Obasi, R. U., Okonkwo, I. I., & Obinwa, C. I. (2025). Voltage stability enhancement of Nigeria 330 kV grid using UPFC FACTS, artificial neural network and Particle Swarm Optimization technique. *International Journal of Innovative Research in Engineering and Management, 12*(4), 30–38. https://doi.org/10.55524/ijirem.2025.12.4.6
[21]. Salman, M. S. D., Sultan, A. J., & Bonneya, M. F. (2024). Power system voltage stability improvement: A review. *AIP Conference Proceedings, 3232*, 050031. https://doi.org/10.1063/5.0236433
[22]. Transmission Company of Nigeria. (2018). *Transmission Network Development Report*. Abuja, Nigeria.
[23]. Transmission Company of Nigeria. (2024). *Nigeria transmission network and system operations report*. Abuja, Nigeria. (Use the latest TCN operational report available to you.)
[24]. Usman, J., Mustafa, M. W., & Aliyu, G. (2021). Coordination of PSS and FACTS devices for power system stability enhancement: A comprehensive review. *Advanced Aspects of Engineering Research, 8*, 30–40. https://doi.org/10.9734/bpi/aaer/v8/8131D
[25]. Wadhwa, G., Kharb, A., Mishra, S., Kumar, M., & Srivastav, S. (2020). A comprehensive survey on real-time voltage stability assessment for power systems. *arXiv*. https://arxiv.org/abs/2011.10885
[26]. Zeitawyeh, R. A., & Faza, A. (2025). Optimal reactive power planning using FACTS devices for voltage stability enhancement in power transmission systems. *Energy Science & Engineering, 13*, 2720–2756. https://doi.org/10.1002/ese3.70064