ISA Journal of Engineering and Technology (ISAJET)

Homepage: https://isapublisher.com/isajet/

Volume 3, Issue 4, July-August, 2026 ISSN: 3049-1843

# Mitigating Voltage Drop Limitations in A Long-Distance Transmission Network: A Case Study of the Nigerian 48-Bus System

**Ogbodo Ikechukwu Ogbodo, Nwaogaidu Simeon Obinna, Egbonwonu Emmanuel livinus, Asanya Onyebuchi Nduka**

Electrical/Electronic Engineering Dept, State University of Medical and Applied Sciences, Igbo-Eno Enugu State Nigeria

***Received:*** *10.06.2026* | ***Accepted:*** *25.06.2026* | ***Published:*** *16.07.2026*

***Corresponding Author:** Ogbodo Ikechukwu Ogbodo

**DOI:** *10.5281/zenodo.21387763*

**Abstract** **Review Article**

Voltage drop remains one of the major operational challenges affecting long-distance transmission networks, particularly in developing power systems where generating stations are located far from major load centers. Excessive voltage drop leads to poor voltage regulation, increased transmission losses, reduced power transfer capability, and weakened system stability. This study investigates the application of the Thyristor Controlled Series Capacitor (TCSC) for mitigating voltage drop limitations in the Nigerian 48-bus transmission network. The Nigerian 330 kV grid was modeled as a 48-bus interconnected power system comprising generating stations, transmission substations, and load centers. Load flow simulation was carried out under two operating scenarios: without compensation and with TCSC integration. Bus voltage profiles and voltage drop indices were compared to evaluate the effectiveness of the device. The results showed that, under the uncompensated condition, several buses experienced significant undervoltage, with the most critical bus voltage recorded at 0.90321 p.u. After the installation of the TCSC, weak buses recorded noticeable voltage improvement, and the minimum bus voltage increased to 0.93048 p.u. Major weak buses such as Jos, Markurdi, Ikot Ekpene, Ugwuaji, and New Haven showed substantial recovery toward acceptable operating limits. The average network voltage drop decreased from 0.00962 p.u. to 0.00550 p.u., representing a 42.83% reduction. The improvement was achieved through the ability of the TCSC to reduce effective transmission line reactance, thereby minimizing reactive voltage losses and enhancing power transfer across long-distance corridors. The study concludes that TCSC is an effective and technically viable FACTS solution for improving voltage regulation, strengthening voltage stability, and enhancing transmission efficiency in the Nigerian power grid. Its deployment can provide a cost-effective alternative to network expansion while improving reliable electricity delivery to distant load centers.

**Index Terms:** Voltage Drop, TCSC, FACTS Devices, Nigerian 48-Bus System, Voltage Stability, Transmission Network, Load Flow Analysis.



## 1. Introduction

Electric power transmission systems are designed to transport bulk electrical energy from generating stations to load centers over long distances with high efficiency and acceptable voltage quality [3], [5], [21]. As power demand continues to grow, transmission networks are increasingly required to operate near their thermal and stability limits. In many developing countries, including Nigeria, the transmission grid spans vast geographical regions where generating stations are located far from major demand centers. This operating condition often results in significant voltage drop, poor voltage regulating, increased transmission losses, and reduced power transfer capability. Voltage drop is one of the major technical challenges in long-distance transmission networks [12]-[15]. It occurs mainly because of the impedance of transmission lines, particularly line reactance, which causes a reduction in receiving-end voltage as power is transmitted from source to load. When the voltage magnitude at load buses falls below acceptable operating limits, the consequences may include poor equipment performance, system instability, increased reactive power demand, and possible voltage collapse under stressed operating conditions. In the Nigeria transmission system, these problems are frequently observed due to long transmission corridors, inadequate reactive power compensation, transmission congestion, and continuous load growth.

The Nigerian national grid operates primarily through a 330 kV transmission backbone interconnecting generating plants, switching substations, and distribution supply points across the country [19], [20], [21]. Despite several expansions over the years, the grid still experiences voltage instability and inadequate power delivery to remote regions. Buses located far from generating stations often suffer low voltage profiles because power must travel through lengthy high-reactance transmission paths [23], [25]. This challenge makes the improvement of voltage profile and reduction of transmission voltage drop an important research and operational priority. Conventional methods of voltage control such as transformer tap changing, shunt capacitor banks, and network reinforcement have been widely used to improve system performance [1], [2], [4]. However, these approaches may be slow, limited in controllability, or capital intensive when applied to modern dynamic power systems. As a result, Flexible AC Transmission System (FACTS) devices have emerged as effective alternatives for enhancing transmission network performance through fast and controllable power flow regulation [6]-[9]. Among the available FACTS controllers, the Thyristor Controlled Series Capacitor (TCSC) has attracted considerable attention because of its ability to provide variable series compensation to transmission lines. The TCSC consists essentially of a fixed capacitor in parallel with a thyristor-controlled reactor, enabling smooth control of line reactance [10], [17], [22]. By reducing the effective series reactance of a transmission corridor, the TCSC increases power transfer capability, improves voltage regulation, dampens power oscillations, and enhances system stability margins. Its dynamic controllability makes it particularly suitable for long-distance transmission systems where voltage drop is a persistent challenge [24]. Several studies have reported the successful application of FACTS devices for improving power system voltage stability and loadability. However, the specific problem of voltage drop mitigation in the Nigeria 48-bus transmission network requires further investigation due to the network's unique geographical spread, loading characteristics, and operational constraints [11], [16], [18]. A detailed assessment of TCSC performance on this system is necessary to determine its suitability as a practical compensation strategy.

Therefore, this study focuses on the application of TCSC for mitigating voltage drop limitati0ns in a long-distance transmission network using the Nigerian 48-bus system as a case study. The network is modeled under steady-state operating conditions and analyzed using load flow simulation. Bus voltage profiles are evaluated before and after TCSC integration to determine the extent of improvement. The objective is to demonstrate how dynamic series compensation can reduce voltage drop, strengthen weak buses, and enhance the overall performance of the Nigerian transmission grid. The significance of this study lies in its contribution to practical solutions for improving transmission efficiency and voltage stability in developing power systems. The findings are expected to provide useful guidance for transmission planners, system operators, and policymakers seeking cost-effective technologies for modernizing the Nigeria electricity network.

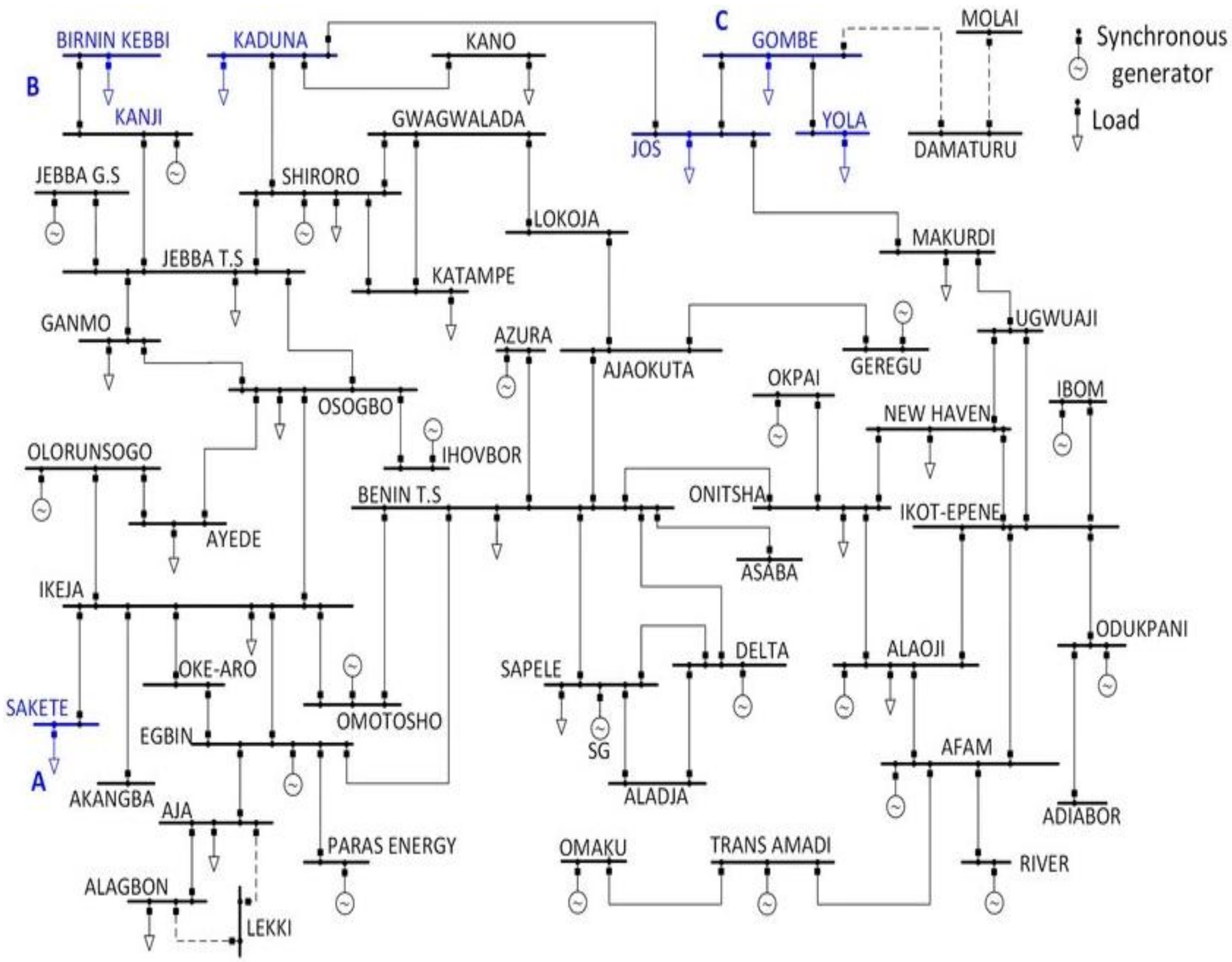


**Figure 1. Single-line diagram of the Nigerian transmission system.**

## 2. System Description and Problem Formulation

### 2.1. Study Network Description

The study is based on the Nigerian 330 kV transmission grid represented as a 48-bus interconnected power system. The network comprises major generating stations, transmission substations, and load centers distributed across different geographical regions of the country. The grid operates as a long-distance transmission system in which bulk electrical power is transferred from generation nodes—primarily located in the southern and central regions—to load centers spread across the northern and eastern regions. The system includes key generating stations such as Jebba, Kainji, Shiroro, Egbin, Delta, Afam, Sapele, and Geregu, which act as slack and PV buses, maintaining voltage magnitude and supplying active power to the network. The remaining buses function as load (PQ) buses where power demand is concentrated. Due to the extensive geographical spread and long transmission corridors, the network is characterized by high line reactance, making it susceptible to voltage drop and weak voltage profiles at remote buses.

To provide a clearer understanding of the system composition, a summary of the network characteristics is presented in Table 1.

**Table 1. Summary of Nigerian 48-Bus System Parameters**

| Parameter | Value |
|---|---|
| Number of Buses | 48 |
| Base Voltage | 330 kV |
| Base Power | 100 MVA |
| Number of Generatr Buses | 16 |
| Number of Load Buses | 32 |
| Transmission Line Type | Long-distance HVAC |
| Load Model | Constant Power (PQ) |

The transmission lines interconnecting these buses possess significant impedance, particularly reactance, which increases with distance. This results in substantial voltage drops as power flows through the network, especially under heavy loading conditions.

### 2.2. Voltage Profile Characteristics of the Network

In long-distance transmission systems, voltage magnitude tends to decrease progressively from the sending end to the receiving end due to reactive power losses. This effect is more pronounced in networks with insufficient reactive power compensation and high loading levels.

The bus voltage magnitude constraint for secure operation is typically given as:

$$0.95 \leq V_i \leq 1.05$$

Buses operating below the lower limit are considered weak and are prone to voltage instability. In the Nigerian grid, several buses fall below this threshold under uncompensated conditions, necessitating the need for corrective measures.

### 2.3. Problem Formulation

The primary problem addressed in this study is the mitigation of voltage drop in long-distance transmission lines. Voltage drop is mainly influenced by line impedance and current flow, and for a transmission line with impedance:

$$Z = R + jX \qquad (1)$$

Applying Kirchh0ff's Voltage Law (KVL) gives:

$$V_s = V_r + IZ \qquad (2)$$

Thus, the voltage drop across the line is:

$$\Delta V = I(R + jX) \qquad (3)$$

For high-voltage transmission systems where reactance dominates resistance (X≫R), the voltage drop simplifies to:

$$\Delta V \approx IX \qquad (4)$$

This relationship indicates that voltage drop is directly proportional to line reactance and current magnitude. Consequently, long transmission distances, which inherently increase reactance, lead to significant voltage reduction at receiving-end buses.

### 2.4. Reactive Power and Voltage Stability Constraint

Voltage stability in power systems is closely linked to reactive power balance. Insufficient reactive power support leads to declining voltage magnitudes and eventual instability. The power flow in a transmission line is governed by:

$$P = \frac{V_{\xi} V_r}{X} \sin \delta \qquad (5)$$

From this expression, it is evident that an increase in line reactance reduces the amount of transferable power, thereby worsening voltage conditions.

### 2.5. Need for Series Compensation

To mitigate voltage drop, it is necessary to reduce the effective reactance of transmission lines. This can be achieved using series compensation devices such as the Thyristor Controlled Series Capacitor (TCSC). The introduction of TCSC modifies the effective line reactance as follows:

$$X_{\text{eff}} = X_L - X_{\text{TCSC}} \qquad (6)$$

This leads to a corresponding reduction in voltage drop:

$$\Delta V_c = I(X_L - X_{\text{TCSC}}) \qquad (7)$$

The reduction in voltage drop due to TCSC is therefore:

$$\Delta V_{\text{red}} = I X_{\text{TCSC}} \qquad (8)$$

This formulation establishes that increasing the level of series compensation directly improves the receiving-end voltage magnitude.

### 2.6. Problem Statement

Based on the foregoing analysis, the core problem of this study can be stated as follows:

- ❖ The Nigerian 48-bus transmission network experiences significant voltage drop due to long transmission distances and high line reactance.
- ❖ Several buses operate below acceptable voltage limits, indicating weak voltage stability conditions.
- ❖ Conventional voltage control methods are insufficient to adequately address these issues in a dynamic and efficient manner.

Therefore, there is a need to investigate the application of controllable series compensation using TCSC to:

- ❖ Reduce transmission line reactance
- ❖ Minimize voltage drop across long-distance lines
- ❖ Improve voltage profile at weak buses
- ❖ Enhance overall system stability and power transfer capability

### 2.7. Analytical Framework

The study adopts a comparative analytical framework in which two scenarios are evaluated:

1. **Base Case (Uncompensated System)**
    - ➢ Original network without TCSC
    - ➢ Voltage drop and weak buses identified
2. **Compensated Case (With TCSC)**
    - ➢ TCSC integrated into selected transmission lines.
    - ➢ Improved voltage profile and reduced voltage drop evaluated.

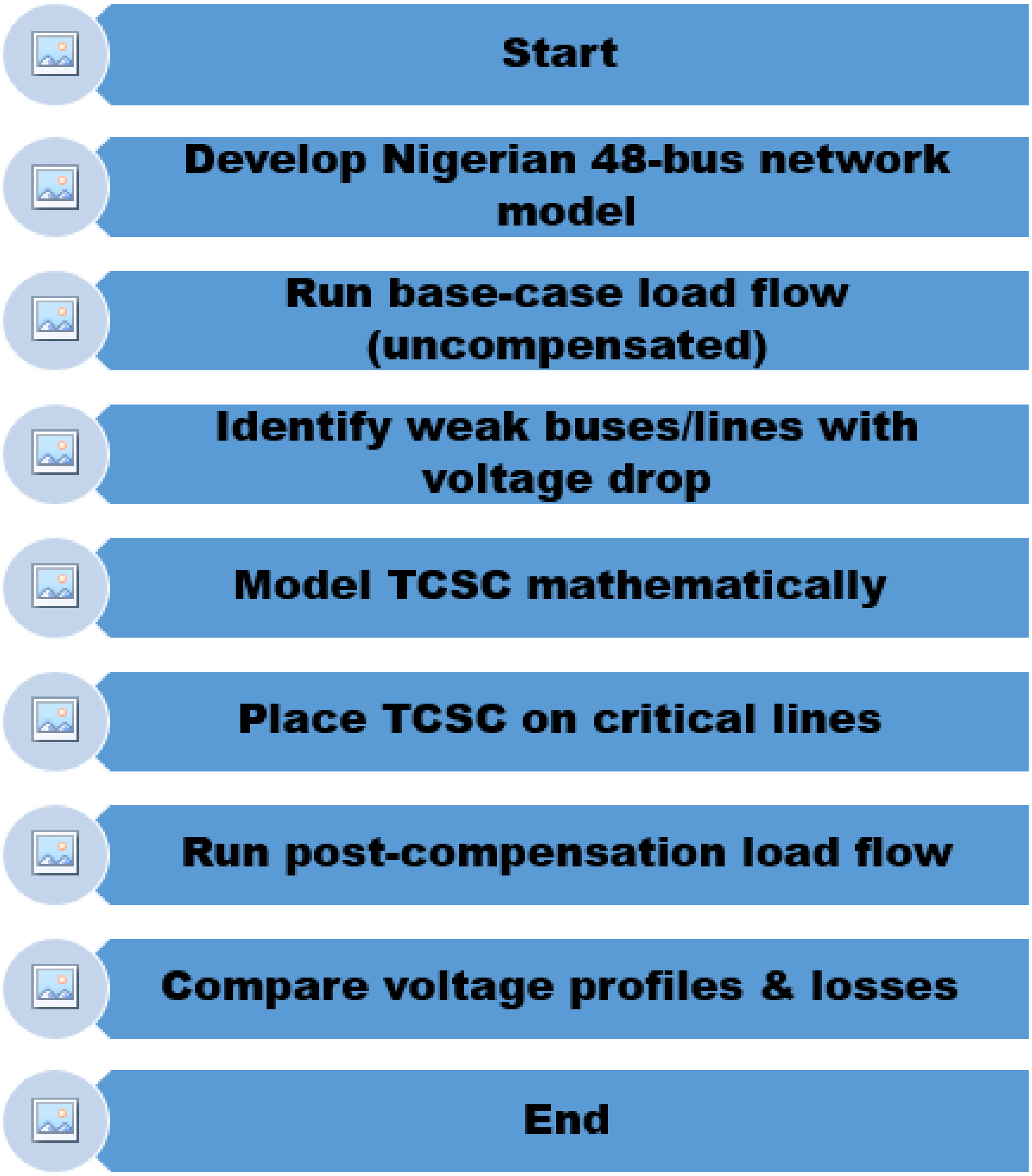


**Figure 2. Analytical framework for voltage drop mitigation`on using TCSC.**

## 3. Materials and Methods

The Materials and Methods involved modeling the Nigerian 48-bus long-distance transmission system, deriving voltage drop relations, integrating TCSC as a controllable series compensator, and evaluating its ability to reduce reactance-induced voltage drops. By lowering effective line reactance, TCSC improved bus voltages, reduced losses, and enhanced transmission efficiency across the Nigerian grid.

### 3.1. Design

The study adopted a simulation-based analytical research design. Load flow studies were performed on the uncompensated Nigerian 48-bus transmission system and compared with the compensated network after the installation of Thyristor Controlled Series Capacitor (TCSC) devices at selected weak transmission corridors.

The methodology involved:

- ❖ Development of the Nigerian 48-bus network model
- ❖ Base-case load flow analysis without compensation
- ❖ Identification of buses and lines with severe voltage drop
- ❖ Mathematical modeling of TCSC in series transmission lines
- ❖ Placement of TCSC on critical long-distance lines
- ❖ Post-compensation load flow analysis
- ❖ Comparison of voltage profiles before and after compensation

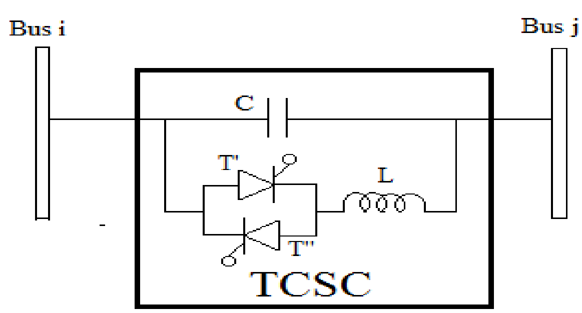


**Figure 3. Circuit Diagram of TCSC Connection in Power System**

### 3.2. Data Requirements

The network data used for the study include:

- ❖ Bus data (generation, load demand, voltage magnitude, angle)
- ❖ Transmission line parameters (resistance, reactance, susceptance)
- ❖ Transformer tap settings
- ❖ Generator reactive power limits
- ❖ Base voltage = 330 kV
- ❖ Base power = 100 MVA

### 3.3. Load Flow Solution Technique

The Newton-Raphson power flow algorithm was adopted due to its fast convergence speed and high accuracy for large-scale interconnected systems.

The active and reactive power mismatch equations are:

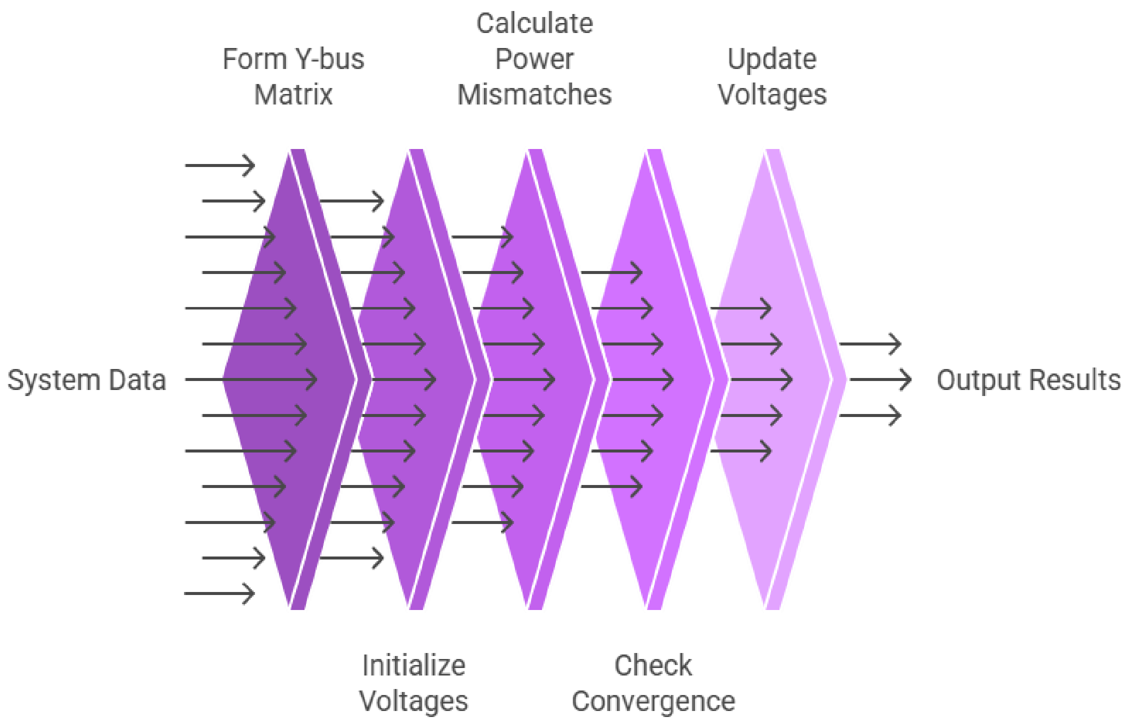


**Figure 4. Power Flow Calculation Process**

$$\Delta P_i = P_i^{spec} - P_i^{calc} \quad (9)$$

$$\Delta Q_i = Q_i^{spec} - Q_i^{calc} \quad (10)$$

Where:

- $P_i^{spec}$ = specified active power at bus iii
- $Q_i^{spec}$ = specified reactive power at bus iii
- $P_i^{calc}$ = calculated active power
- $Q_i^{calc}$ = calculated reactive power

The iterative process continues until the mismatch tolerance is satisfied.

### 3.4. Derivation of Voltage Drop Formula in Transmission Line

Consider a long transmission line represented by series impedance:

$$Z = R + jX \quad (11)$$

Let:

- Sending end voltage = $V_s$
- Receiving end voltage = $V_r$
- Line current = I

From Kirchhoff's voltage law:

$$V_s = V_r + IZ \quad (12)$$

Substituting impedance:

$$V_s = V_r + I(R + jX) \quad (13)$$

Hence:

$$V_s = V_r + IR + jIX \quad (14)$$

The voltage drop across the line is:

$$\Delta V = V_s - V_r \quad (15)$$

Therefore:

$$\Delta V = I(R + jX) \quad (16)$$

Magnitude approximation:

$$|\Delta V| = \sqrt{(IR)^2 + (IX)^2} \quad (17)$$

For high-voltage transmission systems where $X >>$

$R$:

$$\Delta V \approx IX \quad (18)$$

Thus, voltage drop is directly proportional to:

- Line current
- Transmission line reactance
- Transmission distance

Since long-distance lines possess high reactance, voltage drop becomes significant.

### 3.5. TCSC Mathematical Model

The Thyristor Controlled Series Capacitor (TCSC) is a FACTS device consisting of:

- Fixed series capacitor
- Thyristor Controlled Reactor (TCR)

It provides controllable capacitive reactance inserted in series with the transmission line.

If 0riginal line reactance is:

$$X_L$$

And TCSC reactance is:

$$X_{TCSC}$$

Then the effective reactance becomes:

$$X_{eff} = X_L - X_{TCSC} \quad (19)$$

$Where$:

$$0 < X_{TCSC} < X_L$$

#### 3.5.1. Effect of TCSC on Voltage Drop Reduction

Original uncompensated voltage drop:

$$\Delta V_o = IX_L \quad (20)$$

With TCSC compensation:

$$\Delta V_c = I(X_L - X_{TCSC}) \quad (21)$$

Therefore:

$$\Delta V_c < \Delta V_o \quad (22)$$

Voltage drop reduction:

$$\Delta V_{red} = IX_{TCSC} \quad (23)$$

Percentage reduction:

$$\% \text{ Reduction } = \frac{X_{TCSC}}{X_L} \times 100 \quad (24)$$

This shows that as TCSC compensation increases, line reactance decreases, resulting in improved receiving-end voltage.

#### 3.5.2. Power Transfer Enhancement by TCSC

The real power transmitted over a line is:

$$P = \frac{V_s V_r}{X} \sin\delta \quad (25)$$

After TCSC installation:

$$P_c = \frac{V_s V_r}{X_L - X_{TCSC}} \sin\delta \quad (26)$$

Since denominator reduces:

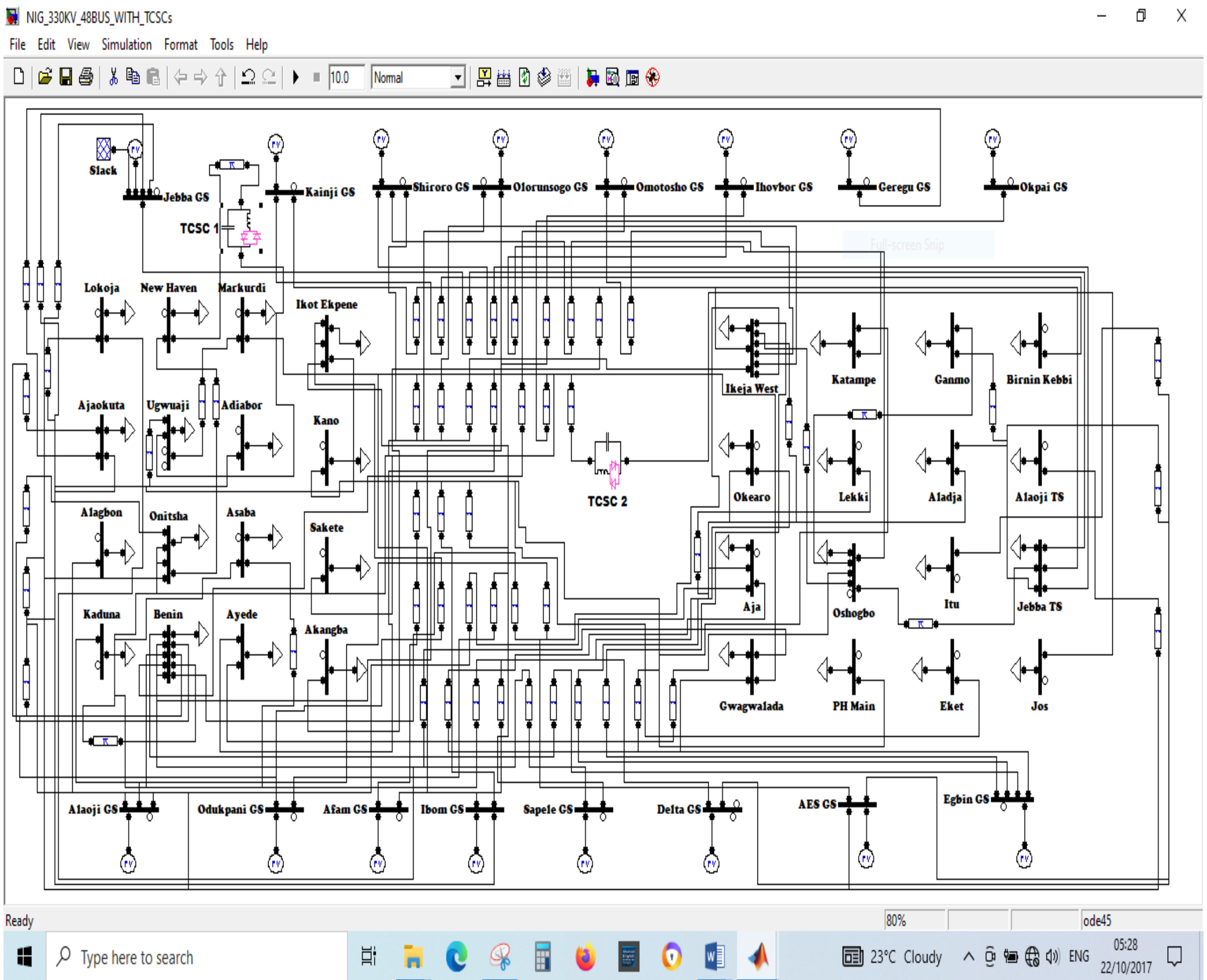


**Figure 5. TCSCs Integrated at New Haven/Ugwuaji line and Markurdi/Jos line**

$$P_c > P$$

Hence TCSC improves both:

- Voltage profile
- Transmission capacity
- Stability margin

### 3.6. TCSC Placement Procedure

TCSC devices were installed on lines satisfying one or more of the following criteria:

- Highest voltage drop
- High line reactance
- Low receiving-end bus voltage (< 0.95 p.u.)
- Heavy power flow congestion
- Long transmission distance

Candidate lines in the Nigerian network were ranked using Voltage Stability Index (VSI) and sensitivity analysis.

### 3.7. Simulation Steps

1. Run base-case load flow on 48-bus system
2. Record weak bus voltages and line drops
3. Select candidate lines for TCSC placement

4. Introduce variable TCSC compensation levels (10%–70%)
5. Re-run load flow for each case
6. Compare results

### 3.8. Performance Indices Evaluated

The following indices were used:

**Voltage Deviation Index**

$VDI = \sum|1.0 - V_i|$ (27) MATLAB was preferred for flexible TCSC modeling and iterative optimization.

### 3.9. Validation of Results

The effectiveness of CSC was validated by comparing:

- Minimum bus voltage before and after compensation
- Total voltage deviation reduction
- Improved stability margin

## 4. Results and Discussions

The load flow simulation results obtained for the Nigerian 48-bus transmission network under the two operating scenarios, namely without TCSC and with TCSC compensation, are presented in Table 2 and Figure 6 to 9. The results clearly demonstrate the influence of the Thyristor Controlled Series Capacitor on the voltage performance of the long-distance transmission grid.

Under the uncompensated condition, several buses experienced noticeable voltage depression below the acceptable operating range of 0.95–1.05 p.u., indicating weak voltage support and the adverse effect of long transmission distances. The most critical buses were Bus 48 (Jos), Bus 25 (Markurdi), Bus 29 (Ikot Ekpene), Bus 22 (Ugwuaji), and Bus 21 (New Haven), with voltage magnitudes of 0.90321 p.u., 0.92417 p.u., 0.92573 p.u., 0.92710 p.u., and 0.94049 p.u., respectively. These values correspond to voltage drops of 0.09679 p.u., 0.07583 p.u., 0.07427 p.u., 0.07290 p.u., and 0.05951 p.u. The results indicate that these buses were electrically weak and highly susceptible to undervoltage problems due to heavy loading and their distance from major generation sources.

**Table 2. Comparison of the Bus Voltage Profiles for the Different Scenarios**

| | | Without TCSC | | With TCSC | |
|---|---|---|---|---|---|
| **Bus No** | **Bus Name** | **Bus voltage (PU)** | **Voltage Drop (PU)** | **Bus voltage (PU)** | **Voltage Drop (PU)** |
| 1 | Jebba GS | 1 | 0.00000 | 1 | 0.00000 |
| 2 | Kainji GS | 1 | 0.00000 | 1 | 0.00000 |
| 3 | Shiroro GS | 1 | 0.00000 | 1 | 0.00000 |
| 4 | Olorunsogo GS | 1 | 0.00000 | 1 | 0.00000 |
| 5 | Omotosho GS | 1 | 0.00000 | 1 | 0.00000 |
| 6 | Ihovbor GS | 1 | 0.00000 | 1 | 0.00000 |

| | | | | | |
|---|---|---|---|---|---|
| 7 | Geregu GS | 1 | 0.00000 | 1 | 0.00000 |
| 8 | Okpai GS | 1 | 0.00000 | 1 | 0.00000 |
| 9 | Alaoji GS | 1 | 0.00000 | 1 | 0.00000 |
| 10 | Odukpani GS | 1 | 0.00000 | 1 | 0.00000 |
| 11 | Afam GS | 1 | 0.00000 | 1 | 0.00000 |
| 12 | Ibom GS | 1 | 0.00000 | 1 | 0.00000 |
| 13 | Sapele GS | 1 | 0.00000 | 1 | 0.00000 |
| 14 | Delta GS | 1 | 0.00000 | 1 | 0.00000 |
| 15 | AES GS | 1 | 0.00000 | 1 | 0.00000 |
| 16 | Egbin GS | 1 | 0.00000 | 1 | 0.00000 |
| 17 | Lokoja | 0.99809 | 0.00191 | 0.99812 | 0.00188 |
| 18 | Ajaokuta | 0.99686 | 0.00314 | 0.99689 | 0.00311 |
| 19 | Alagbon | 1.0003 | -0.00030 | 1.00032 | -0.00032 |
| 20 | Kaduna | 1.00005 | -0.00005 | 1.00007 | -0.00007 |
| 21 | New Haven | 0.94049 | 0.05951 | 0.96777 | 0.03223 |
| 22 | Ugwuaji | 0.9271 | 0.07290 | 0.95438 | 0.04562 |
| 23 | Onitsha | 0.95994 | 0.04006 | 0.98721 | 0.01279 |
| 24 | Benin | 0.9924 | 0.00760 | 1.0015 | -0.00150 |
| 25 | Markurdi | 0.92417 | 0.07583 | 0.95145 | 0.04855 |
| 26 | Adiabor | 1.00005 | -0.00005 | 1.00007 | -0.00007 |
| 27 | Asaba | 0.97616 | 0.02384 | 1.00041 | -0.00041 |
| 28 | Ayede | 0.99981 | 0.00019 | 0.99983 | 0.00017 |
| 29 | Ikot Ekpene | 0.92573 | 0.07427 | 0.953 | 0.04700 |
| 30 | Kano | 1.00005 | -0.00005 | 1.00007 | -0.00007 |
| 31 | Sakete | 0.99866 | 0.00134 | 0.99868 | 0.00132 |
| 32 | Akangba | 0.99866 | 0.00134 | 0.99868 | 0.00132 |
| 33 | Ikeja West | 0.99861 | 0.00139 | 0.99863 | 0.00137 |
| 34 | Okearo | 0.99935 | 0.00065 | 0.99938 | 0.00062 |
| 35 | Aja | 1.00025 | -0.00025 | 1.00027 | -0.00027 |
| 36 | Gwagwalada | 0.9993 | 0.00070 | 0.99932 | 0.00068 |

| | | | | | |
|---|---|---|---|---|---|
| 37 | Katampe | 0.99969 | 0.00031 | 0.99972 | 0.00028 |
| 38 | Lekki | 1.0003 | -0.00030 | 1.00032 | -0.00032 |
| 39 | Oshogbo | 0.99953 | 0.00047 | 0.99956 | 0.00044 |
| 40 | PH Main | 1.00005 | -0.00005 | 1.00007 | -0.00007 |
| 41 | Ganmo | 0.99963 | 0.00037 | 0.99965 | 0.00035 |
| 42 | Aladja | 1.00005 | -0.00005 | 1.00007 | -0.00007 |
| 43 | Itu | 1.00005 | -0.00005 | 1.00007 | -0.00007 |
| 44 | Eket | 1.00005 | -0.00005 | 1.00007 | -0.00007 |
| 45 | Birnin Kebbi | 1.00005 | -0.00005 | 1.00007 | -0.00007 |
| 46 | Alaoji TS | 1.00005 | -0.00005 | 1.00007 | -0.00007 |
| 47 | Jebba TS | 0.99971 | 0.00029 | 0.99973 | 0.00027 |
| 48 | Jos | 0.90321 | 0.09679 | 0.93048 | 0.06952 |
| | **AVERAGE** | | 0.00962 | | 0.00550 |

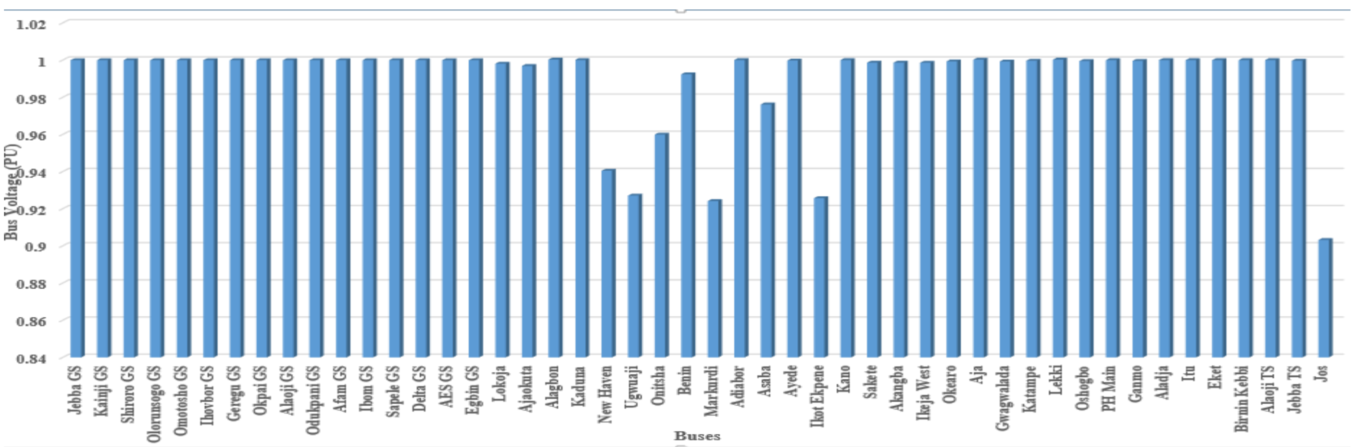


**Figure 6. Bus Voltage Profile without TCSC**

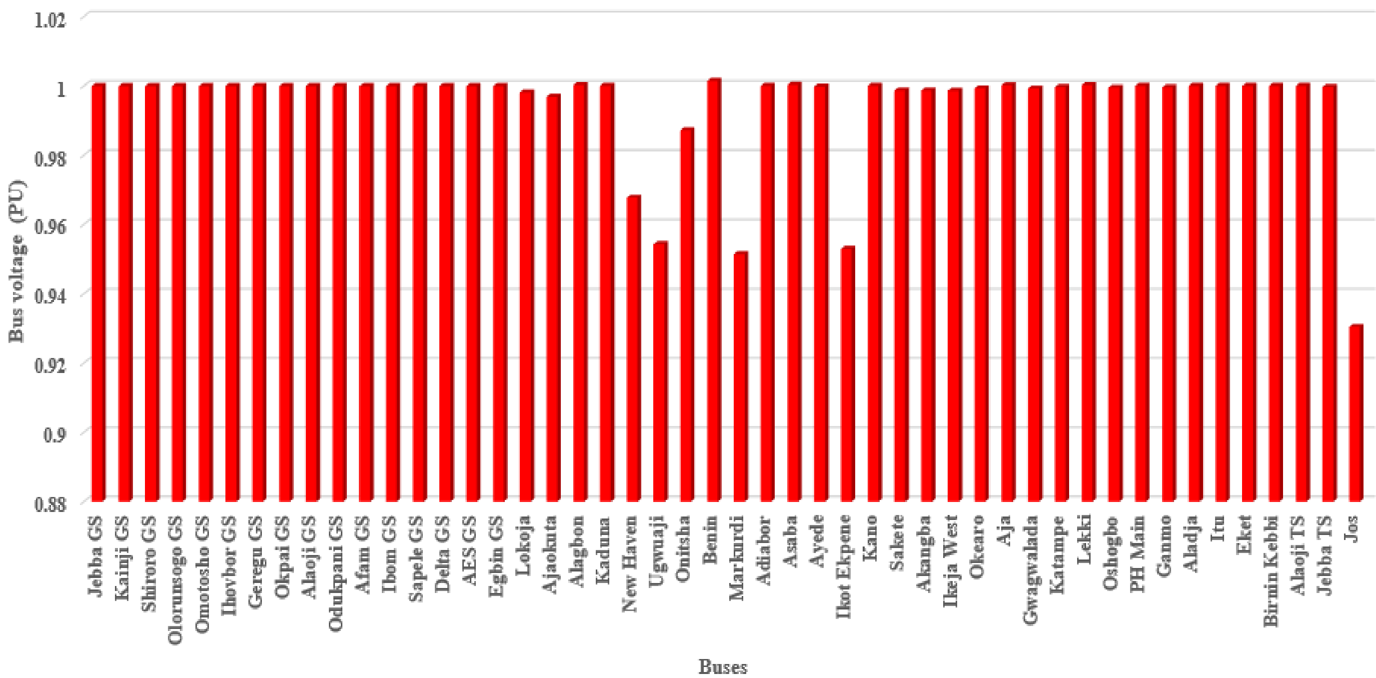


**Figure 7. Bus Voltage Profile with TCSC**

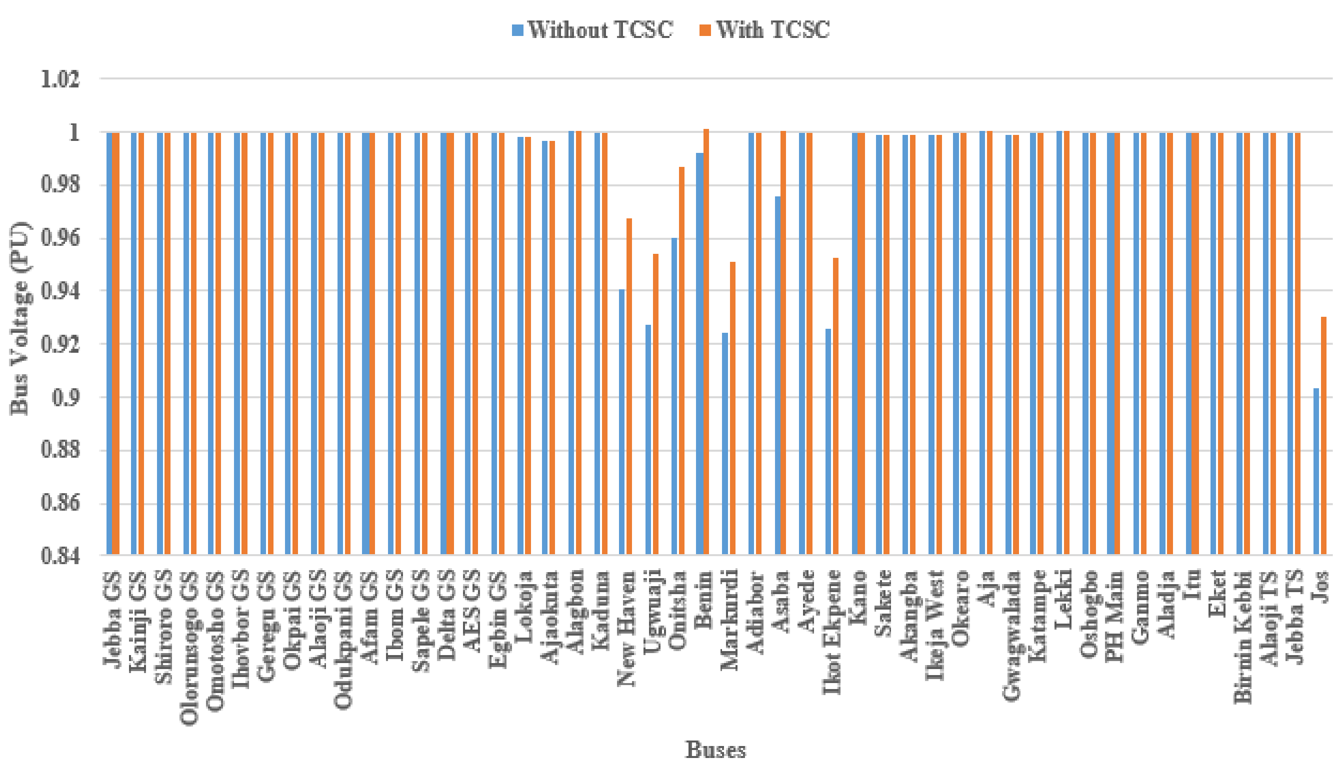


**Figure 8. Comparison of Voltage profile without and with the TCSC Integrated.**

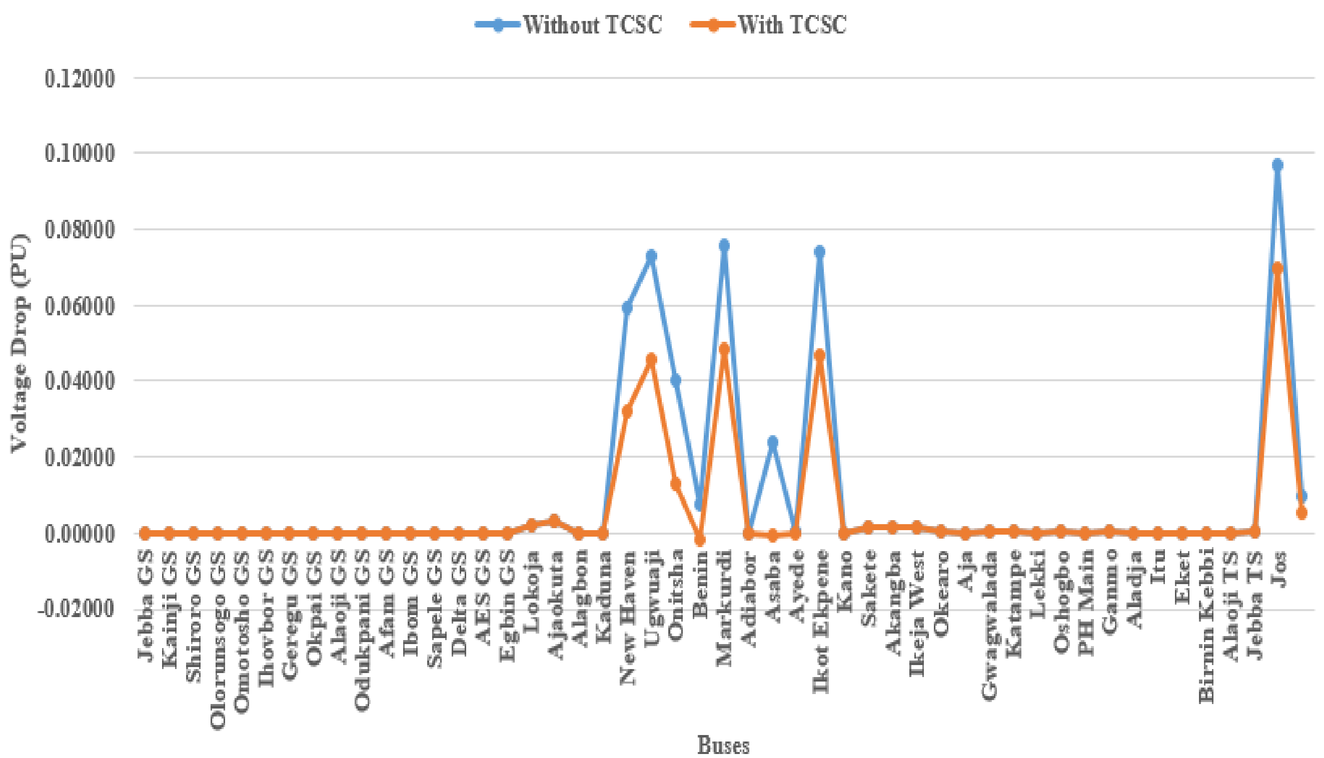


**Figure 9. Comparison of voltage drop without and with the TCSC integrated**

After integrating the TCSC into the selected transmission corridor, significant improvement in the bus voltage magnitudes was observed throughout the network. The weakest bus, Jos, improved from 0.90321 p.u. to 0.93048 p.u., while its voltage drop reduced from 0.09679 p.u. to 0.06952 p.u. Similarly, Markurdi increased from 0.92417 p.u. to 0.95145 p.u., thereby moving into the acceptable voltage stability region. Ikot Ekpene improved from 0.92573 p.u. to 0.95300 p.u., Ugwuaji rose from 0.92710 p.u. to 0.95438 p.u., and New Haven increased from 0.94049 p.u. to 0.96777 p.u. These results confirm that the TCSC effectively restored depressed voltages at weak load buses. The improvement can be attributed to the series compensation effect of the TCSC, which reduces the effective transmission line reactance. Since voltage drop in a transmission line is directly proportional to line reactance and current magnitude, decreasing reactance lowers the reactive voltage loss along the corridor. This enables more efficient transfer of active and reactive power to distant load centers and enhances receiving-end voltage magnitude. The results also show that buses with already satisfactory voltages experienced minor positive changes. For instance, Bus 24 (Benin) improved from 0.99240 p.u. to 1.00150 p.u., while Bus 27 (Asaba) rose from 0.97616 p.u. to 1.00041 p.u. These buses moved closer to the nominal 1.0 p.u. operating point. Such improvements indicate that the benefits of TCSC were not limited only to critical buses but extended to surrounding interconnected buses through improved power flow redistribution. Generator buses and strongly regulated buses such as Jebba GS, Kainji GS, Shiroro GS, Olorunsogo GS, Omotosho GS, Egbin GS, and other major generation nodes remained at approximately 1.0 p.u. in both scenarios. This is expected because generator buses are voltage-controlled buses with automatic excitation systems that maintain scheduled voltage magnitudes. The average network voltage drop reduced from 0.00962 p.u. in the uncompensated case to 0.00550 p.u. after TCSC installation. The percentage reduction in average voltage drop was calculated as:

$$\frac{0.00962 - 0.00550}{0.00962} \times 100 = 42.83\%$$

This substantial reduction confirms the overall effectiveness of the TCSC in mitigating voltage drop limitations across the Nigerian transmission system. Figure 9, which compares the voltage drop values for both scenarios, illustrates a clear downward trend in voltage drop after compensation, particularly at the weak buses. Figure 8 similarly shows that the voltage profile curve shifted upward after TCSC integration, with more buses operating near the nominal voltage level. This reflects improved voltage regulation, stronger system stability margin, and enhanced service reliability. From an operational perspective, the improved voltage profile implies reduced risk of voltage collapse, lower transmission losses, better utilization of existing transmission assets, and increased ability to supply remote load centers without constructing new lines. This is particularly relevant for the Nigerian grid, where long transmission distances between generating stations and major demand centers often create voltage instability challenges.

The findings therefore validate the technical suitability of TCSC as an effective FACTS-based solution for long-distance transmission systems. By dynamically controlling line reactance, the device significantly enhanced voltage stability and reduced average system voltage drop by 42.83%, making it a practical option for strengthening the Nigerian 48-bus transmission network.

## 5. Conclusion

This study investigated the application of the Thyristor Controlled Series Capacitor (TCSC) for mitigating voltage drop limitations in the Nigerian 48-bus long-distance transmission network. The results obtained from load flow simulation demonstrated that the uncompensated network experienced significant voltage depression at several load buses, particularly at remote locations such as Jos, Markurdi, Ikot Ekpene, Ugwuaji, and New Haven. These undervoltage conditions confirmed the operational challenges associated with long transmission distances, high line reactance, and insufficient reactive power support within the Nigerian grid. Following the integration of the TCSC, substantial improvement was achieved in the overall voltage profile of the network. Weak buses recorded noticeable increases in voltage magnitude, while the average system voltage drop reduced from 0.00962 p.u. to 0.00550 p.u., representing a 42.83% reduction. The compensation also shifted several buses from undervoltage conditions to acceptable operating limits, thereby strengthening system reliability and stability.

The study established that the performance improvement resulted from the ability of the TCSC to dynamically reduce effective transmission line reactance, thereby minimizing reactive voltage losses and enhancing power transfer capability. In addition to voltage support, the device contributed to better utilization of the existing transmission infrastructure without the immediate need for costly network expansion. It can therefore be concluded that TCSC is an effective and technically viable FACTS solution for improving voltage regulation in long-distance transmission systems such as the Nigerian 48-bus network. Its deployment would enhance grid stability, improve service delivery to distant load centers, and support the growing demand for reliable electric power in Nigeria. Future studies may consider optimal sizing and placement of multiple TCSC units under contingency and renewable energy integration scenarios for further network performance enhancement.

## References

[1] B. Bhattacharyya and S. Kumar, "Loadability enhancement with FACTS devices using gravitational search algorithm," *Int. J. Electr. Power Energy Syst.*, vol. 78, pp. 470–479, Jun. 2016, doi: 10.1016/j.ijepes.2015.11.114.

[2] G. Gokulakrishnan and V. Ramesh, "MFFA Based Optimal Location and Capacity of UPFC for Improving the Loadability of Power System," *WSEAS Trans. Power Syst.*, vol. 13, pp. 165–173, 2018.

[3] H. Johal and D. Divan, "Distributed FACTS—A New Concept for Realizing Grid Power Flow

Control," *IEEE Trans. Power Electron.* vol. 22, no. 6, pp. 2253–2260, Nov. 2007.

[4] M. L. Kothari and S. Ande, "Optimization of unified power flow controllers (UPFC) using GEA," in *Proc. IEEE Power Eng. Conf. (IPEC)*, Singapore, 2007, pp. 53–58.

[5] N. Mithulananthan, A. Sode-Yome, and N. Acharya, "Comparison of shunt capacitor, SVC and STATCOM in static voltage stability margin enhancement," *Int. J. Electr. Eng. Educ.*, vol. 41, no. 3, pp. 1–6, 2004.

[6] S. A. Nabavi-Niaki, A. Lashkar-Ara, and M. Kefayat, "A hybrid of ant colony optimization and artificial bee colony algorithm for probabilistic optimal placement and sizing of distributed energy resources," *Energy Convers. Manage.*, vol. 92, pp. 149–161, Mar. 2015.

[7] S. O. Okozi, P. C. Chukwudi, M. Olubiwe, and K. C. Obute, "Reliability Assessment of Nigerian Power Systems Case Study of 330kv Transmission Lines in Benin Sub – Region," *Int. J. Eng. Res. Technol. (IJERT)*, vol. 7, no. 3, 2018.

[8] B. Singh, R. P. Payasi, and V. Shukla, "A taxonomical review on impact assessment of optimally placed DGs and FACTS controllers in power systems," *Energy Rep.*, vol. 3, pp. 94–108, Nov. 2017, doi: 10.1016/j.egyr.2017.07.001.

[9] K. Sreerenjini and C. P. S. Nizamoni, "Increasing the Loadability of Power System Network using DSTATCOM," *Int. J. Eng. Res. Technol. (IJERT)*, vol. 12, no. 8, 2019.

[10] K. P. Wong, C. Y. Chung, and H. R. Cai, "Application of differential evolution algorithm for transient stability constrained optimal power flow," *IEEE Trans. Power Syst.*, vol. 23, no. 2, pp. 719–728, May 2008.

[11] M. B. Ali *et al.*, "Voltage Profile Improvement by Integrating Renewable Resources with Utility Grid," *Energies*, vol. 15, no. 22, p. 8561, 2022.

[12] E. Aneke and A. Engla, "Enhancing the voltage stability of the Nigerian 330kv 48-bus power system network using modal/eigenvalue analysis," *Int. J. Eng. Res. Dev.*, vol. 9, no. 7, pp. 31–46, 2019.

[13] E. Aneke, E. Okafor, and J. Iyidobi, "Improving the Voltage Stability of the Nigeria 44-Bus 330KV Power Transmission Network using ANN Based Adaptive STATCOM Device," *Int. J. Adv. Eng. Res. Sci.*, vol. 8, no. 8, 2021.

[14] L. Han, J. Yin, L. Wu, L. Sun, and T. Wei, "Research on Reactive Power Compensation Control Strategy of Flexible On-Load Voltage Regulator," *Energies*, vol. 15, no. 17, p. 6193, 2022.

[15] X. Liang *et al.*, "Improved Hybrid Reactive Power Compensation System Based on FC and STATCOM and Its Control Method," *Chin. J. Electr. Eng.*, vol. 8, no. 2, pp. 29–41, Jun. 2022.

[16] N. W. Ndlela and I. E. Davidson, "Network Coordination between High Voltage DC and High-Voltage AC Transmission Systems Using Flexible AC Transmission System Controllers," *Energies*, vol. 15, no. 19, p. 7402, 2022.

[17] M. Priyadarshini and M. Sushama, "Performance of Static VAR Compensator for Changes in Voltage Due to Sag and Swell," in *Innovations in Electrical and Electronics Engineering*, Springer, 2020, pp. 225–233.

[18] H. Tariq *et al.*, "Comparative analysis 0f reactive power compensation devices in a real electric substation," *Energies*, vol. 15, no. 12, p. 4453, 2022.

[19] D. Sen, S. R. Ghatak, and P. Acharjee, "Optimal allocation of static VAR compensator by a hybrid algorithm," *Energy Syst.*, vol. 10, no. 3, pp. 677–719, 2019.

[20] D. Gaur and L. Mathew, "Optimal placement of FACTS devices using optimization techniques: A review," *IOP Conf. Ser.: Mater. Sci. Eng.*, vol. 331, no. 1, p. 012023, 2018.

[21] A. Das, S. Dawn, and S. Gope, "A Review on Optimal Placement 0f FACTS Devices," *Int. J. Comput. Intell. IoT*, vol. 2, no. 3, 2019.

[22] B. V. Kumar and V. Ramaiah, "Enhancement of dynamic stability by optimal location and capacity of UPFC: A hybrid approach," *Energy*, vol. 190, p. 116464, 2020.

[23] A. Rajan, K. Jeevan, and T. Malakar, "Weighted elitism based Ant Lion Optimizer to solve optimum VAr planning problem," *Appl. Soft Comput.*, vol. 55, pp. 352–370, 2017.

[24] S. Kamel and H. Youssef, "Voltage Stability Enhancement Based on Optimal Allocation of Shunt Compensation Devices Using Lightning Attachment Procedure Optimization," *Int. J. Interact. Multimed. Artif. Intell.*, vol. 5, no. 7, pp. 125–134, 2019.

[25] R. Rao, "Rao algorithms: Three metaphor less simple algorithms for solving optimization problems," *Int. J. Ind. Eng. Comput.*, vol. 11, no. 1, pp. 107–130, 2020.

[26] H. N. Ikeli, "A Critical Analysis of Transient Stability of Electrical Power System: A Case Study of Nigerian 330kv Power System," M. Eng. thesis, Dept. Electr. Eng., Univ. Nigeria, Nsukka, 2019.