

POWER

Comparative Performance Evaluation of FACTS for Transmission Congestion Mitigation in the Nigerian 330 kV Network

Chukwujama Christopher, Ogbonna Bartholomew Odinaka

Department of Electrical/Electronic Engineering, University of Port Harcourt, Port Harcourt, Nigeria

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Abstract

Increasing electricity demand and inadequate transmission capacity have intensified congestion and voltage stability challenges in Nigeria's 330 kV transmission network. This study investigates the effectiveness of Flexible AC Transmission Systems (FACTS), specifically the Static Var Compensator (SVC) and Thyristor-Controlled Series Capacitor (TCSC), in mitigating transmission congestion, improving voltage regulation, and reducing power losses. A representative Nigerian 330 kV transmission network was modelled and analysed using NEPLAN 555. Base-case power-flow analysis was conducted to identify overloaded transmission corridors. The performance of the compensation schemes was evaluated by comparing transmission line loading and active and reactive power losses before and after integration. The base-case analysis recorded total active and reactive power losses of 388.33 MW and 980.82 Mvar, respectively. Following SVC integration, these losses decreased to 244.30 MW and 416.19 Mvar, representing reductions of 37.09% and 57.57%, respectively. TCSC integration achieved greater reductions, lowering active power losses to 109.976 MW and reactive power losses to 252.234 Mvar, corresponding to improvements of 71.68% and 74.28%, respectively. The results demonstrate that both FACTS devices can enhance transmission network performance, with TCSC exhibiting superior performance in reducing system losses under the investigated operating conditions. The findings provide a basis for improving congestion management and operational efficiency in Nigeria's 330 kV transmission network.

Keywords: transmission congestion; FACTS devices; Static Var Compensator (SVC); Thyristor-Controlled Series Capacitor (TCSC); Nigerian 330 kV transmission network

1 Introduction

The increasing demand for electrical energy due to population growth, urbanization, and industrial development has placed significant pressure on power transmission systems, particularly in developing countries. In Nigeria, the 330 kV transmission network constitutes a major backbone for transferring electricity from generating stations to regional and urban load centres. However, ageing infrastructure, inadequate transmission capacity, limited redundancy, increasing load demand, and poor reactive power management have contributed to congestion, voltage instability, and increased transmission losses [1]. Transmission congestion occurs when power flow through a transmission line or transformer exceeds its permissible thermal, voltage, or stability limits. Such conditions may result in uneconomic generation dispatch, increased losses, voltage violations, load curtailment, and, under severe conditions, system instability or collapse [2]. Consequently, effective congestion management is essential for maintaining secure and reliable power-system operation while maximizing the utilization of existing transmission infrastructure. Transmission congestion is a major operational

challenge in modern power systems, occurring when power flow exceeds the thermal, voltage, or stability limits of transmission facilities. It can result in increased transmission losses, voltage violations, uneconomic generation dispatch, load shedding, and, under severe conditions, cascading outages and system collapse. These challenges are particularly significant in developing power systems such as Nigeria, where transmission expansion has not always kept pace with growth in generation and electricity demand. Several approaches have been proposed for congestion management, including network reinforcement, generation rescheduling, demand-side management, optimal power flow (OPF), pricing mechanisms, and Flexible AC Transmission Systems (FACTS). Although network expansion can provide permanent capacity enhancement, its implementation is constrained by high capital requirements, environmental concerns, regulatory procedures, and right-of-way limitations. Consequently, FACTS-based solutions have received increasing attention because they can improve the utilization and controllability of existing transmission infrastructure.

FACTS devices employ power-electronic controllers to regulate voltage, reactive power, impedance, and power flow. Common devices include the Static VAR Compensator (SVC), Static Synchronous Compensator (STATCOM), Thyristor-Controlled Series Capacitor (TCSC), Static Synchronous Series Compensator (SSSC), Unified Power Flow Controller (UPFC), and Unified Power Quality Conditioner (UPQC). Their ability to provide rapid and localized control makes them suitable for congestion mitigation under normal and contingency operating conditions.

A research by [3] investigated optimal UPFC placement using sensitivity- and pricing-based approaches within an OPF framework and reported improvements in transmission losses, voltage profile, and congestion costs. A study by [4] demonstrated that coordinated TCSC and distributed generation could reduce line overloading under stressed operating conditions. Genetic Algorithm (GA) optimization was applied to TCSC placement and there were reported reductions in congestion and transmission losses [5]. Flexible AC Transmission System (FACTS) devices represent a technically sophisticated and dynamic solution for mitigating congestion and enhancing the operational flexibility of power networks. These power electronic-based controllers enable real-time control of key parameters such as voltage magnitude, phase angle, and line impedance. FACTS devices such as Static VAR Compensator (SVC), Static Synchronous Compensator (STATCOM), and Unified Power Flow Controller (UPFC) have the ability to manage reactive power, support voltage profiles, and redirect power flows across designated corridors makes them particularly valuable in congestion management applications [6]. A study showed that strategic coordination of multiple FACTS devices can significantly improve power transfer capability and reduce transmission constraints [7]

Power flow analysis is an essential computational tool used in planning, operating, and optimizing power systems. It provides the steady-state voltage magnitude and phase angle at each bus, and the real and reactive power flows on each line under specified operating conditions. The primary objective is to ensure that the power system operates within its thermal, voltage, and stability limits under various load scenarios [8].

Newton-Raphson and Fast-Decoupled Load Flow methods are particularly suitable for large transmission systems because of their convergence characteristics and computational efficiency [9]. When integrated with optimization algorithms, power-flow analysis can identify critical transmission corridors and determine appropriate FACTS locations and ratings.

Despite the extensive literature on FACTS-based congestion management, important gaps remain. Most existing studies are based on standard IEEE test systems, with limited application to the Nigerian 330 kV transmission network. There is also limited integration of Nigerian network

modelling, congestion severity assessment, and Genetic Algorithm-based optimization for FACTS placement and sizing under both normal and contingency conditions.

This study addresses these gaps by modelling a representative Nigerian 330 kV transmission network in NEPLAN and applying power-flow analysis to identify and quantify congestion. A Genetic Algorithm is subsequently employed to optimize FACTS placement and sizing. The effectiveness of the proposed compensation is evaluated using voltage profile improvement, line-loading relief, transmission loss reduction, and congestion severity indices. The approach provides a framework for assessing the technical feasibility of FACTS-based congestion mitigation in Nigeria's transmission network.

2 Materials and methods

The materials used were collected from Transmission Company of Nigeria (TCN) [10] with particular attention to the schematic diagram of the entire 330kV grid network. The materials collected includes:

Bus data consisting of fourteen (14) generators with Egbin chosen as the slack and thirty four (34) loads. (from March 2024 to November, 2025). Line data consisting of thirty four (34) single circuit, twenty four (24) double circuit, one (1) triple circuit and one (1) quadruple circuit. (Source: Transmission Company of Nigeria). Static Var Compensator (SVC) use for control of reactive power and improves voltage stability by compensating for voltage fluctuations. Thyristor-Controlled Series Capacitor (TCSC) used for enhancing system stability and controlling power flow between different parts of the network by adjusting series reactance. Neplan 555 software package was used for modeling, network analysis and optimization of Nigerian 330 kV network using FACTS devices

This study adopts a simulation-based approach to optimize congestion in the Nigerian 330 kV transmission network through the integration of FACTS devices. A comparative analysis of two selected FACTS devices was conducted to evaluate their effectiveness in mitigating transmission line congestion, relieving overloaded corridors, improving voltage stability, and minimizing system losses. To achieve this, the following steps were undertaken: Load flow analysis was employed to identify overloaded transmission lines and weak voltage buses in the network, providing a diagnostic basis for congestion and voltage instability. Contingency analysis (N-1) was performed to test the network's response to individual line or generator outages to evaluate the robustness of each FACTS device under stressed conditions.

The performance of each FACTS device was evaluated based on key technical indicators, including improvement in voltage profiles, reduction in line loading percentages, minimization of total system losses, and the network's ability to maintain stable operation under both base case and contingency scenarios

2.1 Base case power flow analysis

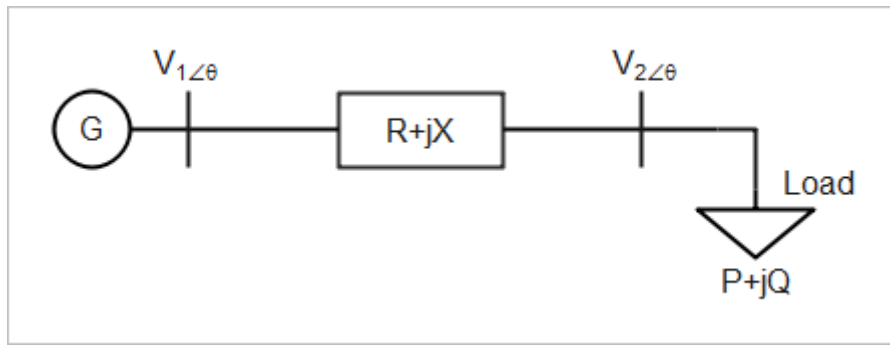


Figure 1. A two-bus system of a transmission line.

where G is the generator; $V_1\angle\theta$ the sending-end voltage and angle; $V_2\angle\theta$ the receiving-end voltage and angle; and $P + jQ$ the complex power at the receiving end.

Figure 1 shows a two-bus system, which consists of a load fed from a source via a transmission line. For any i th bus, let

$$V_i = |V_i|\angle\delta_i, V_i^* = |V_i|\angle -\delta_i \quad (1)$$

For the k th bus,

$$V_k = |V_k|\angle\delta_k, Y_{ik} = |Y_{ik}|\angle\theta_{ik} \quad (2)$$

The real and reactive power injected in the network is given by

$$S_i = V_i I_i^* = P_i + jQ_i \quad (3)$$

$$I_i = \left(\frac{S_i}{V_i} \right)^* = \frac{P_i - jQ_i}{V_i^*} \quad (4)$$

$$I_i = \frac{P_i - jQ_i}{V_i^*} = \sum_{k=1}^n Y_{ik} V_k \quad (5)$$

$$P_i - jQ_i = V_i^* \left(\sum_{k=1}^n Y_{ik} V_k \right) \quad (6)$$

$$P_i - jQ_i = V_i^* \left(\sum_{k=1}^n Y_{ik} V_k \angle\delta_k + \theta_{ik} - \delta_i \right) \quad (7)$$

$$P_i - jQ_i = \sum_{k=1}^n |Y_{ik}| |V_i| |V_k| [\cos(\delta_k + \theta_{ik} - \delta_i) + j \sin(\delta_k + \theta_{ik} - \delta_i)] \quad (8)$$

Separating (8) into real and imaginary parts have,

$$P_i = \sum_{k=1}^n |Y_{ik}| |V_i| |V_k| \cos(\delta_k + \theta_{ik} - \delta_i) \quad (9)$$

$$Q_i = - \sum_{k=1}^n |Y_{ik}| |V_i| |V_k| \sin(\delta_k + \theta_{ik} - \delta_i) \quad (10)$$

where

Y_{ik} : the admittance matrix

P_i : the injected real power

Q_i : the injected reactive power

δ_i : phase angle

Expanding (9) and (10) in Taylor series neglecting higher order terms we have

$$\begin{bmatrix} \Delta P_2^{(k)} \\ \vdots \\ \Delta P_n^{(k)} \\ \Delta Q_2^{(k)} \\ \vdots \\ \Delta Q_n^{(k)} \end{bmatrix} = \begin{bmatrix} \frac{\partial P_2^{(k)}}{\partial \delta_2} & \dots & \frac{\partial P_2^{(k)}}{\partial \delta_n} & \frac{\partial P_2^{(k)}}{\partial |V_2|} & \dots & \frac{\partial P_2^{(k)}}{\partial |V_n|} \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ \frac{\partial P_n^{(k)}}{\partial \delta_2} & \dots & \frac{\partial P_n^{(k)}}{\partial \delta_n} & \frac{\partial P_n^{(k)}}{\partial |V_2|} & \dots & \frac{\partial P_n^{(k)}}{\partial |V_n|} \\ \frac{\partial Q_2^{(k)}}{\partial \delta_2} & \dots & \frac{\partial Q_2^{(k)}}{\partial \delta_n} & \frac{\partial Q_2^{(k)}}{\partial |V_2|} & \dots & \frac{\partial Q_2^{(k)}}{\partial |V_n|} \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ \frac{\partial Q_n^{(k)}}{\partial \delta_2} & \dots & \frac{\partial Q_n^{(k)}}{\partial \delta_n} & \frac{\partial Q_n^{(k)}}{\partial |V_2|} & \dots & \frac{\partial Q_n^{(k)}}{\partial |V_n|} \end{bmatrix} \begin{bmatrix} \Delta \delta_2^{(k)} \\ \vdots \\ \Delta \delta_n^{(k)} \\ \Delta |V_2^{(k)}| \\ \vdots \\ \Delta |V_n^{(k)}| \end{bmatrix} \quad (11)$$

The Jacobian matrix gives the linearized relationship between small changes in voltage angle $\Delta \delta_i^{(k)}$ and magnitude $\Delta |V_i^{(k)}|$ and small changes in real $\Delta P_i^{(k)}$ and reactive power $\Delta Q_i^{(k)}$, respectively.

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_1 & J_3 \\ J_2 & J_4 \end{bmatrix} \begin{bmatrix} \Delta \delta \\ \Delta |V| \end{bmatrix} \quad (12)$$

where

J_1, J_2, J_3 and J_4 are the elements of the Jacobian matrix.

The off-diagonal and diagonal elements of J_1 are

$$\frac{\partial P_i}{\partial \delta_k} = |Y_{ik}| |V_i| |V_k| \sin(\delta_i + \theta_{ik} - \delta_k) \quad (13)$$

$$\frac{\partial P_i}{\partial \delta_i} = - \sum_{k=1, k \neq i}^n |Y_{ik}| |V_i| |V_k| \sin(\delta_i + \theta_{ik} - \delta_k) \quad (14)$$

The off-diagonal and diagonal elements of J_3 are

$$\frac{\partial P_i}{\partial |V_k|} = |Y_{ik}| |V_i| \cos(\delta_i + \theta_{ik} - \delta_k) \quad (15)$$

$$\frac{\partial P_i}{\partial |V_i|} = 2 |Y_{ii}| |V_i| \cos \theta_{ii} + \sum_{k=1, k \neq i}^n |Y_{ik}| |V_k| \cos(\delta_i + \theta_{ik} - \delta_k) \quad (16)$$

The off-diagonal and diagonal elements of J_2 are

$$\frac{\partial Q_i}{\partial \delta_k} = - |Y_{ik}| |V_i| |V_k| \cos(\delta_i + \theta_{ik} - \delta_k) \quad (17)$$

$$\frac{\partial Q_i}{\partial \delta_i} = \sum_{k=1, k \neq i}^n |Y_{ik}| |V_i| |V_k| \cos(\delta_i + \theta_{ik} - \delta_k) \quad (18)$$

The off-diagonal and diagonal elements of J_4 are

$$\frac{\partial Q_i}{\partial |V_k|} = |Y_{ik}| |V_i| \sin(\delta_i + \theta_{ik} - \delta_k) \quad (19)$$

$$\frac{\partial Q_i}{\partial |V_i|} = 2|Y_{ii}||V_i|\sin\theta_{ii} + \sum_{k=1, k \neq i}^n |Y_{ik}||V_k|\sin(\delta_i + \theta_{ik} - \delta_k) \quad (20)$$

Compute the scheduled errors ΔP_i and ΔQ_i for each load bus:

$$\Delta P_i^{(k)} = P_i^{\text{sch}} - P_i^{(k)} \quad (21)$$

$$\Delta Q_i^{(k)} = Q_i^{\text{sch}} - Q_i^{(k)} \quad (22)$$

3 Results and discussion

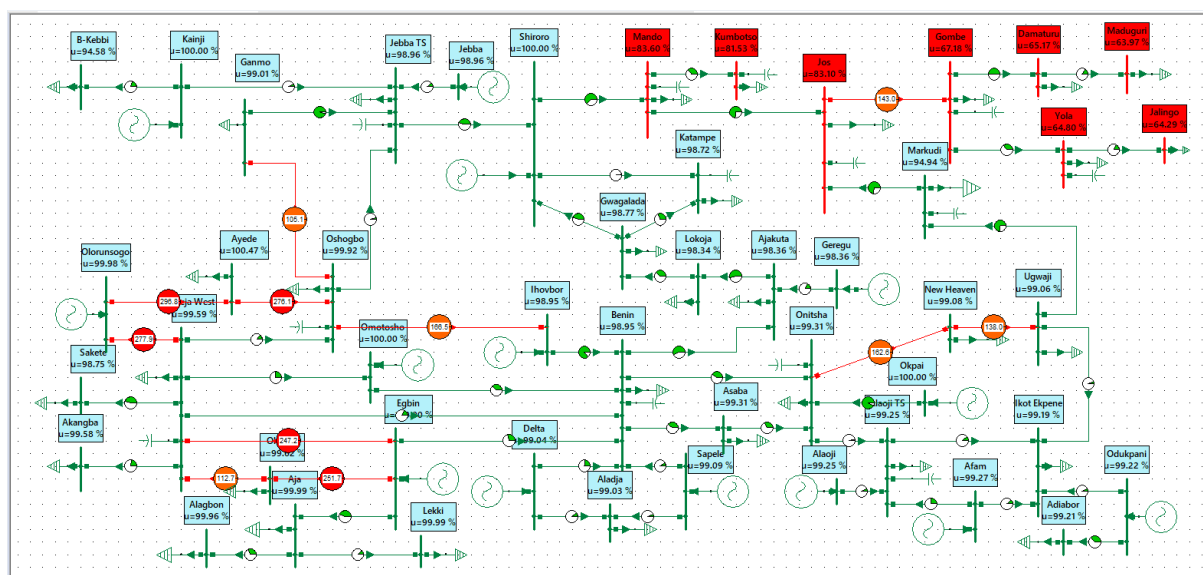


Figure 2. Single-line diagram of the Nigerian 330 kV grid base-case model in NEPLAN software.

Table 1. Branch power flow, line loading and transmission losses of the 330 kV network under normal operating conditions.

BranchID	FromBus	ToBus	Power Flow		Loading	Losses	
MW	MVar	%	MW	MVar			
A1K	Alaoji Ts	Ikot Ekpene	-133.60	-124.31	10.7	0.017	-0.498
A1S	Markudi	Jos	-428.46	-939.53	72.5	17.957	151.878
B11J	Benin	Ajakuta	-954.91	127.68	57.1	6.630	4.999
B1T	Onitsha	Benin	659.67	-205.57	40.7	1.504	12.132
B3D	Asaba	Benin	321.33	-103.31	39.8	0.718	5.775
B5M	Omotosho	Benin	-318.68	-1.42	37.6	2.183	23.364
B5W	Ikeja West	Benin	-155.65	3.66	18.4	1.220	3.016
B6N	Egbin	Benin	-240.62	7.68	28.4	2.267	19.835
B8J	Jebba Gs	Jebba TS	-160.00	-150.69	13.0	0.001	-0.688
D1B	Odukpani	Adiabor	-140.00	-90.00	36.7	0.001	-0.627
D1K	Odukpani	Ikot Ekpene	10.00	110.63	6.5	0.003	-0.614
D1M	Damaturu	Maiduguri	80.40	33.23	15.6	0.396	3.227

BranchID	FromBus	ToBus	Power Flow		Loading	Losses	
D3T	Asaba	Onitsha	220.61	-159.08	31.9	0.088	-0.232
E1D	Gombe	Damaturu	231.91	165.96	49.5	1.517	12.737
E1Y	Gombe	Yola	181.82	83.69	34.8	1.682	14.134
F1A	Afam	Alaoji Ts	417.85	111.01	25.4	0.023	-0.364
F1E	Afam	Ikot Ekpene	-172.12	-111.41	12.1	0.029	-0.418
G1W	Delta	Aladja	82.36	24.44	10.1	0.003	-0.296
G3B	Delta	Benin	-167.60	-95.58	22.7	0.035	-0.024
G5B	Gwagalada	Katampe	271.92	59.24	32.9	0.042	0.038
H1U	New Heaven	Ugwaji	-642.18	-980.43	138.0	0.023	-0.127
H1W	Ikeja West	Oshogbo	-123.25	13.52	14.5	0.689	-2.844
H2A	Ayede	Oshogbo	-2124.62	1039.47	176.1	24.371	20.360
H3G	Oshogbo	Ganmo	-786.52	421.52	105.1	10.054	0.990
H7V	Ihovbor	Oshogbo	-1190.66	760.26	166.5	34.239	28.738
J1B	Aja	Alagbon	-260.00	-120.00	33.4	0.018	-0.163
J1E	Aja	Lekki	100.00	49.68	13.0	0.001	-0.319
J1H	Oshogbo	Jebba TS	-26.36	-23.80	4.2	0.036	0.157
J1L	Ajakuta	Lokoja	924.91	-32.06	54.9	0.210	1.155
J3G	Ganmo	Jebba TS	-634.83	512.64	96.2	1.693	1.119
J3R	Shiroro	Jebba TS	729.45	-186.92	44.4	5.668	47.458
K1J	Kainji	Jebba TS	-108.27	-104.36	8.9	0.163	1.466
K1T	Okpai	Onitsha	-148.73	-1553.77	91.7	1.273	10.164
K1U	Ikot Ekpene	Ugwaji	5.31	-187.50	5.5	0.029	-1.035
K3R	Kainji	B-Kebbi	156.57	71.15	20.1	10.572	-13.854
K7W	OkeAro	Ikeja West	1923.50	90.86	112.7	0.478	3.415
L6G	Gwagalada	Lokoja	-622.85	198.24	38.6	1.844	15.025
L7A	Alaoji	Alaoji Ts	95.00	80.00	7.3	0.000	-0.639
M2S	Jos	Mando	495.19	-198.15	74.4	5.195	4.184
M5W	Omotosho	Ikeja West	-194.86	89.56	25.0	0.392	2.656
M6N	Mando	Kumbotso	241.68	94.14	36.2	1.675	13.997
N3J	Egbin	Aja	660.04	373.96	44.2	0.019	-0.563
N6W	Egbin	Ikeja West	2113.15	166.18	147.2	5.739	43.777
N7K	Egbin	OkeAro	2148.26	200.99	151.7	4.767	40.133
NWIBS	Ikeja West	Sakete	302.52	251.82	46.1	2.519	1.822
R1J	Geregu	Ajakuta	-200.00	-210.63	17.2	0.000	-0.625
R1M	Shiroro	Mando	1085.49	-21.82	63.3	178.624	14.603
R1W	Oloronsogo	Ikeja West	2316.84	-512.72	177.9	11.183	85.649

BranchID	FromBus	ToBus	Power Flow		Loading	Losses	
R2A	Oloronsogo	Ayede	-2423.99	813.11	196.8	7.667	64.744
R4B	Shiroro	Katampe	18.46	12.35	2.6	0.343	-0.348
R5G	Shiroro	Gwagalada	-200.17	333.24	45.3	0.766	5.758
S2B	Sapele	Benin	-142.34	-155.61	8.3	0.013	-0.579
S4G	Sapele	Aladja	17.64	44.97	5.7	0.003	-0.293
SIE	Jos	Gombe	768.45	668.99	143.0	34.719	294.479
T3H	Onitsha	New Heaven	822.63	1109.56	162.2	0.429	-0.741
T4A	Onitsha	Alaoji Ts	20.79	7.62	2.6	0.003	-0.295
U1A	Ugwaji	Markudi	-530.42	-1073.81	73.6	6.447	54.113
V7B	Ihovbor	Benin	-1300.65	669.70	86.2	0.009	-0.559
W3L	Ikeja West	Akangba	300.01	249.42	22.9	0.008	-0.579
Y1G	Yola	Jalingo	80.14	51.04	17.1	0.139	1.041
						388.33	980.82

Table 1 shows that the most critically overloaded lines include R2A (Oloronsogo-Ayede, 196.82 %), R1W (Oloronsogo-Ikeja West, 177.91 %), H2A (Ayede-Oshogbo, 176.11 %), H7V (Ihovbor-Oshogbo, 166.54 %), T3H (Onitsha-New Heaven, 162.64 %), N7K (Egbin-Oke Aro, 151.66 %), N6W (Egbin-Ikeja West, 147.23 %), and SIE (Jos-Gombe, 143.02 %). Other significantly loaded lines include H3G (Oshogbo-Ganmo, 105.14 %) and K7W (Oke Aro-Ikeja West, 112.73 %), all of which exceed acceptable thermal limits and signal potential congestion points. These critical corridors constitute the primary transmission backbones linking major generation centers in the southwest to load centers in the north and southeast, making them highly susceptible to overload and voltage instability.

The cumulative network losses under these conditions amount to 388.33 MW of active power and 980.82 Mvar of reactive power

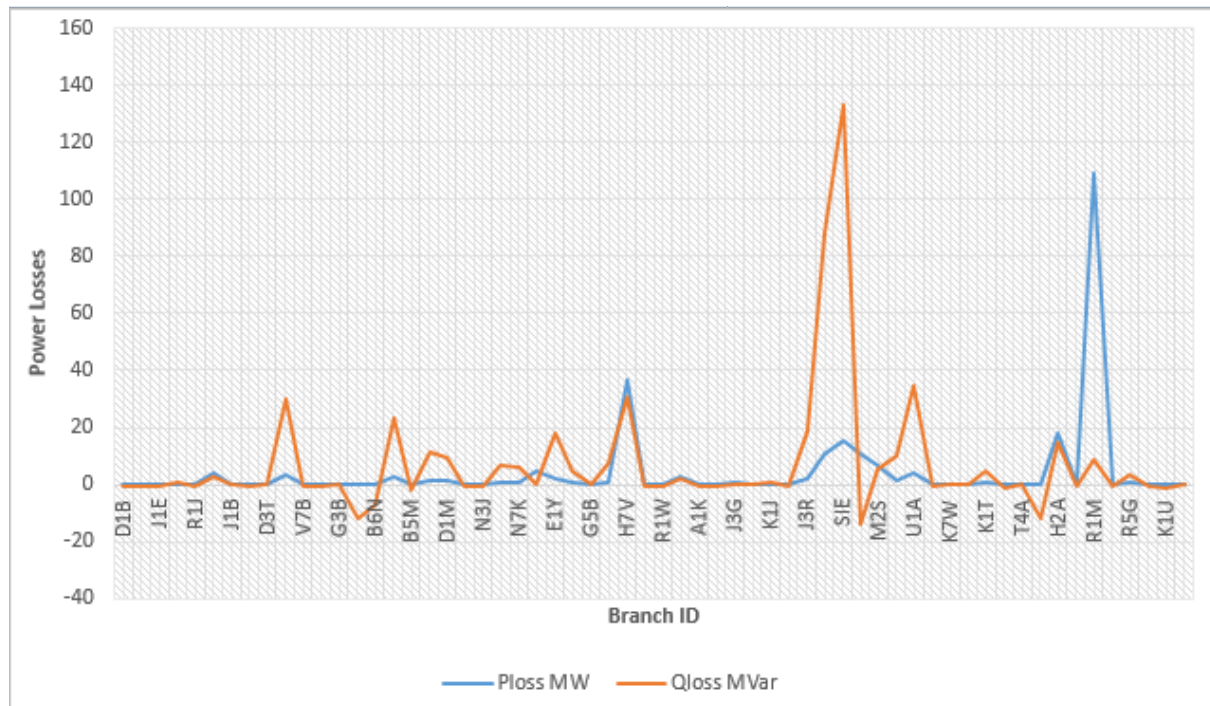


Figure 3. Real and reactive power loss distribution on the Nigerian 330 kV transmission network after SVC integration.

From Figure 3, the most critically overloaded lines in the base scenario R2A (Oloronsogo–Ayede, 196.82 %), R1W (177.91 %), H2A (Ayede–Oshogbo, 176.11 %), H7V (Ihovbor–Oshogbo, 166.54 %), T3H (Onitsha–New Heaven, 162.64 %), N7K (Egbin–Oke Aro, 151.66 %), N6W (Mando–Kubomtso 147.23 %), and SIE (Jos–Gombe 143.02 %) experienced substantial improvement after SVC integration. In the compensated network, the remaining overloaded elements are limited to H2A (Ayede–Oshogbo, 166.36 %), T3H (Onitsha–New Heaven, 147.57 %), H7V (Ihovbor–Oshogbo, 121.66 %), R2A (Oloronsogo–Ayede, 118.04 %), and N7K (Egbin–Oke Aro, 102.30 %). This demonstrates that the SVC devices effectively alleviated congestion on several key transmission corridors, particularly those linking the southwestern generation clusters (Egbin, Oloronsogo, and Ihovbor) to major northern and southeastern load centers. The cumulative network losses under the post-compensation condition amount to 244.30 MW of active power and 416.19 Mvar of reactive power, representing a significant reduction from the 388.33 MW and 980.82 Mvar recorded under the base case. These improvements reflect the SVCs’ capacity to minimize reactive circulation, improve voltage regulation, and lower resistive losses along long-distance transmission lines

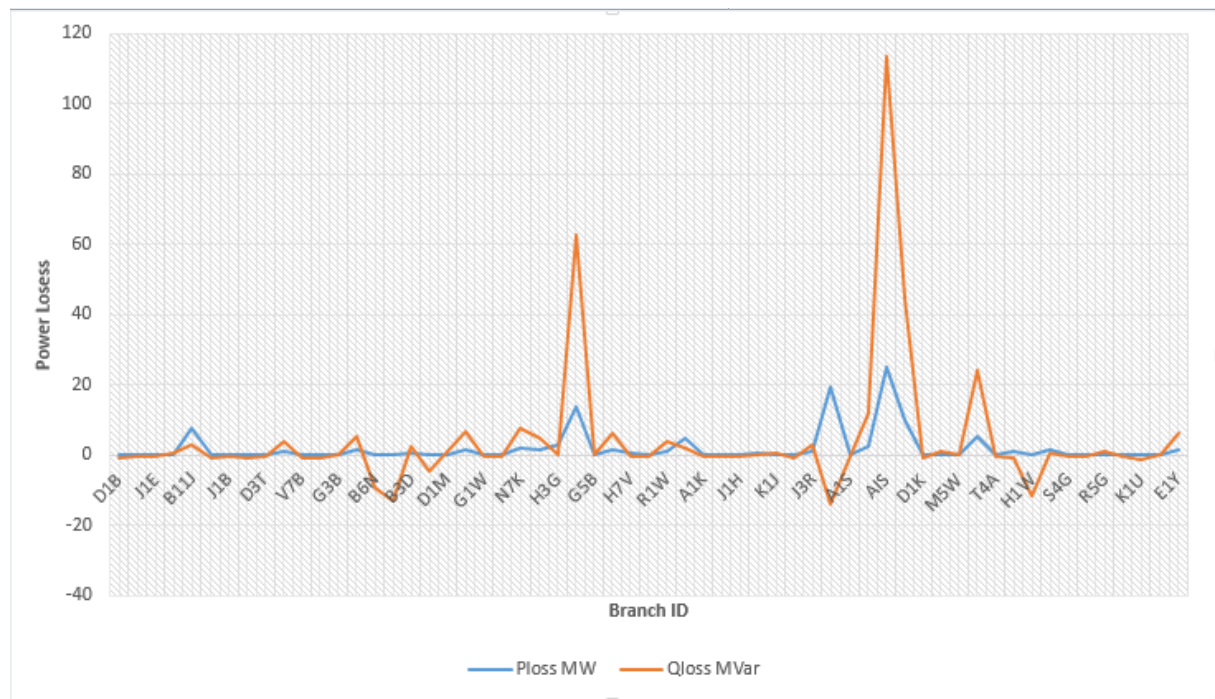


Figure 4. Real and reactive power loss distribution on the Nigerian 330 kV transmission network after TCSC integration.

From Figure 4, the most critically overloaded lines in the base scenario R2A (Oloronsogo–Ayede, 196.82 %), R1W (Oloronsogo-Ikeja West, 177.91 %), H2A (Ayede-Oshogbo, 176.11 %), H7V (Ihovbor-Oshogbo, 166.54 %), T3H (Onitsha-New Heaven, 162.64 %), N7K (Egbin-Oke Aro, 151.66 %), N6W (Mando-Kumbotso, 147.23 %), and SIE (Jos-Gombe, 143.02 %) experienced substantial improvement following TCSC integration. In the compensated network, the remaining overloaded elements were reduced to only T3H (Onitsha-New Heaven), operating at 164.7%, and K1T (Shiroro-Katampe), at 139.15% loading. This reflects a significant reduction in congestion across the grid, demonstrating the TCSCs' effectiveness in redirecting bulk power transfers and relieving stress on long-distance north–south and southwest–central transmission corridors.

The cumulative network losses under the post-compensation condition amount to 109.976 MW of active power and 252.234 Mvar of reactive power, representing a significant improvement compared to the base-case losses of 388.33 MW and 980.82 Mvar. These reductions reflect the TCSC's ability to enhance transmission efficiency by reducing excessive current flows, mitigating reactive power circulation, and minimizing resistive losses along compensated corridors.

4 Conclusion

This study investigated the effectiveness of Flexible AC Transmission Systems (FACTS), specifically the Static Var Compensator (SVC) and Thyristor-Controlled Series Capacitor (TCSC), in mitigating transmission congestion and improving the performance of Nigeria's 330 kV transmission network.

The base-case analysis recorded total active and reactive power losses of 388.33 MW and 980.82 Mvar, respectively, indicating significant transmission inefficiencies. Following SVC integration, active and reactive power losses decreased by 37.09% and 57.57%, respectively. TCSC integration achieved greater reductions of 71.68% in active power losses and 74.28% in reactive power losses. These

results demonstrate the effectiveness of both devices in improving transmission efficiency and mitigating congestion under the operating conditions investigated.

TCSC exhibited superior performance in reducing system losses, highlighting its potential for controlling power flows and relieving congestion along critical transmission corridors. Conversely, SVC remains valuable for reactive power compensation and voltage regulation. Therefore, the strategic deployment of FACTS devices offers a promising approach to enhancing the operational performance of Nigeria's 330 kV transmission network. Further studies incorporating voltage stability indices, bus-voltage profiles, contingency analysis, and economic evaluation are recommended to establish the optimal application of these devices under varying operating conditions.

References

- [1] Akinyele DO, Rayudu RK. Review of energy storage technologies for renewable energy integration and applications in Nigeria. *Renewable and Sustainable Energy Reviews*. 2019;81:1725–1737.
- [2] Abdelaziz AY, Mohamed ES, El-Metwally KA. Optimal power flow considering FACTS devices: A review. *International Journal of Electrical Power & Energy Systems*. 2020;1(7):105–104.
- [3] Kumar R, Sharma V. Congestion mitigation using UPFC in deregulated power systems. *IET Generation, Transmission & Distribution*. 2019;10(9):2261–2269.
- [4] Rajasekar S, Murthy CS. Particle swarm optimization-based TCSC placement in congested transmission networks. *Applied Soft Computing*. 2019;3(1):10–18.
- [5] Zhang L, Singh M, Khatod DK. TCSC placement for congestion mitigation using genetic algorithm. *Energy Reports*. 2019;5:103–112.
- [6] Abido MA. Power system stability enhancement using FACTS controllers: A review. *The Arabian Journal for Science and Engineering*. 2019;3(1):153–172.
- [7] Gupta A, Prakash R, Singh AK. Case study of coordinated FACTS deployment on India's 765 kV system for congestion alleviation. *International Journal of Electrical Power & Energy Systems*. 2023;149:108233. <https://doi.org/10.1016/j.ijepes.2023.108233>
- [8] Sankar S, Raju GK. Power system analysis: Modeling, simulation, and congestion management using Newton-Raphson and FDLF techniques. *International Journal of Electrical Engineering Education*. 2020;57(1):34–49.
- [9] Jain A, Singh SK. Comparative performance analysis of power flow algorithms for contingency evaluation. *Journal of Power System Simulation*. 2022;10(2):93–105.
- [10] Transmission Company of Nigeria (TCN).. *National grid infrastructure summary report*. TCN Planning and Expansion Unit. 2023.