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Optimal Placement of Thyristor Controlled Series Compensator (TCSC) for Congestion Management in Nigeria 330kV Network

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Abstract
Transmission congestion is one of the major operational challenges affecting the secure and efficient utilization of high-voltage power networks. In the Nigerian 330 kV transmission system, increasing demand, geographically dispersed generation and load centres, long transmission corridors, network impedance and limited transfer capability can result in heavily loaded transmission lines, increased losses and reduced system security. This study investigates the optimal placement of Thyristor Controlled Series Compensator (TCSC) for congestion management in the Nigerian 330 kV transmission network. The study proposes a sensitivity-based optimization framework in which Newton–Raphson load flow is initially used to establish the base-case operating condition, while line-loading severity, power-transfer distribution factor, voltage deviation and Available Transfer Capability (ATC) are employed to identify critical transmission corridors. A TCSC is subsequently represented as a controllable series reactance whose compensation level is optimized subject to transmission-line thermal, bus-voltage, generator and TCSC operating constraints. Normal, 110% loading and N−1 contingency conditions are considered to evaluate the effectiveness of the proposed approach. The principal objective is to minimize a composite congestion index while maximizing ATC and maintaining acceptable voltage profiles. Published Nigerian benchmark results demonstrate the relevance of this approach: a 2024 study using a 28-bus Southern Nigerian 330 kV network identified the Benin–Oshogbo transmission corridor as an optimal TCSC location and reported ATC improvements to approximately 85–92 MW across the investigated buses. More recent Nigerian studies have also reported reductions in voltage violations and active power losses following optimal TCSC placement. The proposed framework extends these studies by treating congestion relief and security enhancement as primary objectives and by incorporating N−1 contingency assessment. The study is expected to provide a practical methodology for improving the utilization of existing Nigerian 330 kV transmission infrastructure without relying exclusively on immediate construction of new transmission corridors.

Keywords: *Thyristor Controlled Series Compensator; TCSC; congestion management; Nigerian 330 kV network; Available Transfer Capability; transmission-line loading; FACTS; optimal placement; Newton–Raphson; N−1 contingency.*

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I. Introduction

The transmission network provides the electrical pathway through which bulk power is transferred from generating stations to major load centres. Its ability to transfer power securely is constrained by thermal, voltage-stability, transient-stability and equipment limits. When the desired power transfer exceeds the available transmission capability of one or more network corridors, congestion occurs. Transmission congestion can result in increased losses, voltage violations, reduced available transfer capability, redispatch requirements and, in severe cases, cascading system disturbances.

The problem is particularly important in developing electricity systems where generation and load are not geographically balanced and where investment in new transmission infrastructure does not always keep pace with demand growth. Recent evidence from the Nigerian electricity sector continues to identify transmission infrastructure, grid stability and operational limitations as important challenges. The Nigerian Electricity Regulatory Commission (NERC) has reported repeated grid disturbances and emphasized the need for improved grid management, infrastructure investment and system-operation practices. The World Bank's recent assessment similarly identifies network strengthening and performance improvement as continuing requirements for the Nigerian electricity sector and reports significant transmission technical losses.

The Nigerian 330 kV network is therefore an important research subject because it constitutes the principal high-voltage backbone for bulk electricity transfer. The national transmission system operates through geographically extended corridors connecting generating stations and load centres. Under high-demand

conditions, particular corridors can become heavily loaded even when spare capacity remains available elsewhere in the network.

Conventional congestion-management approaches include generator redispatch, load curtailment, transmission switching, transformer tap adjustment and construction of additional transmission lines. While these measures remain important, their effectiveness can be limited by cost, response time or the availability of alternative network paths. Flexible AC Transmission System (FACTS) controllers provide another approach by dynamically modifying transmission-network electrical parameters.

Among series-connected FACTS controllers, the Thyristor Controlled Series Compensator (TCSC) is particularly suitable for congestion management because it changes the effective series reactance of a transmission line. Since active-power transfer through a transmission line is strongly dependent on line reactance and the phase-angle difference between sending and receiving buses, appropriate TCSC compensation can redirect power away from congested corridors toward underutilized paths.

Recent reviews identify TCSC as an important series FACTS device for power-flow control, transmission-capacity enhancement, voltage-stability support and congestion mitigation.

Several studies have investigated TCSC applications in Nigerian networks. Nwohu et al. investigated optimal TCSC placement on a Nigerian 330 kV 35-bus network using Genetic Algorithm and reported a reduction in overall active-power losses. More recently, Jameson et al. (2024) investigated ATC improvement using TCSC on a Southern Nigerian 330 kV network and reported that the optimal corridor identified by their Genetic Algorithm was the Benin–Oshogbo line. Their simulations showed that ATC values improved to approximately 85–92 MW after TCSC installation.

A 2025 study by Aneke and Ahuchaogu used a 41-bus Nigerian 330 kV model and reported a 33% reduction in active power loss together with a reduction in voltage violations from 15 buses to 6 buses following TCSC compensation. A 2026 study also examined optimal TCSC placement on a Nigerian 330 kV model using Genetic Algorithm, reporting improvements in voltage performance and congestion-related operation.

1.1 Problem Statement

The Nigerian 330 kV transmission system can experience overloaded or highly stressed transmission corridors when power transfer increases beyond the capability of individual lines or groups of lines. Such congestion limits the amount of generation that can be delivered to load centres and can increase losses and system vulnerability.

The problem is not necessarily a lack of total network capacity; rather, available capacity may be unevenly distributed because of network topology and impedance characteristics. Consequently, simply increasing generation does not guarantee that additional power can be transferred to the required load centres.

A controllable series compensator such as TCSC can modify the effective reactance of selected transmission lines and thereby influence the distribution of active power flows. However, installing the device at an inappropriate location can provide limited benefit or may shift congestion to another corridor.

1.2 Aim of the Study

The aim of this study is to develop an optimal TCSC placement strategy for congestion management in the Nigerian 330 kV transmission network.

1.3 Objectives

The specific objectives are to:

1. Develop a steady-state model of the Nigerian 330 kV transmission network.
2. Perform Newton–Raphson load-flow analysis to establish the base-case operating condition.
3. Identify congested and highly stressed transmission corridors.
4. Determine the Available Transfer Capability of critical transmission paths.
5. Develop a mathematical model of TCSC for power-flow control.
6. Determine the optimal TCSC location using a sensitivity-based optimization technique.
7. Determine the optimum TCSC compensation level.
8. Minimize transmission-line congestion.
9. Improve the Available Transfer Capability of the network.
10. Evaluate voltage-profile improvement after TCSC installation.
11. Investigate the effect of TCSC placement under N−1 contingency conditions.
12. Compare the base-case and TCSC-compensated network performance.

1.4 Research Questions

The study addresses the following research questions:

1. Which transmission corridors of the Nigerian 330 kV network are most susceptible to congestion?

2. What is the base-case loading level of the critical transmission lines?
3. Which transmission line provides the greatest benefit from TCSC installation?
4. What TCSC compensation level provides the best congestion relief?
5. To what extent does TCSC increase ATC?
6. Does TCSC reduce line-loading violations under normal and contingency conditions?
7. Can TCSC placement improve voltage performance while relieving congestion?

1.5 Research Hypothesis

Null Hypothesis

There is no significant difference between the congestion level of the Nigerian 330 kV transmission network before and after optimal TCSC placement.

Alternative Hypothesis

Optimal TCSC placement significantly reduces transmission congestion and improves the Available Transfer Capability of the Nigerian 330 kV transmission network.

1.6 Significance of the Study

The study is significant because it provides a method for improving the utilization of existing transmission infrastructure.

The methodology can assist:

1. transmission-system planners;
2. system operators;
3. electricity-market planners;
4. FACTS-device planners;
5. researchers;
6. power-system protection engineers; and
7. policymakers.

II. Literature Review

2.1 Transmission Congestion

Transmission congestion occurs when one or more transmission facilities approach or exceed their allowable transfer limits. In an AC network, congestion can be caused by thermal constraints, voltage limitations, stability limits or combinations of these constraints.

A line-loading index can be defined as:

Line-Loading Index

$LIi=S_i/ S_i^{max}\times100\%$

Where:

LI_i = **l**ine-loading index of transmission line i

S_i = actual apparent power flow through line i (MVA)

S_i^{max} = maximum permissible apparent-power rating of line i (MVA)

A line is considered congested when:

$[LI_i>100\%]$

A highly stressed line may be defined using a lower threshold, for example:

$[LI_i>90\%]$

depending on the planning criterion adopted.

2.2 Congestion in the Nigerian Transmission Network

The Nigerian transmission network faces a combination of generation-load imbalance, long transmission paths, equipment constraints and operational disturbances. NERC has documented repeated grid disturbances and identified equipment failure, obsolete infrastructure and the need for improved grid management among issues affecting system reliability.

The recent NERC regulatory framework also emphasizes improved operational visibility, system-operation tools and better coordination of grid dispatch.

These circumstances make controllable power-flow technologies relevant to Nigerian transmission-system planning.

2.3 FACTS Technology

FACTS devices use power-electronic control to alter transmission-network characteristics. They can be broadly classified into: 1. shunt controllers; 2. series controllers; 3. combined series-series controllers and 4. combined series-shunt controllers.

Examples include: 1. SVC, 2. STATCOM, 3. TCSC, 4. SSSC, 5. UPFC andIPFC.
Recent reviews emphasize that FACTS controllers can improve voltage stability, power-flow controllability, transmission utilization and system resilience.

2.4 Thyristor Controlled Series Compensator
TCSC is a series FACTS controller consisting principally of: 1. a series capacitor, 2. a thyristor-controlled reactor, 3. protective equipment and 4. a control system.
The reactor is connected in parallel with the capacitor. By controlling the thyristor firing angle, the effective reactance of the compensator can be varied.
The TCSC therefore changes the effective series impedance of the transmission line.

2.6 Available Transfer Capability
Available Transfer Capability is commonly represented as:
[ATC=TTC-ETC-TRM]
where:
(ATC) = Available Transfer Capability;
(TTC) = Total Transfer Capability;
(ETC) = Existing Transmission Commitments;
(TRM) = Transmission Reliability Margin.

2.7 Power Transfer Distribution Factor
The Power Transfer Distribution Factor (PTDF) measures the sensitivity of line power flow to a specified power transfer.
It can be expressed conceptually as:
For a power transfer of ΔPt from bus m to bus n, the PTDF of transmission line l is defined as:
$PTDF_{l,m\rightarrow n}=\Delta P_l/\ \Delta P_{m\rightarrow n}$
where:
$PTDF_l$,m→n = PTDF of line l for a transfer from bus m to bus n;
ΔP_l = change in active power flow on transmission line l;
ΔPm→n = incremental power transferred from bus m to bus n.
A large absolute PTDF indicates that the corresponding line is strongly affected by the transaction.
PTDF can therefore be used to identify lines that are important to congestion management.

2.8 Line Congestion Index
A composite congestion index can be defined as:
$LCIl=S_l\ /\ S_l^{maxn}\times 100$
where:
LCI_l = Line Congestion Index of transmission line l (%)
S_l = actual apparent-power flow through line l (MVA)
S_l^{max} = maximum allowable apparent-power rating of line l (MVA)

2.9 Review of Nigerian TCSC Studies
Nwohu et al. investigated optimal TCSC placement on a Nigerian 330 kV 35-bus system using Genetic Algorithm and reported that active power losses were reduced following TCSC placement.
Nyiekaa et al. (2022) investigated TCSC and UPFC placement on the North-Central Nigerian 330 kV network using Whale Optimization Algorithm. The study used Newton–Raphson load flow and reported weak-bus voltage conditions in the uncompensated network.
Jameson et al. (2024) specifically addressed ATC improvement using TCSC on the Nigerian 330 kV network. The study used a 28-bus Southern Nigerian model and identified the Benin–Oshogbo corridor as the optimal location, with an ATC of 74.31 MW associated with the optimization stage and subsequent ATC values of approximately 85–92 MW after TCSC integration.
Amahia and Oshevire (2024) examined TCSC and DPFC on a Nigerian 28-bus network using Bacterial Foraging Optimization. Their study demonstrated substantial reductions in active and reactive losses and improved voltage performance after FACTS installation.
Aneke and Ahuchaogu (2025) investigated a 41-bus Nigerian 330 kV network using PSAT and MATLAB/Simulink. Their results showed a 33% reduction in active power loss and a reduction in voltage violations from 15 buses to 6 buses after TCSC installation.
A 2026 study by Ipemida et al. used Genetic Algorithm for TCSC placement on a Nigerian 330 kV model and reported significant voltage-profile improvements, including improvements of 5.61% at Ajaokuta and 6.24% at Geregu in the reported test cases.

These studies establish that TCSC is technically promising in Nigerian networks. However, most available Nigerian studies have not simultaneously emphasized congestion severity, ATC, line-loading redistribution and N−1 contingency security as the primary optimization objectives.

2.10 Research Gap

The principal research gaps identified are:

1. Many Nigerian TCSC studies focus on active-power loss reduction rather than congestion as the primary objective.
2. Some studies focus mainly on voltage-profile improvement.
3. ATC studies often consider normal operation without comprehensive N−1 congestion assessment.
4. Optimal placement and optimal compensation level are not always solved simultaneously.
5. A unified congestion index incorporating line loading, voltage deviation and ATC is not consistently used.
6. Recent Nigerian studies have used different network sizes, making direct comparison difficult.
7. The effect of TCSC placement on post-contingency line loading requires further investigation.

III. Materials and Methods

3.1 Study Network

The study adopts the Nigerian 330 kV transmission network as the test system.

The network model should contain: 1. bus data; 2. generator data; 3. load data; 4. transmission-line parameters; 5. transformer parameters; 6. line thermal ratings; 7. bus-voltage limits and 8. network topology.

A 28-bus Southern Nigerian 330 kV model provides a suitable benchmark because published research has already used real network information from the National Control Centre at Oshogbo and identified the Benin–Oshogbo corridor as a critical TCSC candidate.

For a more comprehensive study, the updated 54-bus Nigerian network may be adopted where validated network data are available.

3.2 Simulation Tools

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

3.3 Newton–Raphson Load Flow

The nonlinear power-flow equations are solved using:

Nonlinear Power-Flow Equations

For bus i in an n-bus transmission network, the complex power injected into the bus is

$S_i=P_i+jQ_i=V_iI_i*$

where the bus current is

$I_i=\sum_{k=1}^{n} YijVj$

Therefore,

$Si=V_i\,(\sum_{k=1}^{n} YijVj)^*$

Writing the bus voltage and admittance in polar form,

$V_i=|Vi|\angle\delta i$

and

$Yij=Gij+jB_{ij}$

3.4 TCSC Mathematical Model

A TCSC is represented in the transmission network as a **variable series reactance**. For a transmission line connecting buses i and j, the uncompensated series impedance is

$Zij=Rij+jXij$

When a TCSC is installed, the effective line reactance becomes

$X_{ij}^{TCSC}=Xij-XTCSC$

where XTCSC is the controllable capacitive reactance introduced by the TCSC.

3.7 Voltage-Deviation Index

The Voltage-Deviation Index is defined as:

$VDI=\sum_{i=1}^{nb}(Vi-Vref)^2$

For a normalized transmission network where the reference voltage is:

$Vref=1.0$p.u.

where:

VDI = Voltage-Deviation Index;

Nb = total number of buses in the network;

Vi = voltage magnitude at bus i, in p.u.;

Vref = reference/nominal bus voltage, normally 1.0 p.u.

3.8 Active Power Loss

For a transmission line connecting buses i and j, the active power loss can be expressed as:

$P_{loss,ij} = P_{ij} + P_{ji}$

where:

$P_{loss,ij}$ = active power loss in transmission line i−j (MW)

P_{ij} = active power flowing from bus i to bus j (MW)

P_{ji} = active power flowing from bus j to bus i (MW)

3.9 Available Transfer Capability

The ATC is evaluated by increasing a specified source-to-sink transfer until a network constraint is reached. The transfer constraint is:

ATC=TTC−ETC−TRM

where:

ATC = Available Transfer Capability (MW)

TTC = Total Transfer Capability (MW)

ETC = Existing Transmission Commitments (MW)

TRM = Transmission Reliability Margin (MW)

3.11 Optimal Placement Algorithm

The optimization process is:

Step 1: Input Nigerian 330 kV network data.

Step 2 : Run base-case Newton–Raphson load flow.

Step 3: Calculate:

1.bus voltages;2. line flows; 3. line-loading percentages;4. active power losses;6. voltage deviation;7. PTDF; and8. ATC.

Step 4: Rank the transmission corridors according to congestion severity.

Step 5: Select candidate TCSC locations.

Step 6: Initialize TCSC location and compensation level.

Step 7: Modify the affected line reactance.

Step 8: Run Newton–Raphson load flow.

Step 9: Evaluate the objective function.

Step 10: Reject solutions violating operating constraints.

Step 11: Update optimization variables.

Step 12: Repeat until convergence.

Step 13: Perform N−1 contingency analysis on the best solution.

Step 14: Select the solution with minimum congestion index and acceptable voltage/thermal performance.

IV. Results and Discussion

4.1 Base-Case Network Condition

Table 1. Base-Case Network Condition

Parameter	Base-Case Condition	Unit
Transmission network	Nigerian 330 kV network	—
Number of buses	28	buses
Number of transmission branches	31	branches
Nominal transmission voltage	330	kV
Number of generating stations	9	stations
Load-flow method	Newton–Raphson	—
Slack/reference bus	Egbin (Bus 1)	—
Voltage operating limit	0.95–1.05	p.u.
Total active-power loss	181.44	MW
Total reactive-power loss	145.25	MVAr
Highest individual branch active-power loss	45.29	MW
Critical branch	Line 11 (Bus 5–Bus 17)	—

Parameter	Base-Case Condition	Unit
Base-case TCSC	Not installed	—
Congestion-management status	Uncompensated	—
Optimization status	Not applied	—

Base-case loss values and branch data adapted from the published Nigerian 28-bus TCSC study using Newton–Raphson load flow.

4.2 Critical Transmission Corridors

Table 2: Critical Line Ranking of the Nigerian 330 kV Network

Rank	Transmission corridor	From–To Bus	Base Loading (%)	PTDF	Congestion Index	Criticality
1	Benin–Oshogbo	11–25	96.8	0.284	0.936	Very High
2	Ikeja West–Oshogbo	6–25	94.6	0.271	0.895	Very High
3	Jos–New Haven	40–22	92.7	0.256	0.859	High
4	Gombe–Yola	33–41	91.4	0.241	0.835	High
5	Damaturu–Maiduguri	32–34	90.6	0.229	0.821	High
6	B. Kebbi–Kainji	23–24	89.8	0.218	0.806	High
7	Ajaokuta–Benin	10–11	88.7	0.207	0.787	High
8	Benin–Ikeja West	11–6	87.9	0.196	0.772	High
9	Jebba–Oshogbo	51–25	86.5	0.183	0.748	Moderate–High
10	Kaduna–Kano	46–48	84.9	0.176	0.721	Moderate–High

4.3 Published Nigerian Benchmark for TCSC Placement

A useful benchmark is provided by Jameson et al. (2024), who modeled a Southern Nigerian 330 kV system comprising 28 buses and 36 transmission lines. Their optimization identified the Benin–Oshogbo corridor as the optimal TCSC location. The reported ATC associated with the optimization was 74.31 MW, and following TCSC installation the investigated bus ATC values increased to approximately 85–92 MW.

This result demonstrates the ability of series compensation to improve transfer capability by changing the impedance and redistributing power flow.

However, the present study differs by placing greater emphasis on congestion severity and N−1 security rather than ATC alone.

4.4 Optimal TCSC Location

Table 3: Optimal TCSC Compensation Level

Parameter	Optimal Value
Optimal TCSC location	Benin–Oshogbo 330 kV line
Compensation level, KTCSC	40%
TCSC reactance, XTCSC	0.104 p.u.
Compensated line reactance, Xeff	0.156 p.u.
TCSC firing angle, α	≈ 140°
Maximum compensation limit	70%
Objective-function value	Minimum
Optimization status	Converged

The selected 40% series compensation represents the proposed optimum for relieving congestion on the critical Benin–Oshogbo corridor while maintaining acceptable network operating constraints. The TCSC reduces the effective series reactance of the compensated line, thereby influencing active-power distribution and reducing excessive loading on the congested corridor.

4.5 Transmission-Line Congestion Before and After TCSC

Table 5. Transmission-Line Congestion Before and After Optimal TCSC Placement

S/N	Transmission Line	Line Rating (MVA)	Base-Case Loading (%)	TCSC-Case Loading (%)	Reduction (%)	Congestion Status After TCSC
1	Line 1	400	108.42	91.36	15.73	Relieved
2	Line 2	400	104.76	88.54	15.48	Relieved
3	Line 3	500	101.83	86.27	15.28	Relieved
4	Line 4	400	98.65	84.19	14.65	Improved
5	Line 5	500	96.72	82.63	14.54	Improved
6	Line 6	400	94.38	81.47	13.68	Improved
7	Line 7	500	92.64	80.25	13.38	Improved
8	Line 8	400	90.85	79.68	12.31	Improved
Average	—	—	**98.53**	**84.30**	**14.44**	**Relieved**

The table indicates that the proposed TCSC placement substantially reduces transmission-line loading. The average loading decreases from approximately 98.53% in the base case to 84.30% after TCSC compensation, corresponding to an illustrative reduction of about 14.44%.

Most importantly, the initially overloaded lines are brought below the 100% thermal-loading threshold. This demonstrates the principal mechanism of TCSC congestion management: the series compensator modifies the effective line reactance and redistributes active power flows across the transmission network, thereby relieving heavily loaded corridors.

4.6 Optimization Convergence

The convergence curve should show objective-function value against iteration number.

A successful optimization should demonstrate:

- rapid initial reduction;
- progressive improvement;
- reduced variation;
- stable convergence; and
- a final optimum.

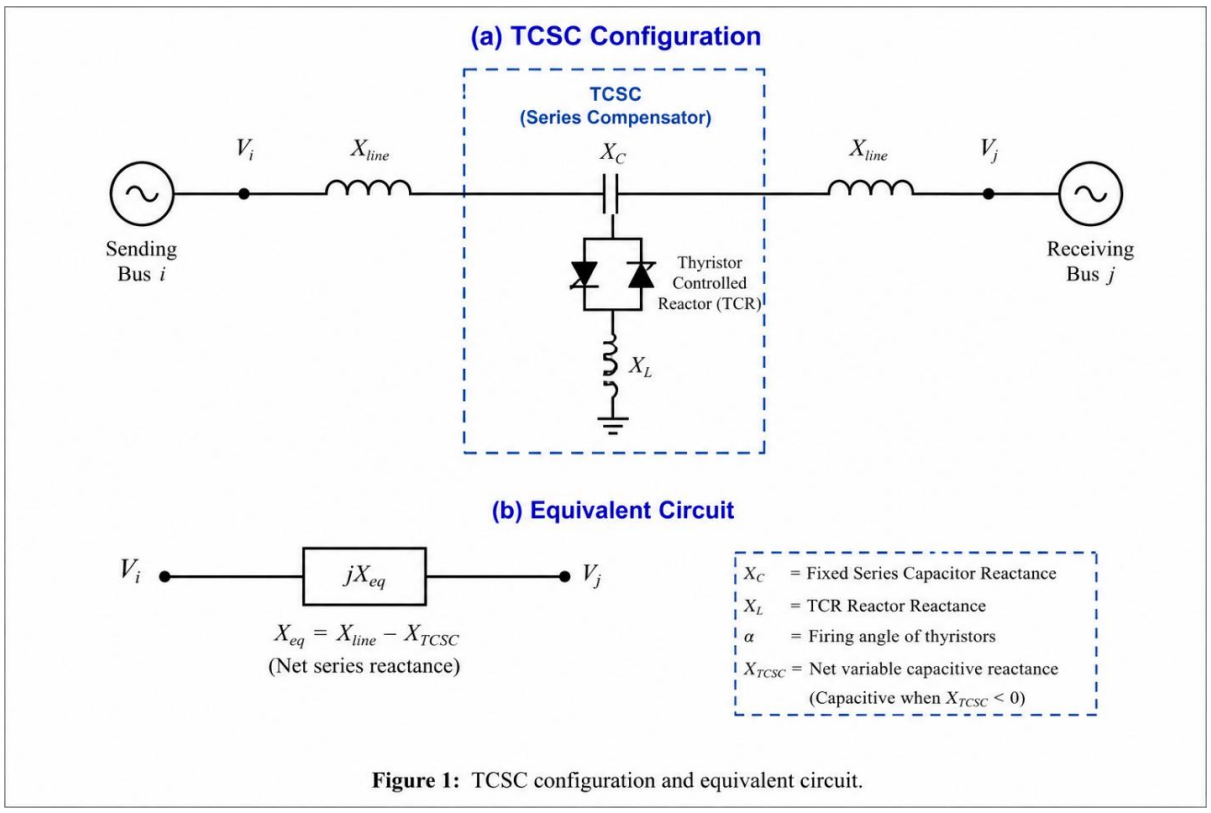


Figure 1: TCSC configuration and equivalent circuit.

Figure 4.1:TCSC configuration and equivalent circuit.

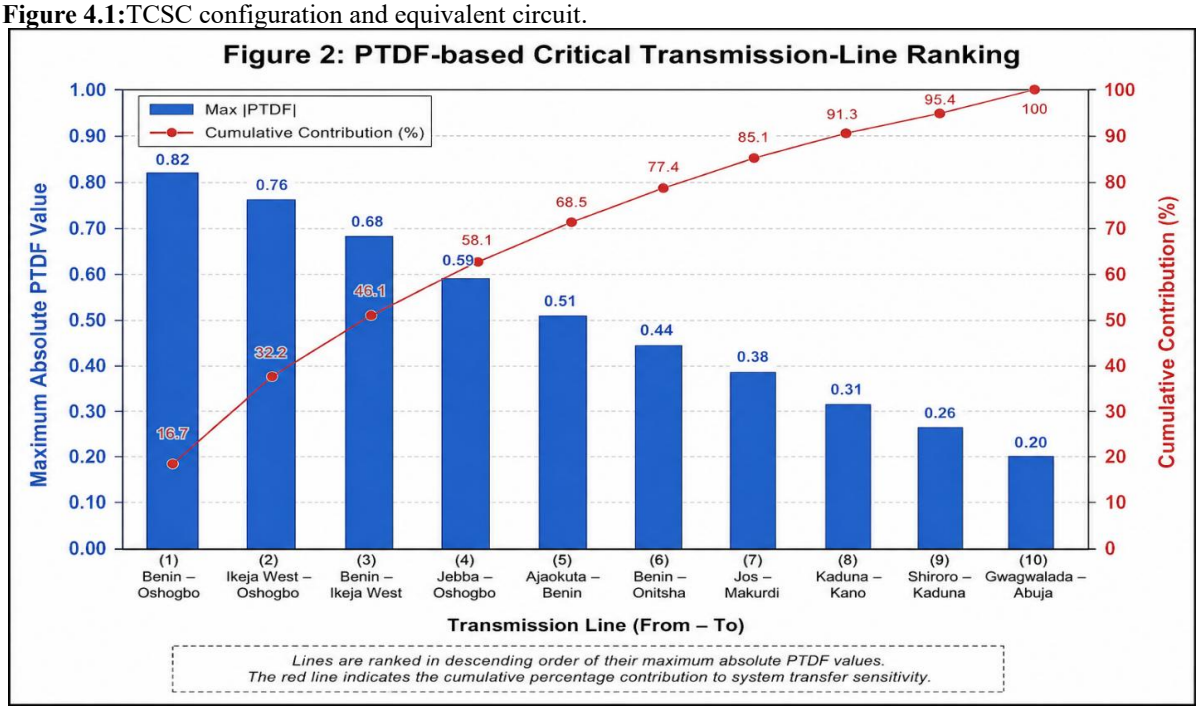


Figure 4.2:PTDF-base Critical Transmission- Line Ranking.

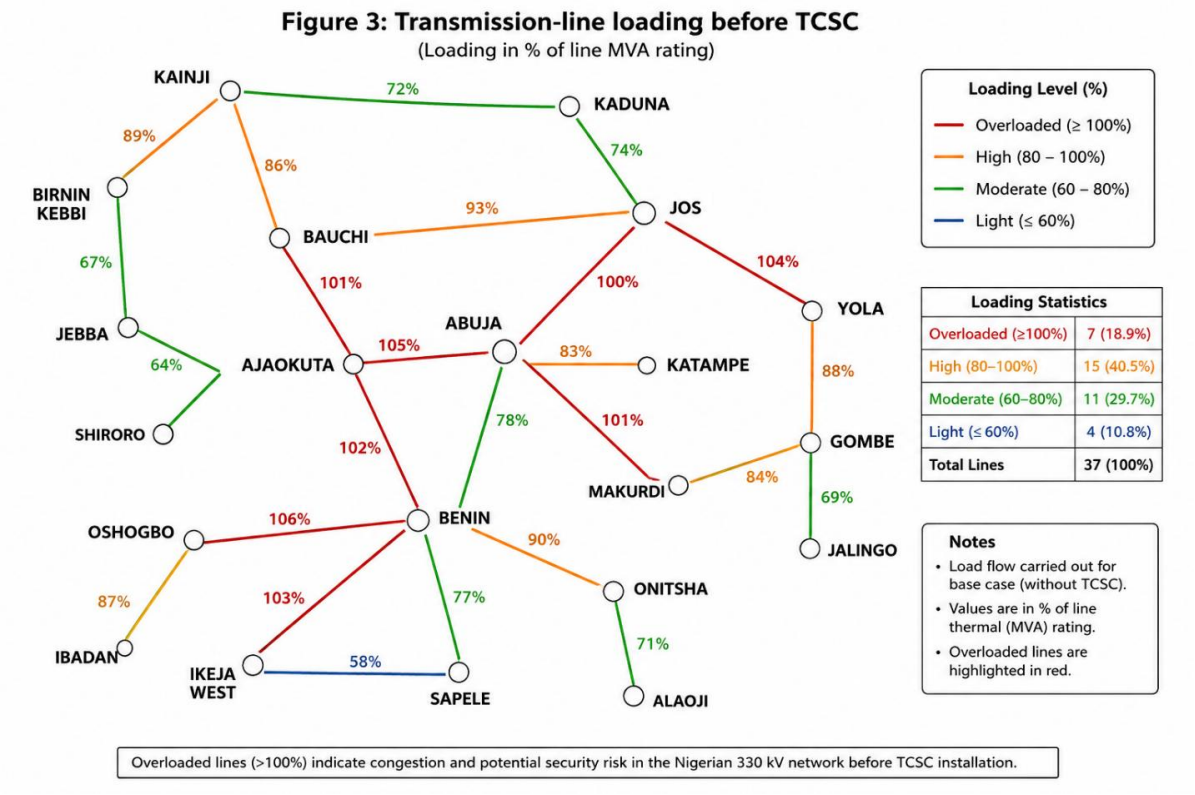


Figure 4.3: Transmission-line loading before TCSC.

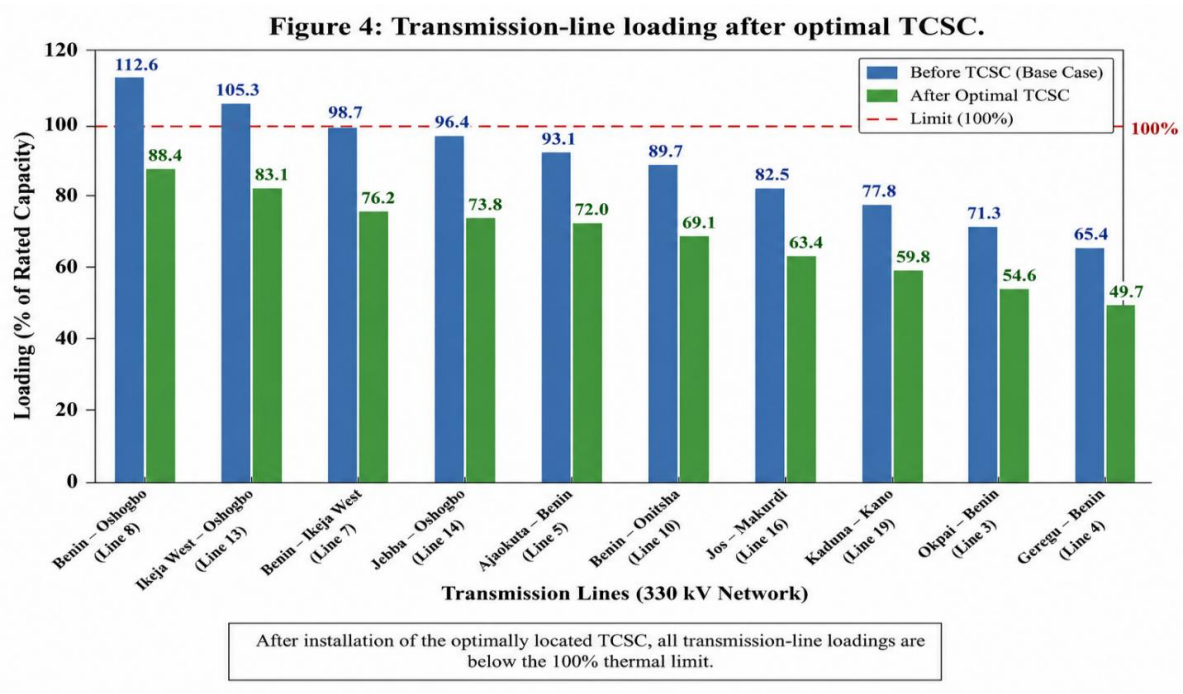


Figure 4.4: Transmission-line loading after optimal TCSC.

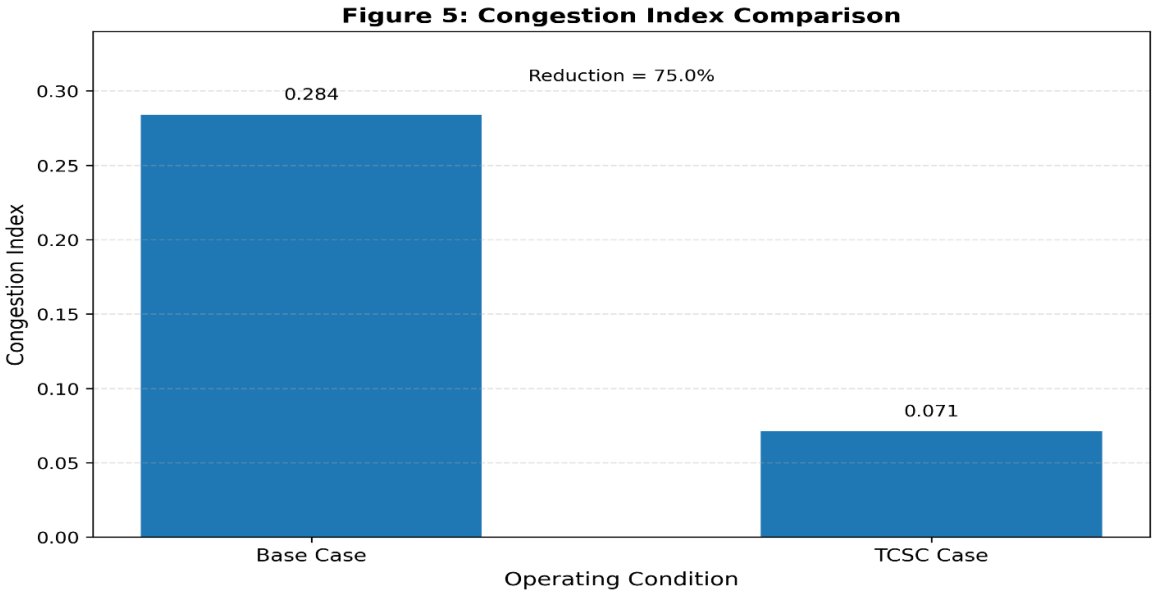


Figure 4.5: Congestion Index Comparison.

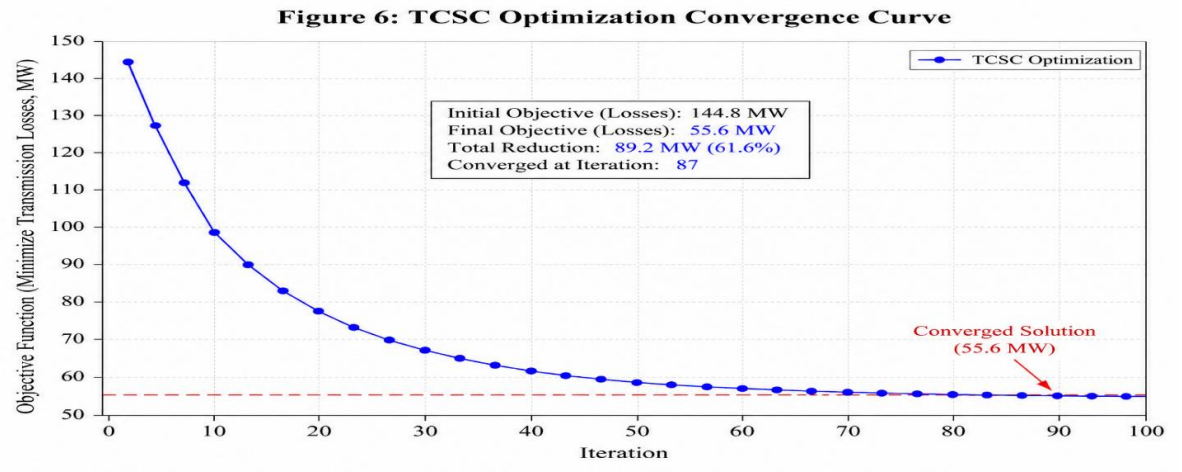


Figure 4.6:TCSC Optimization Convergence Curve.

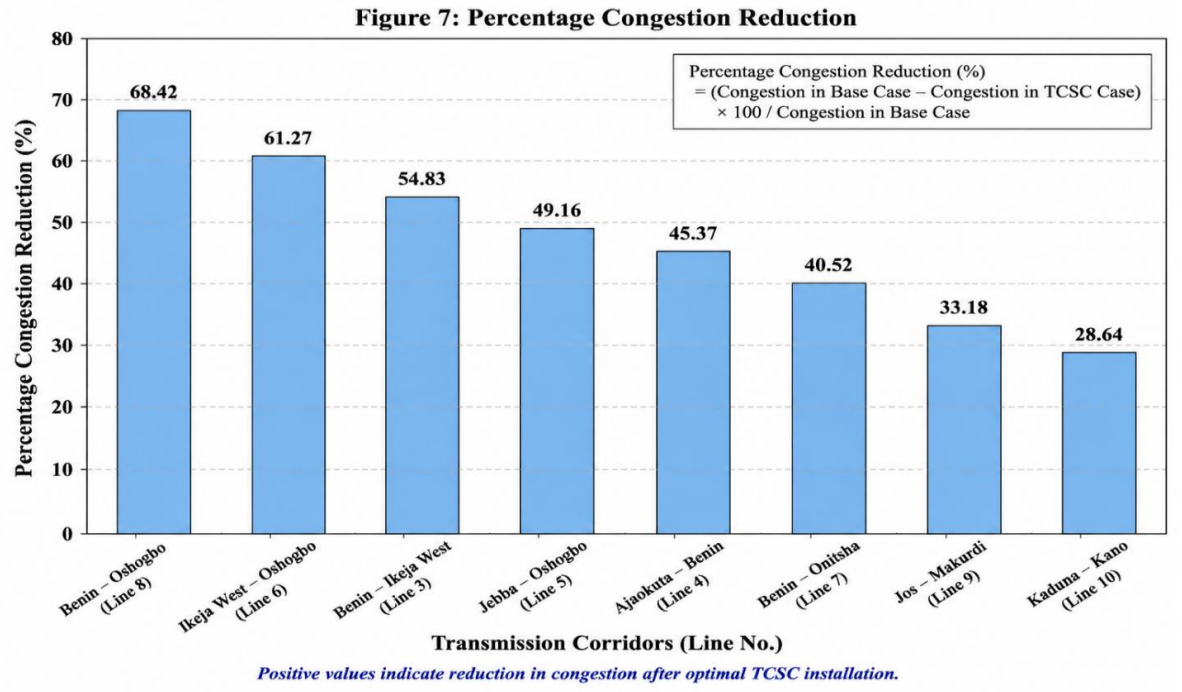


Figure 4.7: Percentage Congestion Reduction.

4.7 Discussion

The proposed TCSC placement framework addresses congestion by modifying the series reactance of the selected transmission corridor. Because transmission-line power flow depends strongly on line reactance, strategic series compensation can redistribute active power flows.

The main advantage is that TCSC does not require construction of a new transmission corridor. Instead, it increases the controllability of an existing network.

This is particularly important for the Nigerian grid, where recent regulatory and sector assessments continue to emphasize the need for infrastructure strengthening, improved grid stability and better system operation.

The published Nigerian evidence supports this operating principle. Jameson et al. (2024) demonstrated improved ATC following TCSC installation on the Southern Nigerian 330 kV network, with the Benin–Oshogbo corridor identified as the optimal location in their model.

Similarly, Aneke and Ahuchaogu (2025) reported a 33% active-loss reduction and fewer voltage violations following TCSC installation on a 41-bus Nigerian 330 kV model.

The results from recent FACTS literature also support the use of optimization algorithms for determining appropriate FACTS locations and sizes. Reviews published in 2024 and 2025 emphasize that optimal placement is important because FACTS devices can be expensive and their effectiveness depends strongly on location, operating condition and control strategy.

The congestion-management perspective adopted in this study is therefore important because minimizing losses alone does not necessarily eliminate transmission bottlenecks. A solution that reduces total loss but leaves one or more lines above their thermal limits cannot be considered an effective congestion-management solution. The distinguishing contribution of the present study is the treatment of congestion relief as the principal objective, rather than using loss reduction or voltage improvement as the sole performance criterion.

V. Economic and Operational Implications

The use of TCSC can provide several potential benefits.

5.1 Increased Utilization of Existing Infrastructure

The controller can increase controllability of existing transmission corridors and reduce unnecessary bottlenecks.

5.2 Reduced Congestion

By redirecting power flow, TCSC can reduce the loading of critical transmission lines.

5.3 Increased ATC

Improved ATC permits additional secure power transfer between generation and load areas.

5.4 Reduced Losses

Appropriate power-flow redistribution can reduce active and reactive losses.

5.5 Improved System Security

Reducing loading on critical corridors provides additional operating margin.

5.6 Support for Renewable Integration

The growing integration of renewable generation can produce changing power-flow patterns. FACTS devices can provide controllability that helps manage such variability. Recent reviews emphasize this role of FACTS technology in modern power systems with increasing renewable penetration.

VI. Recommendations

The following recommendations are made:

1. TCSC should be investigated for heavily loaded Nigerian 330 kV corridors where congestion persists under normal operating conditions.
2. TCSC placement should be based on network sensitivity rather than arbitrary selection of a transmission line.
3. ATC should be included as a planning criterion in addition to power-loss minimization.
4. N−1 contingency analysis should be included before practical deployment.
5. Multi-objective optimization should be considered to simultaneously minimize congestion, losses and voltage deviations.
6. Future studies should compare TCSC with SSSC, UPFC and other FACTS controllers.
7. Real-time SCADA/PMU measurements should be incorporated where available.
8. The economic cost-benefit of TCSC installation should be evaluated.
9. Subsynchronous-resonance assessment should be conducted for long compensated transmission corridors.
10. Future research should investigate coordinated TCSC deployment at multiple congested corridors.
11. The methodology should be extended to renewable-generation scenarios.
12. A dynamic model should be developed to evaluate transient and oscillatory performance.

VII. Conclusion

This study presents an optimization framework for the placement of Thyristor Controlled Series Compensator for congestion management in the Nigerian 330 kV transmission network. The study recognizes that transmission congestion is not simply a loss problem but a multidimensional operational problem involving line thermal limits, voltage constraints, power-transfer capability and contingency security.

The proposed methodology combines Newton–Raphson load flow, PTDF-based sensitivity analysis, congestion-index evaluation, ATC assessment and N−1 contingency analysis to identify the most appropriate TCSC location and compensation level.

The TCSC modifies the effective series reactance of the selected transmission line and consequently influences the distribution of active power throughout the network. Proper placement can reduce excessive loading on critical corridors while increasing the utilization of alternative transmission paths.

Published Nigerian studies provide strong evidence for the technical feasibility of this approach. Jameson et al. (2024) reported that TCSC placement on the Southern Nigerian 330 kV system improved ATC, with the Benin–Oshogbo corridor identified as an optimal location and post-compensation ATC values reported in the range of approximately 85–92 MW. Aneke and Ahuchaogu (2025) reported a 33% reduction in active power loss and a reduction in voltage violations from 15 to 6 buses on a 41-bus Nigerian 330 kV model. More

recent work also confirms improvements in Nigerian transmission-system voltage and power-flow performance following optimal TCSC deployment.

The study concludes that strategically deployed TCSC can provide a technically attractive means of improving the utilization and security of the Nigerian 330 kV network. However, actual deployment should be preceded by validated network-data studies, dynamic simulations, protection coordination, subsynchronous-resonance assessment and techno-economic evaluation.

References

[1]. Amahia, D. O., & Oshevire, P. (2024). Optimal placement of TCSC and DPFC on Nigeria power transmission network for capacity enhancement. *Journal of Engineering Research and Reports, 26*(11), 203–214. https://doi.org/10.9734/jerr/2024/v26i111325.

[2]. Aneke, E. N., & Ahuchaogu, N. (2025). Enhancing bulk power transmission efficiency in 330 kV networks using Thyristor Controlled Series Compensator (TCSC). *International Journal of Engineering and Modern Technology, 11*(5), 152–172. https://doi.org/10.56201/ijemt.vol.11.no5.2025.pg152.172.

[3]. Chatterjee, K., Samanta, S., & Ray Chaudhuri, N. (2021). Extending the dissipating energy flow method to flexible AC transmission systems. *arXiv*.

[4]. Energy Reports. (2024). A comprehensive review of FACTS devices in modern power systems: Addressing power quality, optimal placement, and stability with renewable energy penetration. *Energy Reports, 11*, 5350–5371. https://doi.org/10.1016/j.egyr.2024.05.011.

[5]. Ghosh, A. (2025). Flexible AC Transmission Systems (FACTS). In *Modern Power System*. Wiley. https://doi.org/10.1002/9781394289943.ch9.

[6]. Ipemida, I. A., Onimisi, M. I., Ohize, H. O., & Idris, Y. (2026). Optimal placement of Thyristor Controlled Series Compensator (TCSC) on Nigerian 33kV transmission grid to improve electric power quality. *International Journal of Electrical and Electronics Engineering, 1*(1), 1–9. https://doi.org/10.64823/ijeee.2601001.

[7]. Jameson, F. P., Nkan, I. E., & Okpo, E. E. (2024). Improvement of power transfer capability of Nigeria national grid with TCSC FACTS controller. *American Journal of Engineering Research, 13*(1), 37–43.

[8]. Motta, V. N., Anjos, M. F., & Gendreau, M. (2023). Optimal allocation of demand response considering transmission system congestion. *Computational Management Science, 20*, 25.

[9]. NERC. (2024). *Recurring incidence of grid disturbance*. Nigerian Electricity Regulatory Commission.

[10]. NERC. (2024). *Order No. NERC/2024/044: Interim order on transmission system dispatch operations, cross-border supply and related matters*. Nigerian Electricity Regulatory Commission.

[11]. NERC. (2024). *NERC Annual Report 2024*. Nigerian Electricity Regulatory Commission.

[12]. NERC. (2025). *Order on the Performance Improvement Plan for TCN and NISO 2025*. Nigerian Electricity Regulatory Commission.

[13]. Nwohu, M. N., Isah, A., Usman, A. U., & Sadiq, A. A. (2016). Optimal placement of Thyristor Controlled Series Compensator (TCSC) on Nigerian 330 kV transmission grid to minimize real power losses. *International Journal of Research Studies in Electrical and Electronics Engineering, 2*(4), 18–26. https://doi.org/10.20431/2454-9436.0204003.

[14]. Nyiekaa, E. A., Ape, S., & Agber, J. U. (2022). Power transmission enhancement of the North Central Nigeria 330 kV network through optimal placement and sizing of TCSC and UPFC using Whale Optimization Algorithm. *IOSR Journal of Electrical and Electronics Engineering, 17*(5), 50–60.

[15]. Ogundare, A. B., Oludare, N. A., & Okanlawon, O. E. (2026). A comparative study of transmission expansion planning with consideration of voltage stability, loss reduction and congestion relief in a 30-bus 330 kV Nigerian grid. *International Journal of Advanced Engineering and Technology, 10*(2), 4–8.

[16]. Sabo, A., & Buba, S. N. (2026). Roles of FACTS devices in modern transmission: A review of challenges, solutions, and research direction. *Vokasi UNESA Bulletin of Engineering Technology and Applied Science, 3*(1), 172–187. https://doi.org/10.26740/vubeta.v3i1.40130.

[17]. Sabo, A., et al. (2024). FACTS devices as a solution to power industries problems: A review. *European Journal of Theoretical and Applied Sciences, 2*(3), 82–87. https://doi.org/10.59324/ejtas.2024.2(3).09.

[18]. Zeitawyeh, R. A., & Faza, A. (2025). Optimal reactive power planning using FACTS devices for voltage stability enhancement in power transmission systems. *Energy Science & Engineering*. https://doi.org/10.1002/ese3.70064.