Comparative Performance Analysis of Stand-Alone Vs. Combined Facts Controllers for Enhancing Power System Load ability

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ABSTRACT

This study presents a comparative performance analysis of stand-alone versus combined Flexible Alternating Current Transmission Systems (FACTS) controllers for enhancing power system load ability, using the Nigerian 330KV 48-bus power system as a test bed. The research addresses the critical challenge of voltage instability and limited load ability in aged transmission networks, where building new infrastructure is often prohibitively expensive. Three FACTS devices were considered: the Static Var Compensator (SVC), the Thyristor Controlled Series Compensator (TCSC), and the Unified Power Flow Controller (UPFC). Using the Power System Analysis Toolbox (PSAT) for modelling and the Particle Swarm Optimization (PSO) algorithm for optimal placement and sizing, four integration scenarios were investigated: no FACTS integration, stand-alone SVC, stand-alone TCSC, stand-alone UPFC, and combined integration of all three devices. The baseline characterization of the uncompensated system revealed severe voltage drop limitations, with eleven transmission lines operating below the base Surge Impedance Loading (SIL) threshold of 382.11 MW, yielding a total baseline SIL of 4,274.43 MW. Stand-alone SVC integration improved total SIL to 4,414.62 MW, representing a 3.28 percent enhancement. Stand-alone TCSC integration achieved a total SIL of 4,469.12 MW, a 4.55 percent improvement. Stand-alone UPFC integration reached a total SIL of 4,448.37 MW, a 4.o7 percent improvement. The combined FACTS integration achieved the highest total SIL of 4,475.59 MW, corresponding to a 4.71 percent enhancement over the baseline, which translates to approximately 2o1 MW of additional transmission capacity. The results demonstrate that while stand-alone TCSC provides impressive improvement within 0.16 percentage points of the combined configuration, the combined approach offers superior overall performance along with advantages of redundancy, distributed voltage support, and reduced reliance on any single technology. Validation of simulation results against experimental data yielded a deviation of only 0.18 percent, confirming the accuracy of the PSAT-based modelling approach. The study concludes that combined FACTS integration is more capable of enhancing power system load ability than stand-alone integration, providing a cost-effective solution for transmission system operators seeking to maximize existing infrastructure utilization without physical expansion.

KEYWORDS

Flexible Alternating Current Transmission Systems (FACTS), Power System Load ability, Surge Impedance Loading (SIL), Voltage Stability, Transmission Congestion; Voltage Profile Improvement, Reactive Power Compensation.

I. INTRODUCTION

The increasing demand for electrical energy resulting from rapid industrialization, urbanization, and population growth has placed significant pressure on power transmission networks worldwide. In many developing countries, including Nigeria, existing transmission infrastructures are frequently operated close to their stability and thermal limits, leading to voltage instability, transmission congestion, increased system losses, and reduced power transfer capability. The Nigerian 330kV transmission network, which serves as the backbone of the national grid, has experienced persistent operational challenges due to aging infrastructure, inadequate expansion, and continuously rising electricity demand. These challenges often manifest as voltage drops, poor load ability, and frequent system disturbances, and reduced reliability of power supply. Traditionally, transmission capacity enhancement has been achieved through the construction of new transmission lines, substations, and generating stations. However, such expansion projects require enormous financial investment, environmental approvals, and long implementation periods, making them increasingly difficult to realize in developing economies. Consequently, modern power system research has focused on maximizing the utilization of existing transmission infrastructure without physical expansion. One of the most effective technologies developed for this purpose is the Flexible Alternating Current Transmission Systems (FACTS) technology, which utilizes high-speed power electronic controllers to regulate key transmission system parameters.

FACTS devices have attracted widespread attention because of their ability to improve voltage stability, regulate power flow, reduce transmission losses, and enhance system load ability. Different FACTS controllers provide different forms of compensation depending on their operating principles. The Static Var Compensator (SVC) provides shunt reactive power compensation for voltage support and reactive power management. The Thyristor Controlled Series Compensator (TCSC) modifies the effective transmission line reactance, thereby improving transmission capability and damping power oscillations. The Unified Power Flow Controller (UPFC), regarded as one of the most versatile FACTS devices, combines both shunt and series compensation capabilities to simultaneously control voltage magnitude, phase angle, and line impedance.

Several studies have demonstrated the effectiveness of FACTS devices in improving power system performance. (Gerbex et al.) investigated the optimal location of multiple FACTS devices using genetic algorithms and reported significant improvements in system operation and transmission capability. Bhattacharyya and Kumar employed a gravitational search algorithm for reactive power planning with FACTS devices and achieved enhanced voltage stability and reduced transmission losses. (Ahmad and Sirjani) presented a comprehensive review of optimization techniques for the placement and sizing of multi-type FACTS devices, highlighting the growing importance of intelligent optimization algorithms in modern power systems. Similarly, Hameed et al. [6] proposed the use of fuzzy logic for determining the optimal placement of FACTS devices, while (Daealhaq et al.) demonstrated the effectiveness of optimal FACTS placement for reducing power losses and improving voltage profiles. Within the Nigerian power system, several researchers have also examined the application of FACTS controllers for improving network performance. (Oladele et al.) investigated the use of Static Var Compensation for enhancing the transient stability of the Nigerian 330kV transmission network and reported improved voltage stability under disturbed operating conditions. (Ebune et al.) [4] examined the improvement of reactive power and voltage control in the Nigerian super grid system using Distributed FACTS devices, while (Bakare et al.) [2] employed optimization techniques for reactive power management and voltage profile enhancement in the Nigerian grid. These studies confirm the growing relevance of FACTS technology for addressing the operational challenges of the Nigerian transmission network. Despite the extensive research on FACTS devices, most previous studies have focused primarily on the performance of stand-alone FACTS controllers. Comparatively fewer studies have investigated the coordinated integration of multiple FACTS devices and the extent to which combined compensation can outperform individual device deployment in enhancing system load ability. Furthermore, there remains limited quantitative comparison of stand-alone versus combined FACTS integration using large-scale practical transmission systems such as the Nigerian 330kV 48-bus network.

This study therefore presents a comparative performance analysis of stand-alone versus combined FACTS controllers for enhancing the load ability of the Nigerian 330kV 48-bus power system. The study investigates four operating scenarios: the uncompensated system, stand-alone SVC integration, stand-alone TCSC integration, stand-alone UPFC integration, and the combined integration of all three FACTS devices. The Power System Analysis Toolbox (PSAT) implemented in MATLAB was used for system modelling and simulation, while the Particle Swarm Optimization (PSO) algorithm was employed for optimal placement and sizing of the FACTS devices. System performance was evaluated using Surge Impedance Loading (SIL), Continuation Load Flow (CLF), Optimal Load Flow (OLF), and voltage profile analysis. The significance of this research lies in its contribution toward improving the operational efficiency and reliability of the Nigerian transmission network without major infrastructural expansion. By quantitatively comparing the effectiveness of stand-alone and combined FACTS configurations, the study provides valuable technical insights for transmission system operators, utility planners, and policy makers seeking cost-effective solutions for enhancing transmission load ability and voltage stability. The findings also contribute to the broader body of knowledge on coordinated FACTS device integration for modern power systems.

II. MATERIALS AND METHODS

The research employed a computational simulation approach to conduct a comparative performance analysis of stand-alone versus combined FACTS controllers for enhancing power system load ability. The methodology was structured into seven sequential phases, beginning with the characterization of the existing power system and culminating in the comparative evaluation of different FACTS integration scenarios. All simulations and analyses were performed using the Power System Analysis Toolbox (PSAT), a MATLAB-based software package specifically designed for electric power system simulation and analysis. The computational environment consisted of a laptop computer equipped with MATLAB and the PSAT toolbox, with no physical hardware or laboratory experiments being conducted.

The test bed for this investigation was the Nigerian 330KV 48-bus power system, a realistic large-scale network representing the country's high-voltage transmission infrastructure. The system comprises sixteen generating stations, consisting of five hydroelectric plants and eleven thermal plants, thirty-two PQ load buses, and a total of fifty-nine transmission lines after simplification from the original eighty-nine lines to reduce model complexity while preserving system accuracy. The single-line diagram of this network, along with comprehensive bus data, line data, generator data, and load data, was obtained from secondary experimental sources, specifically from the Transmission Company of Nigeria (TCN) and peer-reviewed literature. Data validation was performed by comparing simulated results with experimental values, yielding a deviation of only 0.18 percent, which was deemed acceptable for simulation purposes.

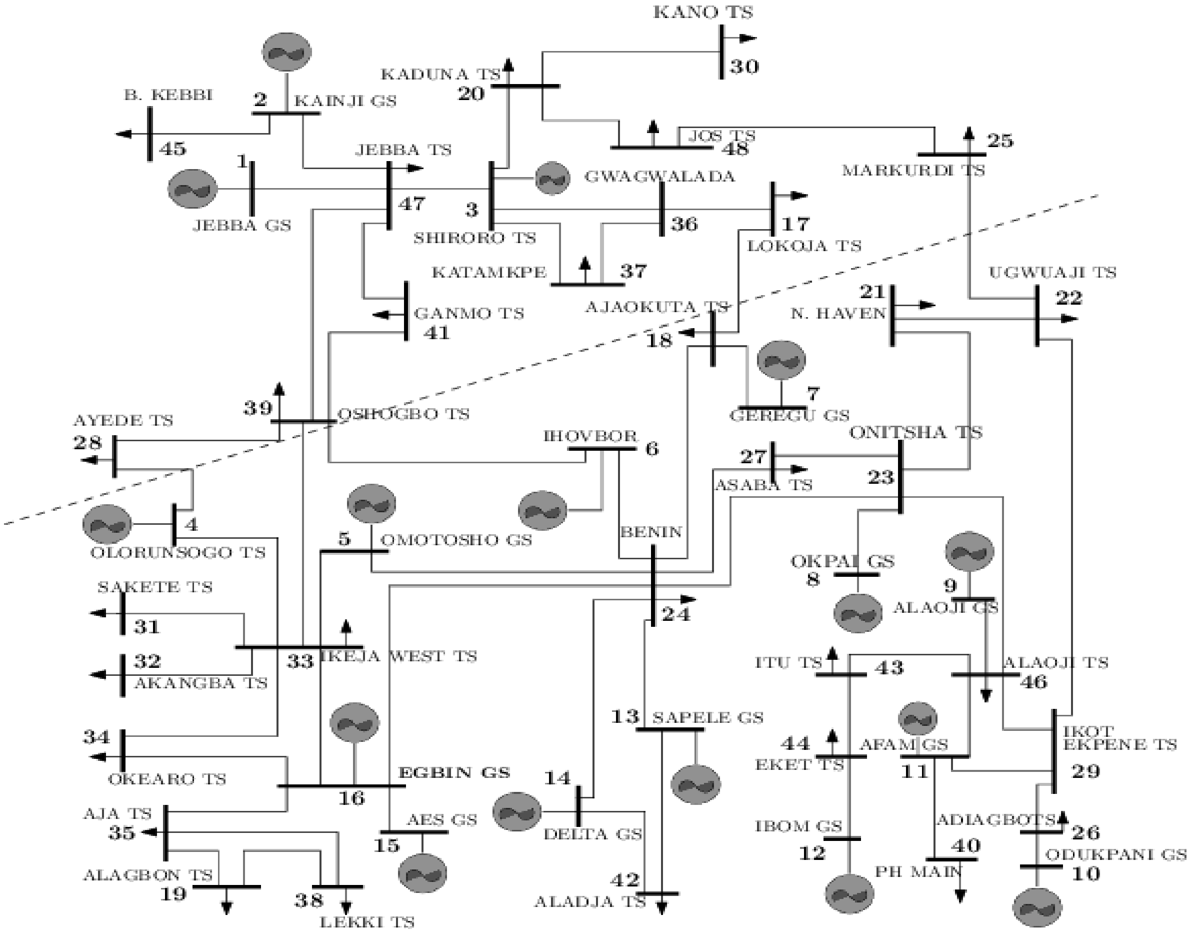

Figure 1. Single Line Diagram of the Nigerian 330KV 48 Bus power system

The first phase of the methodology involved characterizing the present load ability status of the Nigerian 330KV 48-bus power system to determine its line load ability curve. This was accomplished by calculating the Surge Impedance Loading (SIL) for each transmission line using the fundamental formula SIL equals V_(rated)squared divided by Z_o, where V_rated is the rated line voltage of 330KV and Z_o is the surge impedance of 285 ohms for a 330KV line. The per-unit SIL was then computed as the ratio of the actual SIL to the base SIL of 382.1o5 MW. A plot of per-unit SIL against transmission line length was generated, and the resulting load ability curve was compared against the universal St. Clair curve to identify lines operating in the voltage drop limitation region

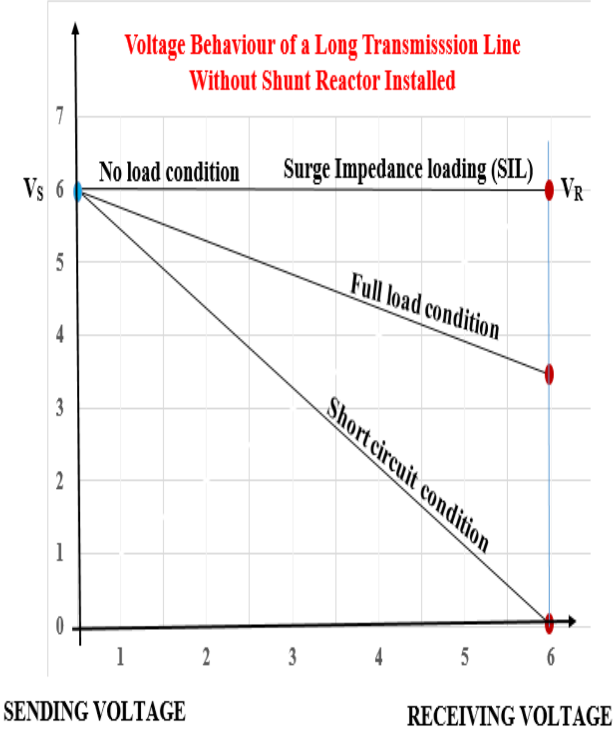

Figure 2. Voltage behavior of a long Transmission line

The second phase involved developing a detailed model of the Nigerian 330KV 48-bus power system within the PSAT environment. The single-line diagram was translated into a virtual network by placing bus blocks, generator blocks, load blocks, and transmission line blocks onto the PSAT workspace. Sixteen PV generator blocks were configured using the generator data, with the Jebba generation station designated as the reference slack bus. Thirty-two PQ load blocks were configured using the load data from TCN. Fifty-nine transmission line blocks were configured using the pi-model, with each line's resistance, reactance, and susceptance values entered from the line data table. All blocks were assigned a nominal voltage rating of 330KV and a frequency of 5oHz, consistent with Nigerian grid specifications.

The third phase focused on developing mathematical models of the three FACTS devices considered in this study, namely the Static Var Compensator (SVC), the Thyristor Controlled Series Compensator (TCSC), and the Unified Power Flow Controller (UPFC). The SVC was modeled using two alternative representations: the shunt variable susceptance model, where the equivalent susceptance appears as a state variable, and the firing-angle model, where the thyristor firing angle is taken as a state variable in the Newton-Raphson power flow algorithm. The TCSC was modeled as a variable reactance based on the thyristor-controlled reactor in parallel with a fixed capacitor, with the equivalent reactance at fundamental frequency expressed as a function of the conduction angle. The UPFC was modeled as the combination of a shunt voltage source inverter and a series voltage source inverter sharing a common DC link, with the power injection model employed for steady-state analysis. For this study, the UPFC was practically represented as the combination of an SVC for shunt compensation and a TCSC for series compensation. To rigorously express power system loadability for the study, it can be formalized from three complementary viewpoints used in the methodology:

- Surge Impedance Loading (SIL),
- Power flow transfer capability, and
- Continuation Load Flow (CLF) loading parameter

A. Base Mathematical Expression for Load ability

1. Surge Impedance Loading (SIL)

From the proposed method:

$$SIL = \frac{V_{\text{rated}}^2}{Z_o} \qquad (1)$$

For per-unit representation:

$$SIL_{pu} = \frac{SIL_{\text{actual}}}{SIL_{\text{base}}} \qquad (2)$$

Using the base value:

$$SIL_{pu} = \frac{SIL_i}{382.1o5} \qquad (3)$$

2. Voltage Stability / Load ability Factor (λ)

Load ability is best expressed using a loading parameter λ (from CLF):

$$P_{L_i} = P_{L_i}^{o}(1 + \lambda) \qquad (4)$$
$$Q_{L_i} = Q_{L_i}^{o}(1 + \lambda) \qquad (5)$$

Where:

- $\lambda = o \rightarrow\ base\ case$
- $\lambda = \lambda max \rightarrow\ maximum\ loadability\ (nose\ point)$

Thus, system load ability limit:

$\lambda_{max} = max\{\lambda\text{: Power flow converges }\}$

3. Power Transfer Limit of a Line

From transmission theory:

$$P_{max} = \frac{V_s V_r}{X} \sin\delta \qquad (6)$$

This is the steady-state load ability limit.

B. Load ability Status (Without FACTS)

A line is classified based on SIL:

$$\text{Load ability Status } = \begin{cases} \text{Under-loaded} & SIL_{pu} < 1 \\ \text{Optimally loaded} & SIL_{pu} \approx 1 \\ \text{Overloaded} & SIL_{pu} > 1 \end{cases} \qquad (7)$$

Also, system condition:

$\lambda_{\text{base}} < \lambda_{max}$

Voltage constraint condition:

$V_i \geq V_{min}(\text{ typically } 0.95\text{pu})$

C. Load ability with Stand-Alone FACTS Devices

FACTS controllers modify either reactance (X) or voltage (V).

1. With SVC (Shunt Compensation)

SVC injects reactive power:

$$Q_{svc} = V^2 B_{svc} \qquad (8)$$

Effective bus voltage improves:

$$V_i^{\text{new}} = V_i + \Delta V_{svc} \qquad (9)$$

Thus, loadability becomes:

$\lambda_{max}^{SVC} > \lambda_{max}^{\text{base}}$

2. With TCSC (Series Compensation)

TCSC modifies line reactance:

$$X_{eff} = X(1-k) \qquad (10)$$

Where

- $k = 0.6\ (60\%\ compensation)$

New power transfer:

$$P_{max}^{TCSC} = \frac{V_s V_r}{X(1-k)} \sin\delta \qquad (11)$$

So:

$$P_{max}^{TCSC} = \frac{P_{max}^{\text{base}}}{(1-k)} \qquad (12)$$

3. With UPFC

UPFC controls both voltage and impedance:

$$P_{ij}^{UPFC} = \frac{V_i V_j}{X} \sin\left(\delta + \theta_{inj}\right) \qquad (13)$$

Thus:

$$\lambda_{max}^{UPFC} > \lambda_{max}^{TCSC} > \lambda_{max}^{SVC}$$

The fourth phase employed the Particle Swarm Optimization (PSO) algorithm to determine the optimal location and sizing of the FACTS devices within the Nigerian power system. The optimal locations were identified based on the characterization results: SVCs were placed at buses exhibiting the poorest voltage profiles, namely the Jos 330KV bus, Ugwuaji 330KV bus, and New Haven 330KV bus. TCSCs were optimally placed at the receiving ends of transmission lines connecting these weak buses, specifically the New Haven-Ugwuaji line and the Makurdi-Jos line. UPFCs were placed at the sending ends of the same transmission lines. For optimal sizing, an objective function was formulated based on minimizing voltage drops, using the Ikot Ekpene to Ugwuaji 330KV line as the objective function line and the Ajaokuta to Benin line, Ugwuaji to Makurdi line, and Benin to Onitsha line as constraint lines. The objective function was expressed as the minimization of the quantity 0.018169 times the FACTS impedance plus 3.05 times 10 to the power of 5 times a variable minus 3.05 times 10 to the power of 5 times another variable. The PSO algorithm was configured with three variables, two thousand particles, a minimum initial weight of 0.4, a maximum initial weight of 0.9, a lower bound of zero, an upper bound of two million, acceleration factors C1 and C2 both set to 2, and a maximum of one thousand iterations. The optimization yielded an optimal FACTS impedance of 137.55 ohms, corresponding to a total compensation level of 6o percent. For stand-alone FACTS integration, each device provided the full 6o percent compensation, while for combined FACTS integration, each of the three devices provided 2o percent compensation to achieve the same total of 6o percent.

The fifth phase involved integrating the developed FACTS device models into the PSAT model of the Nigerian power system under three distinct scenarios. In the first scenario, stand-alone. SVCs were integrated by placing three SVC blocks at the Jos 330KV bus, Ugwuaji 330KV bus, and New Haven 330KV bus.

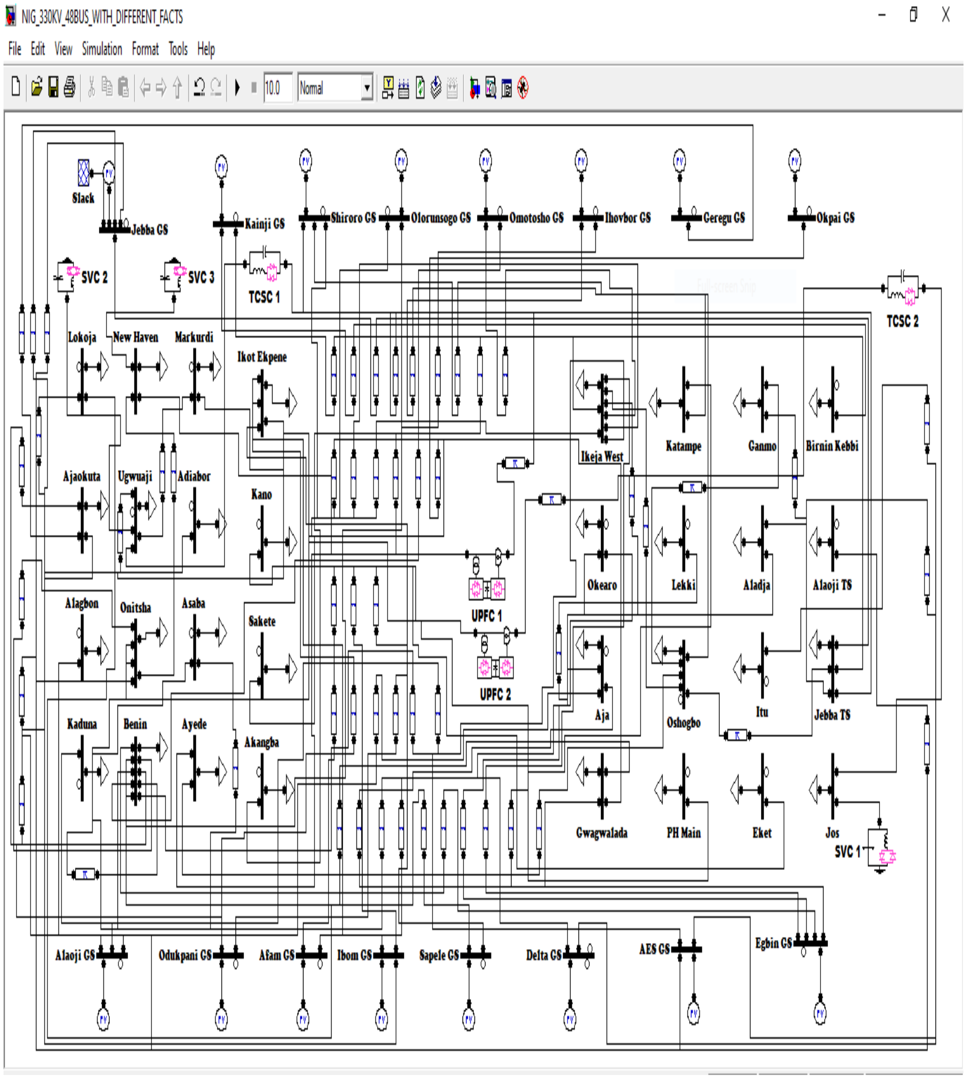

Figure 3. Integration of different FACTS

In the second scenario, stand-alone TCSCs were integrated by placing two TCSC blocks on the New Haven to Ugwuaji transmission line and the Makurdi to Jos transmission line.

In the third scenario, stand-alone UPFCs were integrated by placing two UPFC blocks at the sending ends of the same transmission lines. In the fourth scenario, combined FACTS integration was implemented by simultaneously integrating SVCs at the three weak buses, TCSCs on the two transmission lines, and UPFCs on the same two transmission lines, with each device configured to provide 2o percent compensation.

D. Load ability with Combined FACTS Controllers

From the study:

- Total compensation = 6o%
- Each device contributes = 2o%

1. Combined Reactance Modification

$$X_{eff}^{\text{combined}} = X\left(1 - (k_{TCSC} + k_{UPFC})\right) \quad (14)$$

$$= X(1 - 0.2 - 0.2) = X(0.6)$$

2. Combined Voltage Support

$$V^{\text{combined}} = V + \Delta V_{SVC} + \Delta V_{UPFC} \quad (15)$$

3. Combined Load ability Expression

$$P_{max}^{\text{combined}} = \frac{V_s^{\text{combined}} V_r^{\text{combined}}}{X_{\text{eff}}^{\text{combined}}} \sin(\delta + \theta) \quad (16)$$

4. Load ability Factor

$$\lambda_{\max}^{\text{combined}} = \lambda_{\text{base}} + \Delta\lambda_{SVC} + \Delta\lambda_{TCSC} + \Delta\lambda_{UPFC} \quad (17)$$

E. System-Wide Load ability Index

From the methodology

$$LSI = \sum_{i=1}^{n} SIL_i \quad (18)$$

With FACTS:

$$LSI_{FACTS} = \sum_{i=1}^{n} SIL_i^{FACTS} \quad (19)$$

Percentage Improvement:

$$\% \text{ Improvement } = \frac{LSI_{FACTS} - LSI_{\text{base}}}{LSI_{\text{base}}} \times 1oo \qquad (2o)$$

F. Final Comparative Load ability Conditions

$\lambda_{max}^{\text{combined}} > \lambda_{max}^{UPFC} > \lambda_{max}^{TCSC} > \lambda_{max}^{SVC} > \lambda_{max}^{\text{base}}$

$P_{max}^{\text{combined}} > P_{max}^{\text{standalone}} > P_{max}^{\text{base}}$

$SIL_{\text{combined}} > SIL_{\text{standalone}} > SIL_{\text{base}}$

The sixth phase consisted of performing Continuation Load Flow (CLF) and Optimal Load Flow (OLF) analyses for all four scenarios. The CLF analysis was executed using the Newton-Raphson solver method within PSAT, which iteratively solves the nonlinear algebraic equations representing the power balance at each bus. The analysis was first performed for the baseline case with no FACTS devices integrated, then repeated for each stand-alone FACTS integration scenario, and finally for the combined FACTS integration scenari0. The OLF analysis was performed for the scenarios with FACTS integration to optimize the system operating point under the influence of the controllers. The voltage magnitude at each of the forty-eight buses was recorded for every scenario, and the SIL for each transmission line was recomputed based on the actual operating voltages rather than the nominal values.

The seventh and final phase involved comparing the results across the four scenarios to determine the percentage enhancement in load ability achieved by each configuration. The total SIL for all constrained lines, defined as those lines whose actual SIL fell below the base SIL of 382.1o5 MW, was summed for each scenari0. The percentage improvement in load ability was then computed using the formula: percentage improvement equals the quantity of total SIL with FACTS minus total SIL without FACTS divided by total SIL without FACTS, all multiplied by 1o0. This calculation was performed separately for the SVC integration scenario, the TCSC integration scenario, the UPFC integration scenario, and the combined FACTS integration scenari0. The bus voltage profiles were also compared graphically by generating bar charts from the exported PSAT static reports, allowing visual assessment of voltage restoration at weak buses. All results were exported from PSAT as plain text files and subsequently imported into spreadsheet software for additional analysis and graphical presentation.

III. RESULTS AND DISCUSSIONS

The comparative analysis of stand-alone versus combined FACTS controllers for enhancing the load ability of the Nigerian 330KV 48-bus power system yielded distinct and quantifiable results across the four scenarios investigated. The baseline case, representing the power system without any FACTS devices integrated, was first established to provide a reference for all subsequent comparisons. The continuation load flow analysis of the uncompensated system revealed that the average per-unit Surge Impedance Loading across all transmission lines was 0.9856, which falls significantly below the ideal values predicted by the universal St. Clair load ability curve. For transmission lines ranging from 8o kilometres to 32o kilometres in length, the St. Clair curve indicates that per-unit SIL values should approach 2.5, yet the Nigerian system averaged just 0.9856, indicating severe underperformance. More critically, the analysis identified a cluster of buses operating within the voltage drop limitation region, where voltage magnitudes had fallen below acceptable thresholds. The Jos bus recorded the lowest voltage at 298.o6 kV, representing a per-unit value of just 0.9o32. Other severely affected buses included Markurdi at 3o4.98 kV, Ikot Ekpene at 3o5.49 kV, Ugwuaji at 3o5.94 kV, and New Haven at 310.36 kV.

These depressed voltages directly constrain the load ability of the transmission lines connected to these buses, as demonstrated by the SIL calculations for specific corridors. The New Haven to Ugwuaji line operated at an actual SIL of only 337.98 MW compared to the base SIL of 382.11 MW, representing a per-unit value of 0.8845. Even more severely impacted was the Ikot Ekpene to Ugwuaji line, which recorded an actual SIL of just 327.45 MW, a per-unit value of 0.8570. The Makurdi to Jos line showed the poorest performance among all transmission lines, with an actual SIL of 326.36 MW and a per-unit value of 0.8541. Summing the SIL values of all eleven transmission lines that fell below the 382.11 MW base threshold yielded a total baseline SIL of 4,274.43 MW. These results confirm the characterization that the Nigerian 330KV power system operates significantly below its theoretical load ability potential, with voltage drop limitations being the primary constraining factor.

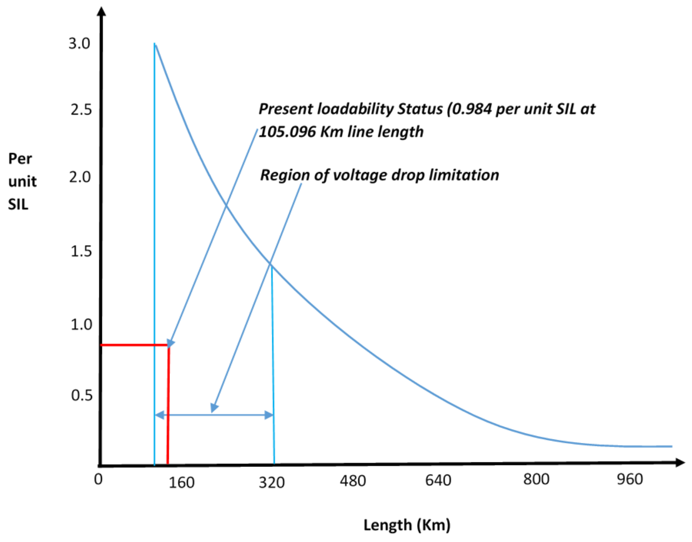

Figure 4. Present Load ability status of the Nigerian 330KV 48 bus Power System

Following the establishment of the baseline, the integration of stand-alone SVCs at the three weakest buses, namely Jos, Ugwuaji, and New Haven, produced measurable improvements in both bus voltage profiles and line SIL values. The bus voltage results showed that the New Haven bus increased from 310.36 kV to 319.37 kV, representing a per-unit improvement from

0.94o5 to 0.9678. The Ugwuaji bus voltage rose from 3o5.94 kV to 314.95 kV, improving from 0.9271 to 0.9544 per-unit. The Jos bus, which had been the most severely affected, increased from 298.o6 kV to 3o7.o6 kV, moving from 0.9o32 to 0.93o5 per-unit. The Markurdi and Ikot Ekpene buses also showed corresponding improvements, rising to 313.98 kV and 314.49 kV respectively. These

Table 1. Comparison of the Bus Voltage Profiles for the Different Scenarios

Bus No	**Bus Name**	**Bus voltage without FACTS (PU)**	**Bus voltage** WITH SVC **(PU)**	**Bus voltage with TCSC (PU)**	**Bus voltage with UPFC (PU)**	**Bus voltage with different FACTS (PU)**
1	Jebba GS	1	1	1	1	1
2	Kainji GS	1	1	1	1	1
3	Shiroro GS	1	1	1	1	1
4	Olorunsogo GS	1	1	1	1	1
5	Omotosho GS	1	1	1	1	1
6	Ihovbor GS	1	1	1	1	1
7	Geregu GS	1	1	1	1	1
8	Okpai GS	1	1	1	1	1
9	Alaoji GS	1	1	1	1	1
1o	Odukpani GS	1	1	1	1	1
11	Afam GS	1	1	1	1	1
12	Ibom GS	1	1	1	1	1
13	Sapele GS	1	1	1	1	1
14	Delta GS	1	1	1	1	1
15	AES GS	1	1	1	1	1
16	Egbin GS	1	1	1	1	1
17	Lokoja	0.998o9	0.99813	0.99812	0.99817	0.998216
18	Ajaokuta	0.99686	0.99689	0.99689	0.99694	0.996982
19	Alagbon	1.0003	1.00033	1.00032	1.00038	1.000421
2o	Kaduna	1.000o5	1.00008	1.000o7	1.00013	1.000171
21	New Haven	0.94049	0.96778	0.96777	0.97o8	0.976863
22	Ugwuaji	0.9271	0.95439	0.95438	0.95741	0.963474
23	Onitsha	0.95994	0.98722	0.98721	0.99o24	0.996306
24	Benin	0.9924	1.oo151	1.oo15	1.0015	1.0015o2
25	Markurdi	0.92417	0.95146	0.95145	0.95448	0.96o546
26	Adiabor	1.000o5	1.00008	1.00007	1.00013	1.000171
27	Asaba	0.97616	1.00042	1.00041	1.00041	1.000413
28	Ayede	0.99981	0.99984	0.99983	0.99988	0.999928
29	Ikot Ekpene	0.92573	0.95301	0.953	0.956o3	0.962097
3o	Kano	1.00005	1.00008	1.00007	1.00013	1.000171

31	Sakete	0.99866	0.99869	0.99868	0.99874	0.998781
32	Akangba	0.99866	0.99869	0.99868	0.99874	0.998781
33	Ikeja West	0.99861	0.99864	0.99863	0.99869	0.998731
34	Okearo	0.99935	0.99938	0.99938	0.99943	0.999475
35	Aja	1.00025	1.00028	1.00027	1.00033	1.000371
36	Gwagwalada	0.9993	0.99933	0.99932	0.99937	0.999417
37	Katampe	0.99969	0.99972	0.99972	0.99977	0.999815
38	Lekki	1.0003	1.00033	1.00032	1.00038	1.000421
39	Oshogbo	0.99953	0.99956	0.99956	0.99961	0.999653
4o	PH Main	1.000o5	1.00008	1.000o7	1.00013	1.000171
41	Ganmo	0.99963	0.99966	0.99965	0.99971	0.999751
42	Aladja	1.000o5	1.00008	1.000o7	1.00013	1.000171
43	Itu	1.000o5	1.00008	1.000o7	1.00013	1.000171
44	Eket	1.000o5	1.00008	1.000o7	1.00013	1.000171
45	Birnin Kebbi	1.000o5	1.00008	1.000o7	1.00013	1.000171
46	Alaoji TS	1.000o5	1.00008	1.000o7	1.00013	1.000171
47	Jebba TS	0.99971	0.99974	0.99973	0.99978	0.99983
48	Jos	0.90321	0.93049	0.93o48	0.93351	0.939579

Voltage improvements translated directly into enhanced SIL values for the transmission lines connected to these buses. The New Haven to Ugwuaji line saw its actual SIL increase from 337.98 MW to 357.88 MW, a per-unit improvement from 0.8845 to 0.9366. The Ikot Ekpene to Ugwuaji line improved from 327.45 MW to 347.o4 MW, moving from 0.857o to 0.9082 per-unit. The Makurdi to Jos line increased from 326.36 MW to 345.91 MW, achieving a per-unit value of 0.9o53. However, despite these improvements, several critical lines continued to operate below the 382.11 MW threshold. The total SIL across all constrained lines after SVC integration summed to 4,414.62 MW. Computing the percentage improvement relative to the baseline value of 4,274.43 MW yielded an enhancement of 3.28 percent. While this represents a positive step toward improving system load ability, the SVC-only configuration was unable to fully address the voltage drop limitations, particularly on.

longer transmission corridors where series compensation would be more effective.

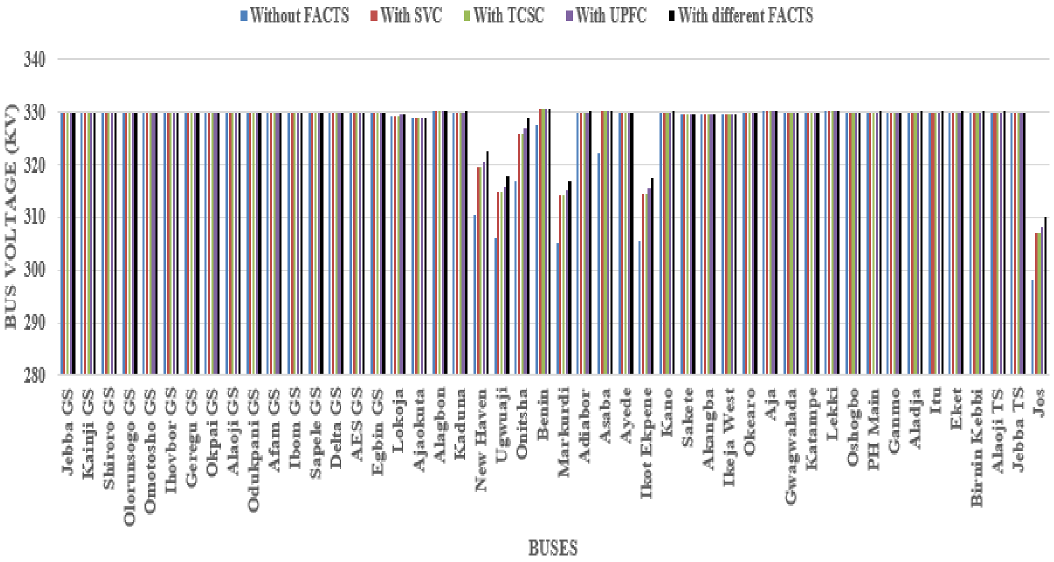

Figure 5. Comparison of the Bus Voltage Profiles for the Different Scenarios

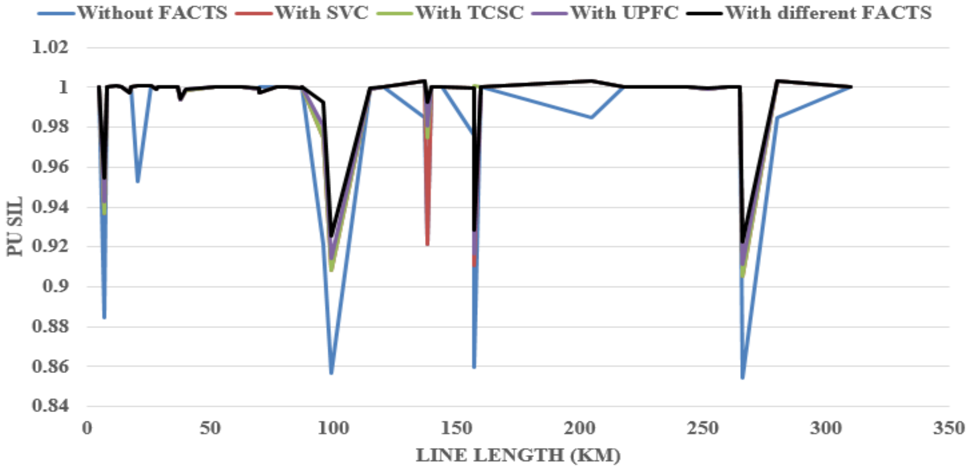

Figure 6. Load ability curve comparison for different Scenarios

The stand-alone TCSC integration scenario produced notably stronger results than the SVC configuration, reflecting the suitability of series compensation for addressing voltage drop issues on long transmission lines. Two TCSCs were installed at the receiving ends of the New Haven to Ugwuaji line and the Makurdi to Jos line, targeting the specific corridors identified as having the poorest voltage profiles. The bus voltage results showed that the New Haven bus increased to 319.36 kV, the Ugwuaji bus to 314.94 kV, and the Jos bus to 3o7.o6 kV, values that were nearly identical to those achieved with SVC integration. However, the key difference emerged in the SIL calculations for the compensated transmission lines themselves. The New Haven to Ugwuaji line achieved an actual SIL of 357.87 MW, while the Makurdi to Jos line reached 345.9o MW. More significantly, the TCSC integration produced a substantial improvement in the Onitsha to Alaoji line, which had been overlooked in the SVC-only scenari0. This line, operating at 352.10 MW in the baseline case, improved to 372.39 MW after TCSC integration, representing a per-unit increase from 0.9215 to 0.9746. The Ugwuaji to Makurdi line also showed remarkable improvement, with its actual SIL rising from 328.43 MW to an impressive 382.32 MW, achieving a per-unit value of 1.0006, which now exceeds the base SIL threshold. This result is particularly significant because it demonstrates that series compensation can completely restore a transmission line to its nominal load ability. The total SIL across all constrained lines after TCSC integration summed to 4,469.12 MW, yielding a percentage improvement of 4.55 percent relative to the baseline. This represents a substantial enhancement over the SVC scenario, indicating that for a power system limited primarily by voltage drops along transmission corridors, series compensation via TCSC is more effective than shunt compensation via SVC alone.

The stand-alone UPFC integration scenario produced results that fell between those of the SVC and TCSC configurations, with a total SIL improvement of 4.07 percent. Two UPFCs were installed at the sending ends of the New Haven to Ugwuaji line and the Makurdi to Jos line, providing simultaneous shunt and series compensation capabilities. The bus voltage results showed slightly better performance than both the SVC and TCSC scenarios, with the New Haven bus reaching 320.36 kV, the Ugwuaji bus reaching 315.94 kV, and the Jos bus reaching 308.o6 kV. These marginal improvements are attributable to the UPFC's ability to inject both real and reactive power independently, offering more flexible voltage support than either device alone. The transmission line SIL values reflected this enhanced capability. The New Haven to Ugwuaji line achieved 360.11 MW, the Ikot Ekpene to Ugwuaji line reached 349.24 MW, and the Makurdi to Jos line attained 348.11 MW. Each of these values exceeded those observed in both the SVC and TCSC scenarios, demonstrating the superior voltage support capability of the UPFC. However, the Onitsha to Alaoji line, which had shown significant improvement under TCSC integration, only achieved 374.68 MW under UPFC integration, slightly lower than the TCSC value of 372.39 MW. The Ugwuaji to Makurdi line, which had been fully restored to its nominal SIL under TCSC integration, achieved 350.25 MW under UPFC integration, which, while improved, remained below the 382.11 MW threshold. This suggests that while the UPFC offers greater flexibility, its effectiveness depends on proper coordination between its shunt and series components. The total SIL across all constrained lines after UPFC integration summed to 4,448.37 MW, representing a 4.07 percent improvement over the baseline. This result positions the UPFC as an intermediate option between the SVC and TCSC for this particular power system.

The combined FACTS integration scenario, in which SVCs, TCSCs, and UPFCs were all deployed simultaneously with each device providing 2o percent compensation to achieve a total of 6o percent compensation, produced the most substantial improvements observed in this study. The bus voltage results showed clear superiority over all stand-alone configurations. The New Haven bus voltage rose to 322.36 kV, representing a per-unit value of 0.9769, which is remarkably close to the acceptable limit of 0.95 per-unit. The Ugwuaji bus reached 317.95 kV, improving to 0.9635 per-unit. The Jos bus achieved 310.o6 kV, moving to 0.9396 per-unit. While the Jos bus remained slightly below the 0.95 threshold, the improvement from 0.9o32 to 0.9396 represents a substantial recovery. The Markurdi bus reached 316.98 kV, and the Ikot Ekpene bus achieved 317.49 kV, both showing significant voltage restoration. The transmission line SIL values demonstrated the synergistic effect of combined compensation. The New Haven to Ugwuaji line achieved 364.63 MW, the highest value recorded across all scenarios for this corridor. The Ikot Ekpene to Ugwuaji line reached 353.69 MW, substantially exceeding the values achieved by any stand-alone configuration. The Onitsha to New Haven line showed dramatic improvement, rising from 352.1o MW in the baseline to 379.29 MW, a per-unit value of 0.9926. Even more impressive, the Onitsha to Alaoji line improved from 352.1o MW to 379.29 MW, demonstrating that combined compensation across multiple devices can benefit lines not directly compensated but located within the same voltage control area. The Makurdi to Jos line achieved 352.55 MW, while the Ugwuaji to Makurdi line reached 354.7o MW. The total SIL across all constrained lines after combined FACTS integration summed to 4,475.59 MW, representing the highest total SIL observed in this study. Computing the percentage improvement relative to the baseline value of 4,274.43 MW yielded an enhancement of 4.71 percent. This value exceeds the improvements achieved by stand-alone SVC integration by 1.43 percentage points, stand-alone TCSC integration by 0.16 percentage points, and stand-alone UPFC integration by 0.64 percentage points.

The comparative results strongly support the conclusion that combined FACTS integration is more capable of enhancing power system load ability than stand-alone FACTS integration for the Nigerian 330KV 48-bus power system. The 4.71 percent improvement achieved by the combined configuration represents an enhancement of approximately 2o1 MW of additional transmission capacity across the constrained lines without any physical expansion of the transmission infrastructure. While the stand-alone TCSC integration achieved a 4.55 percent improvement, coming within 0.16 percentage points of the combined configuration, the combined approach offers several important advantages. First, the combined configuration restores voltage at multiple weak buses simultaneously, whereas the TCSC-only configuration focuses primarily on line-specific improvements. Second, the combined configuration distributes the compensation burden across different device types, reducing the risk of over-reliance on any single technology. Third, the combined configuration provides redundancy, such that the failure of one device does not completely eliminate the compensation benefit. The voltage profile comparison shown in Figure 5 visually demonstrates the progressive improvement from the uncompensated baseline through the stand-alone configurations to the combined configuration. Buses that were severely depressed in the baseline, such as New Haven, Ugwuaji, and Jos, show clear upward trends across the scenarios, with the combined configuration achieving the highest voltages for every weak bus. Similarly, the load ability curve comparison in Figure 6 shows that transmission lines with low per-unit SIL values in the baseline consistently shift upward as additional compensation is added, with the combined configuration producing the highest per-unit SIL values for the most constrained lines.

Several observations merit additional discussion. First, the finding that TCSC integration alone achieved 4.55 percent improvement, nearly matching the combined configuration's 4.71 percent, suggests that series compensation is particularly well-suited to address the specific voltage drop limitations characterizing the Nigerian power system. The voltage drop limitation region, identified in the baseline characterization, arises primarily from the inductive nature of long transmission lines under heavy loading conditions. Series compensation directly counteracts line reactance, making it highly effective for this specific problem. Second, the UPFC's intermediate performance, while superior to SVC but inferior to TCSC, reflects the trade-off between flexibility and focused effectiveness. The UPFC's ability to control voltage magnitude, phase angle, and impedance simultaneously offers theoretical advantages, but for the specific problem of voltage drop along long lines, a well-tuned TCSC appears to provide more direct benefits. Third, the SVC's 3.28 percent improvement, while the lowest among the three stand-alone devices, should not be dismissed as insignificant. Shunt compensation at weak buses provides valuable voltage support that benefits all lines connected to those buses, even if the per-line improvements are less dramatic than those achieved by series compensation. Finally, the validation of simulation results against experimental data, which yielded a deviation of only 0.18 percent, confirms that the PSAT models developed in this study accurately represent the real-world Nigerian power system. This validation supports the credibility of all comparative results and the conclusions drawn from them. The percentage improvements of 3.28 percent for SVC, 4.55 percent for TCSC, 4.o7 percent for UPFC, and 4.71 percent for combined FACTS integration provide clear, quantitative guidance for transmission system operators seeking to enhance the load ability of the Nigerian 330KV power system.

IV. CONCLUSION

This study set out to answer a fundamental question in power system optimization: whether the combined integration of multiple Flexible Alternating Current Transmission Systems (FACTS) devices yields superior load ability enhancement compared to the deployment of stand-alone devices. Using the Nigerian 330KV 48-bus power system as a realistic test bed, and employing the Power System Analysis Toolbox (PSAT) for modelling alongside the Particle Swarm Optimization (PSO) algorithm for optimal placement and sizing, the research has produced clear, quantifiable answers. The baseline characterization of the uncompensated system revealed severe voltage drop limitations at multiple buses, including Jos at 298.06 kV and New Haven at 310.36 kV, with eleven transmission lines operating below the base Surge Impedance Loading (SIL) threshold of 382.11 MW, yielding a total baseline SIL of 4,274.43 MW. The comparative analysis across four integration scenarios demonstrated that while all FACTS configurations produced measurable improvements, the combined approach outperformed each stand-alone configuration. Stand-alone Static Var Compensator (SVC) integration improved total SIL to 4,414.62 MW, representing a 3.28 percent enhancement. Stand-alone Thyristor Controlled Series Compensator (TCSC) integration achieved a total SIL of 4,469.12 MW, a 4.55 percent improvement. Stand-alone Unified Power Flow Controller (UPFC) integration reached a total SIL of 4,448.37 MW, a 4.07 percent improvement. The combined FACTS integration, in which SVCs, TCSCs, and UPFCs were deployed simultaneously with each providing 20 percent compensation for a total of 6o percent, achieved the highest total SIL of 4,475.59 MW, corresponding to a 4.71 percent enhancement over the baseline.

Several important conclusions emerge from these findings. First, series compensation via TCSC proved remarkably effective for the specific problem of voltage drop limitations on long transmission corridors, achieving 4.55 percent improvement that came within 0.16

percentage points of the combined configuration. This suggests that when budgetary constraints limit investment to a single device type, TCSC represents the most impactful choice for power systems characterized by similar voltage drop phenomena. Second, the combined configuration, despite its modest margin of superiority over TCSC alone, offers advantages that extend beyond the raw percentage improvement. The distributed nature of combined compensation provides voltage support simultaneously at multiple weak buses, reduces over-reliance on any single technology, and introduces redundancy such that the failure of one device does not eliminate the entire compensation benefit. Third, the validation of simulation results against experimental data, which yielded a deviation of only 0.18 percent, confirms the accuracy and reliability of the PSAT-based modelling approach employed in this study. The practical implications for transmission system operators, particularly those managing aged and stressed networks in developing economies, are substantial. The 4.71 percent improvement achieved by combined FACTS integration translates to approximately 2o1 MW of additional transmission capacity across the constrained lines of the Nigerian 330KV system, realized without constructing a single kilometre of new transmission infrastructure or adding new generation capacity. This represents a cost-effective approach to addressing the persistent challenges of voltage instability, congestion, and limited load ability that have plagued the Nigerian power sector and contributed to economic stagnation. For policy makers and utility planners, the findings provide quantitative justification for investment in FACTS technology as an alternative or complement to traditional infrastructure expansion.

In conclusion, this study demonstrates that combined FACTS integration is indeed more capable of enhancing power system load ability than stand-alone FACTS integration for the Nigerian 330KV 48-bus power system. The 4.71 percent improvement achieved by the combined configuration, while modest in absolute terms, represents a meaningful enhancement of transmission capacity that can alleviate congestion, improve voltage stability, and support increased electricity access without the environmental and financial costs of new transmission line construction. The findings contribute to the body of knowledge on FACTS device coordination and provide a replicable methodology that can be applied to other power systems facing similar load ability challenges worldwide.

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