

Enhancing Surge Impedance Loading (SIL) as a Metric for Transmission Line Capacity Improvement using UPFC

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Abstract

The increasing demand for electrical energy and the limitations of existing transmission infrastructure have made transmission capacity enhancement an important objective in modern power systems. This study investigates the enhancement of Surge Impedance Loading (SIL) as a metric for transmission line capacity improvement through the application of a Unified Power Flow controller (UPFC) on selected weak transmission corridors of the Nigerian 330 kV power network. SIL was adopted as the principal performance index because it represents the natural loading capability of a transmission line under balanced reactive power conditions. A mathematical formulation of SIL was developed from the transmission line surge impedance relationship, while the UPFC was modeled as a combined shunt-series Flexible AC Transmission System (FACTS) controller capable of voltage regulation, reactive power compensation, and power flow control. Comparative simulations were carried out for transmission lines with initial SIL values below 382.1053 MW under uncompensated and UPFC-Compensated conditions. The results showed that the total SIL of the studied network increased from 4274.427 MW to 4448.370 MW after UPFC integration, corresponding to an overall improvement of 4.0694%. Significant line-by-line enhancements were also recorded on major corridors such as Onitsha/New Haven, Onitsha/Alaoji, New Haven/Ugwuaji, Ikot Ekpene/Ugwuaji, Makurdi/Jos, and Ugwuaji/Makurdi. Several lines attained or exceeded the benchmark SIL threshold following compensation. The findings demonstrate that the UPFC is highly effective

for improving transmission loadability, voltage stability, and utilization of existing grid assets. The study concludes that UPFC deployment offers a practical and economically attractive approach for strengthening the Nigerian transmission system and meeting future electricity demand without immediate large-scale network expansion.

Keywords

FACTS, Nigerian 330 kV network, SIL enhancement, Transmission capacity, UPFC, Voltage stability.

1. Introduction

Electric power transmission networks are expected to deliver increasing amounts of electrical energy from generating stations to load centers in a reliable, stable, and economical manner [3], [9], [15]. In many developing countries, including Nigeria, rapid population growth, industrial expansion, and urbanization have led to continuous growth in electricity demand. However, expansion of transmission infrastructure has not always kept pace with this demand, resulting in overloaded lines, voltage instability, high transmission losses, and operational constraints [17]-[19]. As a result, improving the capacity of existing transmission corridors has become a major priority in modern power system planning and operation. One of the most important indices used in evaluating the natural loading capability of a transmission line is the Surge Impedance Loading (SIL) [2], [6], [10]. SIL is defined as the loading level at which the reactive power generated by the shunt capacitance of a transmission line is equal to the reactive power absorbed by its series inductance [1], [22]-[24]. At this operating point, the line neither supplies nor consumes

net reactive power. SIL therefore serves as a useful benchmark for determining the efficient utilization of transmission lines. When a line operates below its SIL, it tends to generate reactive power, while operation above SIL causes the line to absorb reactive power and experience voltage drops [4], [5], [7]. Consequently, increasing SIL provides an opportunity to transmit more active power while maintaining acceptable voltage performance and system stability. For a three-phase transmission line, SIL depends mainly on the system voltage level and the surge impedance of the line. Since surge impedance is influenced by the line inductance and capacitance, any technology capable of modifying these effective parameters or regulating voltage magnitude can improve the transmission loading capability [8]. Traditional approaches to increasing transmission capacity often involve construction of new transmission lines, substations, or network reinforcements. However, such solutions require high capital investment, long implementation time, environmental approvals, and right-of-way acquisition [11]-[13]. Therefore, utilities increasingly seek advanced technologies that can maximize the use of existing infrastructure.

Flexible AC Transmission System (FACTS) devices have emerged as effective tools for enhancing the performance of power transmission networks. FACTS controllers employ modern power electronics to provide fast and controllable regulation of voltage, impedance, phase angle, and reactive power flow [14], [16], [20]. By improving these operating variables, FACTS devices can increase line loadability, enhance voltage stability, reduce losses, and relieve congestion. Among the available FACTS devices, the Unified Power Flow Controller (UPFC) is widely recognized as one of the most versatile and powerful controllers. The UPFC combines the functions of both shunt and series compensation in a single device through two voltage source converters connected by a common DC link. The shunt converter operates similarly to a Static Synchronous Compensator (STATCOM), supplying or absorbing reactive power to regulate bus voltage [2], [21]. The series converter injects a controllable voltage in series with the transmission line, thereby modifying effective line impedance and

controlling real and reactive power flow. Through simultaneous control of voltage magnitude, line reactance, and phase angle, the UPFC can substantially improve transmission line capacity and system security.

The Nigerian 330 kV transmission grid forms the backbone of bulk power transfer across the country, interconnecting generating stations, switching substations, and major load centers [5]-[8]. Despite its strategic importance, the network is characterized by long transmission distances, regional loading imbalances, voltage weakness in some corridors, and increasing stress due to rising electricity demand. Several transmission lines operate below desirable loading limits because of reactive power constraints and insufficient controllability [15], [19]. These conditions make the Nigerian grid an appropriate case study for evaluating the potential benefits of advanced FACTS technology.

This study focuses on enhancing Surge Impedance Loading as a metric for transmission line capacity improvement using the Unified Power Flow Controller. Selected transmission lines with relatively low SIL values in the Nigerian 330 kV system were analyzed under uncompensated and UPFC-compensated operating conditions. The objective was to determine the extent to which UPFC integration can improve line loadability and overall system performance. By adopting SIL as the principal performance index, the study provides a practical framework for assessing transmission capacity enhancement without immediate physical expansion of the grid.

The significance of this work lies in its contribution to transmission system modernization and optimal utilization of existing assets. Improved SIL implies higher transferable power, better voltage profile, reduced congestion, and increased operational flexibility. The findings are expected to support planners, utilities, and policymakers in adopting advanced compensation technologies for strengthening the Nigerian power network and meeting future electricity demand efficiently.

2. Analytical Framework and System Modeling

The analytical framework for this study is built upon the fundamental relationship between transmission line parameters, surge impedance

loading (SIL), and the compensative capability of the Unified Power Flow Controller (UPFC). This section presents the mathematical models, system assumptions, and performance indices used to evaluate SIL enhancement on selected weak corridors of the Nigerian 330 kV transmission network.

2.1 Conceptual Framework

The framework follows a sequential analytical path: transmission line parameterization → SIL computation → UPFC modeling → compensated SIL evaluation → performance comparison. Figure 1 illustrates the logical flow of the analytical process.

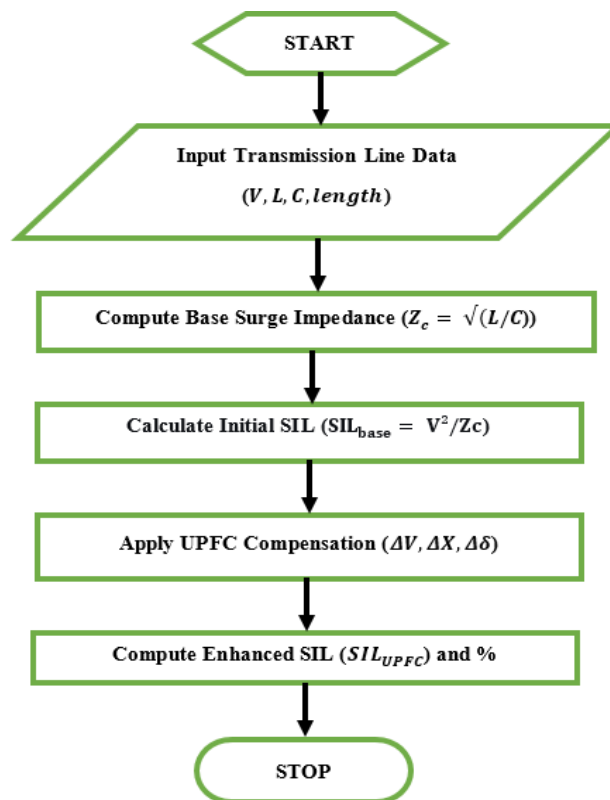


Figure 1. Analytical Framework Flowchart

For high-voltage transmission lines operating at steady state, the following assumptions hold:

2.2 Mathematical Model of Transmission Line for SIL Analysis

A three-phase, 330 kV overhead transmission line is modeled using distributed parameters.

Table 1. Assumptions for Transmission Line Modelling

Parameter	Symbol	Assumed Value / Condition
Series resistance	R	≈ 0 (negligible compared to reactance)
Shunt conductance	G	≈ 0 (negligible leakage)
Frequency	f	50 Hz (constant)
Line length	l	Variable per corridor (km)
Operating voltage	V	330 kV (nominal)

Under these lossless conditions, the surge impedance is given by:

$$Z_c = \sqrt{\frac{L}{C}} \tag{1}$$

Where:

- $Z_c =$ Surge impedance (Ω)
 - $L =$ Inductance per phase (H/km)
 - $C =$ Capacitance per phase (F/km)
- The Surge Impedance Loading (SIL) for a three-phase line is derived as:

Table 2. Interpretation of Line Loading Relative to SIL

Operating Condition	Reactive Power Behavior	Voltage Characteristic
$P < P_{SIL}$	Line generates reactive power	Voltage rises
$P = P_{SIL}$	Reactive power balance	Voltage stable
$P > P_{SIL}$	Line absorbs reactive power	Voltage drops

$$P_{SIL} = \frac{V_L^2}{Z_c} \tag{2}$$

Where:

- $P_{SIL} =$ Surge Impedance Loading (MW)
- $V_L =$ Line – to – line voltage (kV)

Substituting Equation 1 into Equation 2 gives the expanded form:

$$P_{SIL} = V_L^2 \sqrt{\frac{C}{L}} \tag{3}$$

2.3 Unified Power Flow Controller (UPFC) Model

The UPFC is modeled as a combination of shunt and series voltage-source converters

sharing a common DC link, as shown conceptually in Figure 2.

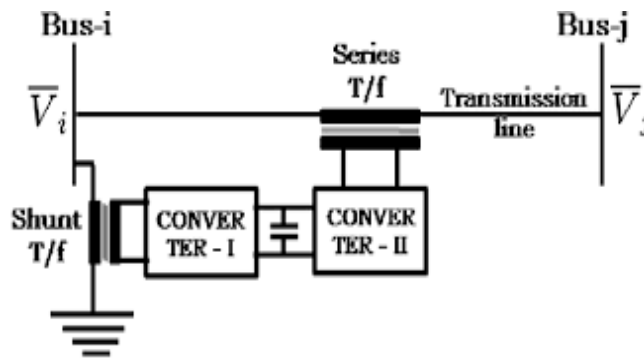


Figure 2. UPFC Basic Configuration

2.3.1 Shunt Converter Model (Voltage Regulation)

The shunt converter operates as a STATCOM, injecting reactive current to maintain bus voltage at a reference value. The reactive power exchange is:

$$Q_{sh} = V_m \cdot I_{sh} \tag{4}$$

The voltage regulation effect on SIL is derived from Equation 2. If the UPFC raises the bus voltage from V to V' , the new SIL becomes:

$$P'_{SIL} = \frac{(V')^2}{Z_c} \tag{5}$$

The percentage improvement due to voltage rise alone is:

$$\% \Delta P_{SIL} = \frac{(V')^2 - V^2}{V^2} \times 100 \quad (6)$$

2.3.2 Series Converter Model (Impedance Control)

The series converter injects a voltage at magnitude $|V_{se}|$ and phase angle ϕ , which appears in series with the line. This effectively modifies the net line reactance:

$$X_{eff} = X - X_c \quad (7)$$

Where:

- X = Original line reactance (Ω)
- X_c = Compensating reactance introduced by UPFC (Ω)
- X_{eff} = Effective reactance after compensation (Ω)

Since $X = \omega L$, the effective inductance becomes:

$$L_{eff} = \frac{X_{eff}}{\omega} = L - \frac{X_c}{\omega} \quad (8)$$

Substituting into Equation 3, the SIL after series compensation is:

$$P'_{SIL} = V^2 \sqrt{\frac{C}{L_{eff}}} \quad (9)$$

Because $L_{eff} < L$, the enhanced SIL is always greater than the base SIL.

2.3.3 Power Angle Control

The real power transferred over the line is expressed as:

$$P = \frac{V_s V_x}{X} \sin \delta \quad (10)$$

Where:

- V_s, V_x = Sending and receiving end voltages
 - δ = Power angle
- The UPFC injects a series voltage that effectively controls δ , allowing operation closer to the enhanced SIL limit without stability violation.

2.4 Combined UPFC Compensation Effect

The total SIL after UPFC installation integrates all three mechanisms:

$$P_{SIL,UPFC} = \frac{(V + \Delta V)^2}{Z_c - \Delta Z_c} \cdot k_\delta \quad (11)$$

Where:

- ΔV = Voltage rise from shunt compensation

- ΔZ_c = Reduction in surge impedance from series compensation

- k_δ = Power angle improvement factor (≥ 1)

For practical purposes, a simplified combined model is used:

$$P_{SIL,UPFC} = \frac{(k_v V)^2}{k_x Z_c} \quad (12)$$

Where:

- k_v = Voltage regulation factor (1.00 – 1.05 typical)
- k_x = Reactance reduction factor (0.85 – 0.95 typical)

2.5. Performance Indices

To quantify transmission capacity enhancement, three indices are defined.

2.5.1 SIL Enhancement Index (Primary Index)

$$\eta_{SIL} = \frac{P_{SIL,UPFC} - P_{SIL,base}}{P_{SIL,base}} \times 100\% \quad (13)$$

2.5.2 SIL Threshold Attainment

A benchmark SIL threshold is defined as:

$$P_{threshold} = 0.85 \times \frac{V^2}{Z_{c,typical}} \quad (14)$$

For the Nigerian 330 kV network, using typical conductor parameters, the threshold is established at 382.1053 MW.

2.5.3 Line Loading Margin Improvement

$$\Delta M = \frac{P_{SIL,UPFC} - P_{actual}}{P_{SIL,base}} \times 100\% \quad (15)$$

Table 3. Base System Parameters

Parameter	Value
System voltage (nominal)	330 kV
Frequency	50 Hz
Base SIL threshold	382.1053 MW
UPFC voltage regulation range	$\pm 10\%$
UPFC series compensation range	0–20%
Converter efficiency (assumed)	98%
Simulation steady-state condition	Balanced three-phase

2.6 Simulation Parameters

The parameters in Table 3 were used for the Nigerian 330 kV network analysis.

Table 4. Selected Weak Corridors (Initial SIL < 382.1053 MW)

Transmission Line	Initial SIL (MW)
Onitsha/New Haven	352.101
Onitsha/Alaoji	352.101
New Haven/Ugwuaji	337.981
Ikot Ekpene/Ugwuaji	327.452
Makurdi/Jos	326.356
Ugwuaji/Makurdi	328.427
Benin/Asaba	376.322
Asaba/Onitsha	364.106
Jebba TS/Osogbo	372.898
Ajaokuta/Lokoja	379.710
Lokoja/Gwagwalada	380.651
Benin/Ikeja West	376.322
Total	4274.427

3. Materials and Methods

3.1. Study Approach

This study investigates the enhancement of transmission line capacity using the Unified Power Flow Controller (UPFC) with Surge Impedance Loading (SIL) adopted as the principal performance metric. SIL is selected because it represents the natural loading point of a transmission line at which the reactive power generated by the line capacitance equals the reactive power absorbed by the line inductance. At this operating point, the line neither supplies nor consumes net reactive power. The methodology combines analytical derivation of SIL equations with UPFC-based compensation modeling to determine how controllable voltage injection, series reactance regulation, and phase-angle adjustment improve the SIL of the line.

3.2. Transmission Line Modeling

A three-phase transmission line was modeled using distributed parameters:

- ❖ *Series inductance per phase* = $L \text{ H/km}$

- ❖ *Series resistance per phase* = $R \text{ } \Omega/\text{km}$
- ❖ *Shunt capacitance per phase* = $C \text{ F/km}$
- ❖ *Shunt conductance per phase* = $G \text{ S/km}$
- ❖ Line length = 1 km

For high-voltage overhead transmission lines, resistance and leakage conductance are usually small compared with reactance and susceptance. Hence:

$$R \approx 0, G \approx 0$$

Thus, the line is approximated as a lossless transmission line.

3.2. Derivation of Surge Impedance

The characteristic or surge impedance of a transmission line is defined as:

$$Z_c = \sqrt{\frac{R + j\omega L}{G + j\omega C}} \quad (16)$$

For a lossless line:

$$R = 0, G = 0$$

Hence:

$$Z_c = \sqrt{\frac{j\omega L}{j\omega C}} = \sqrt{\frac{L}{C}} \quad (17)$$

Where:

- Z_c = Surge impedance (Ω)
- L = Inductance per phase
- C = Capacitance per phase

This impedance is purely real for a lossless line and is commonly called the Surge Impedance.

3.3. Derivation of Surge Impedance Loading (SIL)

For a balanced three-phase line, the active power transmitted is:

$$P = \sqrt{3}V_L I_L \quad (18)$$

Where:

- V_L = line-to-line voltage (kV)
- I_L = line current (A)

At SIL, the line current is:

$$I_L = \frac{V_{ph}}{Z_c} \quad (19)$$

Since:

$$V_{ph} = \frac{V_L}{\sqrt{3}} \quad (20)$$

Then:

$$I_L = \frac{V_L}{\sqrt{3}Z_c} \quad (21)$$

Substituting into power equation:

$$P_{SIL} = \sqrt{3}V_L \left(\frac{V_L}{\sqrt{3}Z_c} \right) \quad (22)$$

Therefore:

$$P_{SIL} = \frac{V_L^2}{Z_c} \quad (23)$$

Where:

- $P_{SIL} = \text{Surge Impedance Loading}$
(MW when V_L in kV and Z_c in Ω)

Thus, SIL depends directly on the square of transmission voltage and inversely on surge impedance.

3.4. Expanded SIL Expression in Terms of

Line Parameters

Substituting:

$$Z_c = \sqrt{\frac{L}{C}}$$

Into SIL equation:

$$P_{SIL} = \frac{V_L^2}{\sqrt{L/C}} \quad (24)$$

Hence:

$$P_{SIL} = V_L^2 \sqrt{\frac{C}{L}} \quad (25)$$

This shows that SIL increases when:

- ✓ Capacitance increases
- ✓ Inductance decreases
- ✓ Voltage level increases

3.5. Effect of Line Loading Relative to SIL

The operating condition of the line is interpreted as:

- If $P < SIL$: line behaves capacitively and generates reactive power
- If $P = SIL$: reactive balance occurs
- If $P > SIL$: line absorbs reactive power and voltage drops

Thus, increasing SIL allows higher real power transfer before voltage instability occurs.

3.6. Modeling the Unified Power Flow

Controller (UPFC)

The Unified Power Flow Controller (UPFC) consists of:

1. Shunt Converter (STATCOM mode)
Injects or absorbs reactive power to regulate bus voltage.
2. Series Converter (SSSC mode)
Injects a controllable AC voltage in series with the line.
3. Common DC link coupling both converters.

The injected series voltage is:

$$V_{se} = |V_{se}| \angle \phi \quad (26)$$

This modifies the effective sending-end and receiving-end voltage relationship.

3.7. How UPFC Enhances SIL

The UPFC improves SIL through three major mechanisms:

3.7.1. Voltage Regulation Effect

Since:

$$P_{SIL} \propto V^2 \quad (27)$$

If UPFC maintains bus voltage from V to V' :

$$P'_{SIL} = \frac{V'^2}{Z_c} \quad (28)$$

Percentage SIL improvement:

$$\% \Delta SIL = \frac{V'^2 - V^2}{V^2} \times 100 \quad (29)$$

Even a modest voltage rise significantly increases SIL.

3.7.2. Effective Reactance Reduction

The series converter injects compensating voltage equivalent to reducing net line reactance:

$$X_{eff} = X - X_c \quad (30)$$

Where:

- $X = \text{original line reactance}$
- $X_c = \text{compensating reactance introduced by UPFC}$

Since:

$$L = \frac{X}{\omega} \quad (31)$$

Then reduced reactance lowers equivalent inductance:

$$L_{eff} < L$$

Hence:

$$P'_{SIL} = V^2 \sqrt{\frac{C}{L_{eff}}} \quad (32)$$

Because $L_{eff} < L$, the new SIL becomes higher.

3.7.3. Power Angle Control

General transmission power equation:

$$P = \frac{V_s V_r}{X} \sin \delta \quad (33)$$

The UPFC controls the effective angle δ and injected voltage magnitude, allowing more real power transfer without exceeding stability margins. This permits operation nearer the enhanced SIL limit.

3.8. SIL Enhancement Index

To quantify performance:

$$\eta_{SIL} = \frac{SIL_{UPFC} - SIL_{base}}{SIL_{base}} \times 100\% \quad (34)$$

Where:

- SIL_{base} = original surge impedance loading
- SIL_{UPFC} = surge impedance loading after UPFC installation

The simulation procedure commenced by determining the transmission line voltage, inductance, and capacitance parameters

required for analysis. The base surge impedance of the line was then computed

using after which the initial Surge Impedance Loading (SIL) was evaluated from A Unified Power Flow Controller (UPFC) model was subsequently introduced at the selected bus or transmission line location within the network. Appropriate voltage regulation and series compensation settings were applied to represent the operating capability of the UPFC. Following compensation, the effective inductance, updated voltage magnitude, and enhanced SIL were recalculated. The obtained results before and after UPFC installation were compared in order to determine the impact of the device on transmission performance. The percentage improvement in SIL and the corresponding transmission capacity gain were then evaluated.

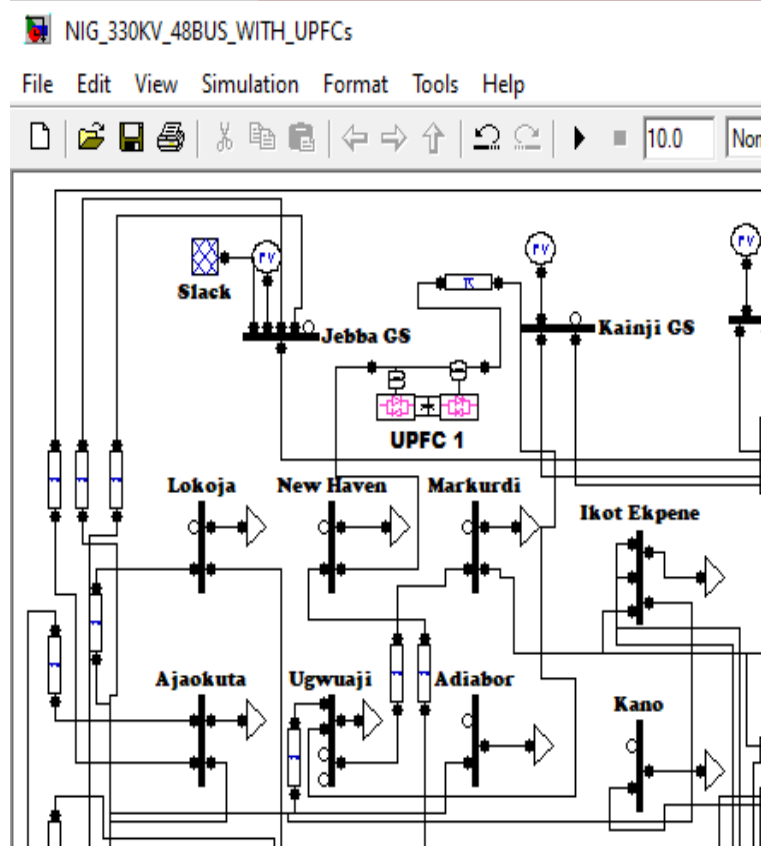


Figure 3. Integration of UPFC at New Haven/Ugwuaji line

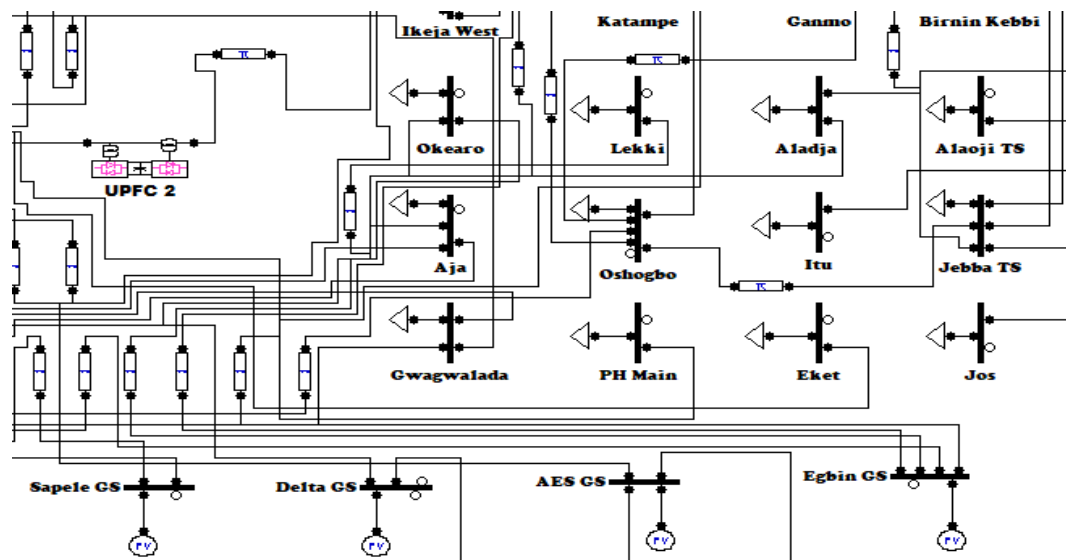


Figure 4. Integration of UPFCs at Markurdi/Jos line

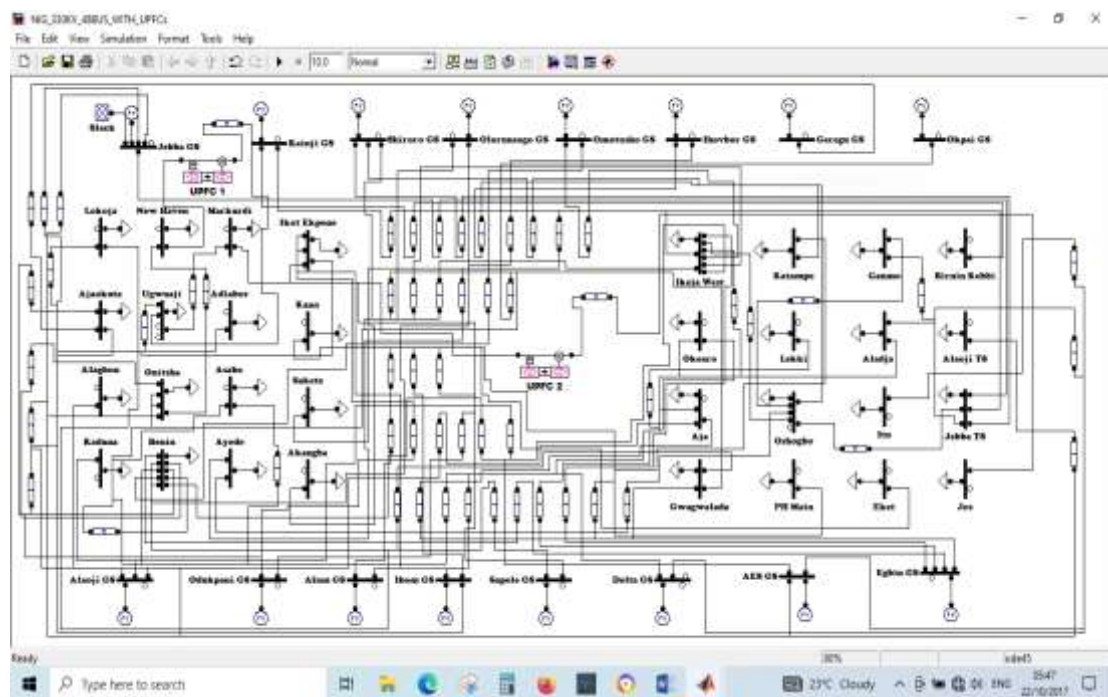


Figure 5. Integration of the UPFCs at both Lines

The performance of the system was assessed using several technical indicators, including Surge Impedance Loading expressed in megawatts, percentage improvement in SIL, voltage profile enhancement, reactive power compensation capability, increase in real power transfer, and available line loading margin.

In carrying out the analysis, it was assumed that the system operated under balanced three-phase steady-state conditions with sinusoidal

supply frequency. The resistance of the extra-high-voltage transmission line was considered negligible compared with its reactance, while the UPFC converters were assumed to operate ideally. It was also assumed that the thermal limits of the transmission line were not exceeded during the study period. The methodology derives SIL from first principles using line inductance and capacitance, then demonstrates mathematically that the Unified

Power Flow Controller (UPFC) increases SIL by:

- Raising effective bus voltage
- Reducing equivalent line reactance
- Controlling power angle
- Improving voltage stability margin

Therefore, the UPFC enables greater transmission line loading while preserving secure operation.

4. Results and Discussions

The comparative results for transmission lines whose initial Surge Impedance Loading (SIL) values were below 382.1053 MW are

presented in Table 5. These lines represent relatively weak sections of the Nigerian 330 kV transmission network where capacity enhancement is most required. The study evaluated the effect of integrating a Unified Power Flow Controller (UPFC) on the loading capability of these lines by comparing the uncompensated case with the UPFC-compensated condition.

Table 5. Transmission lines with current SIL less than 382.1053 MW (Comparison)

Transmission Line	SIL (MW)	
	Without UPFC	With UPFC
Jebba TS/Osogbo	372.898	381.902
Onitsha/New Haven	352.101	374.683
Onitsha/Alaoji	352.101	374.683
Ajaokuta/Lokoja Line	379.71	379.768
Lokoja/Gwagwalada	380.651	380.709
New Haven/Ugwuaji	337.981	360.113
Ikot Ekpene/Ugwuaji	327.452	349.242
Benin/Asaba line	376.322	383.249
Asaba/Onitsha line	364.106	382.416
Makurdi/Jos line	326.356	348.109
Ugwuaji/Makurdi line	328.427	350.248
Benin/Ikeja West	376.322	383.249
Total	4274.427	4448.37
% Improvement		4.0 694

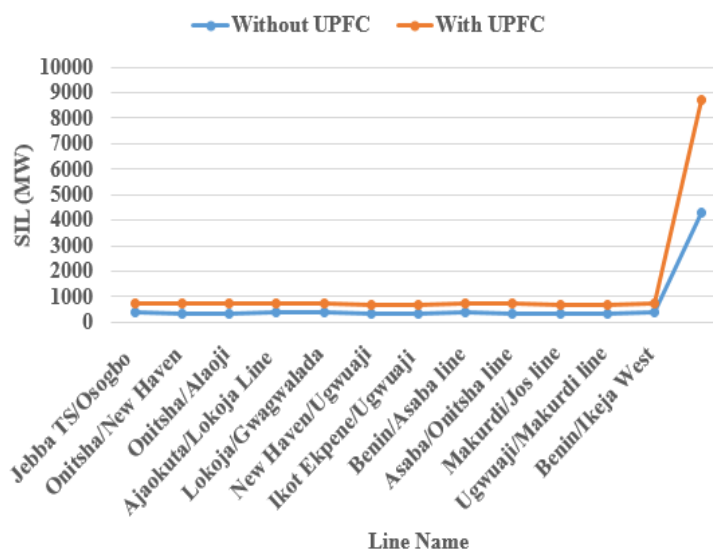


Figure 6. Line-by-Line Improvement

The uncompensated network recorded a cumulative SIL of 4274.427 MW for the selected transmission corridors. After the installation of the UPFC, the total SIL increased to 4448.370 MW. This corresponds to a percentage improvement of 4.0694%, confirming that the UPFC significantly enhances the SIL of the Nigerian transmission grid. The increase in SIL demonstrates the ability of the UPFC to improve voltage regulation, provide reactive power support, and control effective line impedance, thereby allowing more real power transfer through existing transmission infrastructure.

The percentage improvement in SIL was determined using:

$$\% \text{ Improvement} = \frac{\text{Total SIL}_{\text{with UPFC}} - \text{Total SIL}_{\text{without UPFC}}}{\text{Total SIL}_{\text{without UPFC}}} \times 100$$

Substituting the obtained values:

$$\% \text{ Improvement} = \frac{4448.370 - 4274.427}{4274.427} \times 100 = 4.0694\%$$

This result indicates that the introduction of the UPFC increased the transmission capacity of the studied weak corridors by approximately 4.1%.

At the individual transmission line level, substantial improvements were recorded on several critical corridors. The Jebba TS/Osogbo line increased from 372.898 MW to 381.902 MW, showing that the UPFC improved the loading margin of this western transmission path. The Onitsha/New Haven and Onitsha/Alaoji lines both rose from 352.101 MW to 374.683 MW, indicating strong enhancement of power transfer capability in the southeastern region of the network.

Similarly, the New Haven/Ugwuaji line improved from 337.981 MW to 360.113 MW, while the Ikot Ekpene/Ugwuaji corridor increased from 327.452 MW to 349.242 MW. These gains suggest that the UPFC effectively mitigated voltage instability and reactive power limitations on long-distance eastern transmission routes. The Makurdi/Jos line also increased significantly from 326.356 MW to 348.109 MW, while the Ugwuaji/Makurdi line

improved from 328.427 MW to 350.248 MW. These results imply stronger interconnection capability between northern and southeastern load centers. The Benin/Asaba and Benin/Ikeja West lines increased from 376.322 MW to 383.249 MW, while the Asaba/Onitsha line rose from 364.106 MW to 382.416 MW. These lines moved above or very close to the benchmark SIL threshold of 382.1053 MW after UPFC compensation. This is operationally important because lines operating near or above their SIL values can transmit more active power without excessive reactive power absorption or severe voltage drops. The Ajaokuta/Lokoja and Lokoja/Gwagwalada lines recorded smaller improvements, rising from 379.710 MW to 379.768 MW and from 380.651 MW to 380.709 MW respectively. The modest gains observed on these lines suggest that they were already operating close to their natural loading limits, leaving less room for enhancement compared with more constrained lines. The observed system-wide improvements are attributable to the multifunctional nature of the UPFC. Unlike single-purpose FACTS devices, the UPFC combines both shunt and series compensation. The shunt converter regulates bus voltage and supplies reactive power support, while the series converter injects controllable voltage in series with the transmission line to modify line reactance and power angle. This dual control mechanism enables simultaneous improvement in voltage profile, reduction in effective impedance, and increase in real power transfer capability, which collectively enhance SIL.

From a practical viewpoint, the 4.1% increase in total SIL is highly significant for a large interconnected network such as the Nigerian grid. Even moderate percentage gains in transmission capacity can translate into hundreds of megawatts of additional transferable power, reduced congestion, improved system reliability, and deferred capital investment in new transmission lines.

Table 6. Overall SIL Comparison

Scenario	Total SIL (MW)	Increase (MW)	Improvement (%)
Without UPFC	4274.427	0.000	0.000
With UPFC	4448.370	173.943	4.0 69

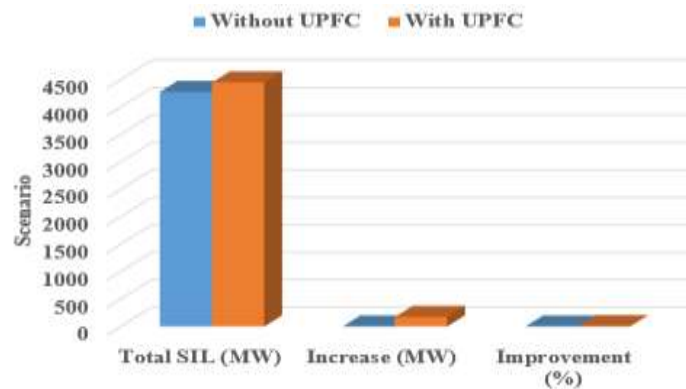


Figure 7. Total SIL before and after UPFC integration.

Table 7. Lines above Threshold after UPFC

Transmission Line	SIL with UPFC (MW)	Status
Benin/Asaba	383.249	Above Threshold
Benin/Ikeja West	383.249	Above Threshold
Asaba/Onitsha	382.416	Above Threshold
Jebba TS/Osogbo	381.902	Near Threshold

The results confirm that the UPFC is an effective FACTS controller for improving the Surge Impedance Loading of weak transmission corridors in the Nigerian 330 kV network. Its installation produced measurable gains across all studied lines and increased total system SIL by approximately 4.1%, thereby enhancing transmission capacity, voltage stability, and network operational efficiency.

5. Conclusion

This study investigated the enhancement of Surge Impedance Loading (SIL) of selected weak transmission corridors in the Nigerian 330kV power network through the integration of a Unified Power Flow Controller (UPFC). SIL was adopted as the principal performance index because it reflects the natural loading capability of a transmission line and its ability to transfer real power under balanced reactive power conditions. The results obtained showed

that the installation of the UPFC produced significant improvements in the loadability of all selected transmission lines whose initial SIL values were below the benchmark value of 382.1053 MW. The total SIL of the studied network increased from 4274.427 MW in the uncompensated condition to 4448.370 MW after UPFC integration, representing an overall improvement of 4.0694%. This confirms that the UPFC is highly effective in increasing transmission capacity through simultaneous voltage regulation, reactive power compensation, and controllable series impedance adjustment. Notable improvements were recorded on critical corridors such as Onitsha/New Haven, Onitsha/Alaoji, New Haven/Ugwuaji, Ikot Ekpene/Ugwuaji, Makurdi/Jos, and Ugwuaji/Makurdi, demonstrating the suitability of the UPFC for strengthening weak and heavily constrained transmission paths. Several lines also attained or exceeded the target SIL threshold after

compensation, indicating reduced congestion risk and improved operational margins.

The findings further establish that the deployment of UPFC technology can enhance power transfer capability, improve voltage stability, optimize utilization of existing transmission assets, and reduce the immediate need for costly network expansion. Therefore, the UPFC represents a technically viable and economically attractive solution for modernizing the Nigerian transmission grid and supporting reliable bulk power delivery. It is recommended that future work should consider optimal placement of multiple UPFC devices, dynamic stability assessment under disturbance conditions, and techno-economic evaluation for large-scale implementation within the national grid.

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