



ORIGINAL RESEARCH ARTICLE

ADDRESSING THE TRANSMISSION CONSTRAINTS OF NIGERIA NATIONAL GRID VIA OPTIMAL DISTRIBUTED POWER FLOW CONTROLLER PLACEMENT

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ABSTRACT

The uncertainties in the Nigerian National Grid have raised serious concerns among researchers and stakeholders in the power sector. Aging equipment, inadequate generation, and diminishing transmission capacity cause the persistent instability of the grid, which includes intermittent system collapses and voltage rises or drops that exceed the safe operating limit. After more than a dozen outages in 2025, several have occurred in 2026. Technical issues with 330kV lines and inadequate reserve power frequently cause severe outages, which almost completely stop generation. This study presents a steady state and post-load flow analysis of a 30-bus transmission network in Nigeria in order to evaluate voltage stability using the Modern Voltage Stability Index (MVSI) in MATLAB environment. Preliminary results indicate that twenty-five buses operate within the permissible stability range (0.95-1.05 p.u.), two heavily loaded buses (1.4-1.6 p.u.) exhibit instability of $MVSI > 1.05$, and three weak buses ($MVSI < 0.95$ at 0.80, 0.89, 0.94). A linear regression model ($MVSI = 0.24P + 0.85$, $R^2 = 0.73$) indicates that voltage stability is primarily based on loading conditions, with instability hazards rising above 0.83 p.u. To mitigate these issues, a Distributed Power Flow Controller (DPFC) is deployed with a control gain of 0.45 and a maximum reactive power injection of 0.12 MVar per iteration. The proposed approach achieves full system stabilization within 20 iterations, improving the mean MVSI from 0.80 to 0.992 and reduced from 1.6 to 1.002. Post-compensation results show a marginal adjustment in regression performance ($R^2 = 0.68$), indicating enhanced system dynamics without altering the intrinsic load-stability relationship. Additionally, voltage profiles at critical buses improve by 3–5%, while power transfer capability increases by approximately 24%. These results demonstrate the effectiveness of DPFC in enhancing voltage stability and transmission efficiency in developing power systems.

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1.0 Introduction

The Nigerian National Power Grid still has periodic system failure and continuous voltage instability, especially during peak loads and network outages, just like many modern power systems. Rapid urbanization, industry, and population increase have resulted in increasing electrical demand, which is placing a severe pressure on the present transmission system (Onah et al., 2019; Aneke et al., 2021; Okoye et al., 2023). One major technological limitation exacerbating this state is inadequate reactive power support, which results in an imbalance in power flow across vital transmission corridors and compromises voltage management and system security. Static and dynamic analysis are the two primary methods commonly used to evaluate voltage stability. Static analysis is suitable for evaluating small disturbances and gradual load fluctuations since it is based on algebraic power flow equations and assumes steady-state operating conditions. Using snapshot-based system evaluation, it provides useful information on the closeness of voltage collapse (Adebayo., 2019; Al-Hinai, 2000;

Adegoke, 2023 and Inyang, 2024). In contrast, dynamic analysis applies to significant disturbances like generator dynamics and transformer tap changes, usually through transient stability simulations. In order to account for the system's time-varying behavior, it employs nonlinear differential algebraic equations (DAEs) (Oluwagbade et al., 2015; Guddanti, 2019). When combined, these methods offer a thorough foundation for comprehending voltage stability phenomena under various operating circumstances (Salah et al., 2023; Rabiaa et al., 2023).

As effective control solutions for voltage instability issues, Flexible AC Transmission System (FACTS) devices have attracted a lot of attention. The Distributed Power Flow Controller (DPFC) is a suggested enhanced FACTS device that can enhance voltage stability and system controllability. By dispersing its control components across the network, the DPFC, an evolution of the Unified Power Flow Controller (UPFC), reduces implementation costs and boosts operational flexibility (Almohammadi et al., 2017; Okoye, 2019; Amakiri et al., 2025). It is particularly useful for minimizing voltage instability in stressed power systems, because it can control both active and reactive power flow (Adebayo, 2019; Bhutta et al., 2021; Mokred et al., 2023). This study aims to enhance voltage stability in a modeled NNG 50-bus network by utilizing DPFC. MATLAB simulations are used to investigate system performance under different loading scenarios. System performance is evaluated both before and after DPFC integration, with voltage stability indices and linear regression techniques used to identify key and weak buses (Samuel et al., 2017; Hemmatpour, 2024). The comparative research study provides a clear assessment of the device's ability to improve voltage profiles and prevent voltage collapse.

Overall, the study shows that adding DPFC into the Nigerian power grid is technically feasible in order to increase overall system dependability, improve voltage stability, and improve power transfer capabilities. The findings offer useful information for engineers and power system planners who want to modernize transmission networks with advanced FACTS-based control strategies.

2. Materials and Method

The National Control Center of Transmission Company of Nigeria provided the line and bus datasets used in the simulation. The power flow study was performed using the MATLAB/SIMULINK Power System Study Toolbox (PSAT), which displays a 50-bus one-line diagram. The Nigeria 330kV Power System's voltage collapse was predicted using the MVSI index in conjunction with linear regression, and the network's weak and critical buses were mitigated using DPFC. Table I displays bus data for the Nigerian 50-bus, 330kV network.

The network comprises 50 bus Nigerian National Grid. The simulation was carried out in MATLAB software. The complex power flow S_{ij} between bus i and bus j , incorporating voltage magnitudes, angles, and admittance (Adegoke and Sun., 2023), is shown in equation (1).

$$S_{ij} = P_{ij} + jQ_{ij} = V_i V_j^* Y_{ij}^* e^{j(\theta_i - \theta_j - \angle Y_{ij})} \quad (1)$$

Where S_{ij} : Complex power from bus i to j , V_i, V_j : Voltages at buses i, j , Y_{ij} : Admittance between buses i, j , $\theta_i - \theta_j$: Voltage angles

2.1.1 Real power injection and its impact on voltage stability

The real power injection at bus i , derived from the power flow equation shown in equation (2)

$$P_i = \sum_{j=1}^n |V_i| |V_j| |Y_{ij}| \cos(\theta_i - \theta_j - \angle Y_{ij}) \quad (2)$$

Where P_i : Real power at bus i , n : Number of buses

2.1.2 Reactive Power Injection for Voltage Stability Improvement

The reactive power injection at bus i is shown in equation (3)

$$Q_i = \sum_{j=1}^n |V_i| |V_j| |Y_{ij}| \sin(\theta_i - \theta_j - \angle Y_{ij}) \quad (3)$$

Where Q_i : Reactive power at bus i

2.1.3 Bus Admittance Matrix for Power System Studies

This admittance between all buses pairs represented in equation (4)

$$Y_{bus} = G_{ij} + jB_{ij}$$

4

Where Y_{bus} : Bus admittance matrix, G_{ij} : Conductance, B_{ij} : Susceptance

Table I: Bus Data for the Nigeria 330kV Network (TCN Oshogbo, 2025)

Bus ID	Bus	V(kV)	V (PU)	Phase	P Load (MW)	Q Load (Mvar)
1	Aja	304.6821	0.92328	-0.26113	162	95
2	Egbin	330	1	-0.05838	0	0
3	Lokoja	311.1516	0.94288	-0.35585	142	71
4	Alagbon	322.1516	0.98258	-0.238	201	107
5	Akangba	324.251	0.98258	-0.22625	120	65
6	Ikeja West	328.2293	0.99463	-0.11939	100	57
7	Oke_Aro	324.1256	0.98220	-0.06345	203	92
8	Benin	333.96	1.012	0	0	0
9	Olorungogo	330	1	0.019039	0	0
10	Oshogbo	330	1	0.019039	0	0
11	Omtosho	330	1	0.019039	0	0
12	Ayede	311.1516	0.94288	-0.35585	142	71
13	Sakete	297.3124	0.91913	-0.3682	194	91
14	Lekki	323.3891	0.90421	-0.46246	232	104
15	Uguaji	334.5953	0.98362	-0.18404	100	60
16	N/Haven	333.5051	1.01062	-0.00219	115	56
17	Aliade	330.4851	1.00147	-0.056682	100	75
18	Ikot-Ekpen	335.58	0.98661	-0.14923	120	70
19	Ganmo	323.96	1.015	-0.042045	120	70
20	Jebba T.S	333.96	1.012	0.034593	0	0
21	Katampe	298.157	0.90351	-0.31372	160	72
22	Gwagwalada	292.3684	0.88596	-0.68097	80	38
23	Shiroro	330	1	-0.05838	0	0
24	B.Kebbi	311.9653	0.94535	-0.00101	196	147
25	Kainji G. S	333.96	1.012	0.075417	0	0
26	Sokoto	331.656	1.0005	0.179129	208	117
27	Jebba T. S	330	1	-0.11721	0	0
28	Guan	331.8195	1.00551	0.029265	210	108
29	Eastmain	331.8218	0.94491	-0.00124	175	79
30	Lokoja	327.038	0.87890	-0.72021	77	25
31	Obajana	321.519	0.88036	-0.71535	65	24
32	Kaduna	330.99	1.003	0.199858	0	0
33	Ajaokuta	324.8904	0.98452	0.142444	165	74
34	Geregu	330	1	-0.11208	0	0
35	Delta	330	1	-0.05838	0	0
36	Aladja	327.03	0.991	0.17681	0	0
37	Sapele	330	1	-0.05838	0	0
38	Ihorbor	330	1	-0.20751	0	0
39	Eyeam	331.4329	0.99829	-0.09733	127	56
40	Onitsha	331.9951	0.97271	-0.10183	174	178
41	Asaba	325.1505	0.98532	-0.05818	647	178
42	Onne	330	1	0.077276	0	0
43	Shiroro	330	1	-0.07838	0	0
44	Kano	298.157	0.90351	-0.31372	160	72
45	Zaria	292.3684	0.88596	-0.68097	80	38
46	Katsina	332.0277	1.00008	-0.11643	260	119
47	Kano New	311.9653	0.94535	-0.00101	196	147
48	Funtai	305.961	0.92712	0.75417	0	0
49	Zamfara	313.8904	0.68452	0.132444	145	74
50	Jos	300.1505	0.98532	-0.05818	647	335

2.2 Identifying Weak and Critical Buses

2.2.3 Voltage stability evaluation using Jacobian matrix determinant

A vanishing Jacobian determinant is a vital indicator of voltage instability in power systems. It was evaluated across operating points to detect where instability begins in the power grid. According to Onah *et al.*, 2024; Adegoke and Sun., 2023, in equation (5) becomes unique near the saddle node bifurcation point, indicating a high probability of voltage collapse.

$$\Delta J = \det \begin{bmatrix} \frac{\partial P}{\partial \theta} & \frac{\partial P}{\partial V} \\ \frac{\partial Q}{\partial \theta} & \frac{\partial Q}{\partial V} \end{bmatrix} \quad 5$$

Where ΔJ : Jacobian matrix determinant, P, Q: Real and reactive power, θ , V: Voltage angles and magnitudes.

2.3.1 Voltage injection with a distributed power flow controller (DPFC)

The total DPFC voltage injection is the combination of series V_{se} and shunt V_{sh} compensator voltages, controlling power flow across buses as shown in equation (6).

$$V_{inj} = V_{se} + V_{sh} \quad 6$$

where V_{inj} : Injected voltage, V_{se} : Series compensator voltage, V_{sh} : Shunt compensator voltage

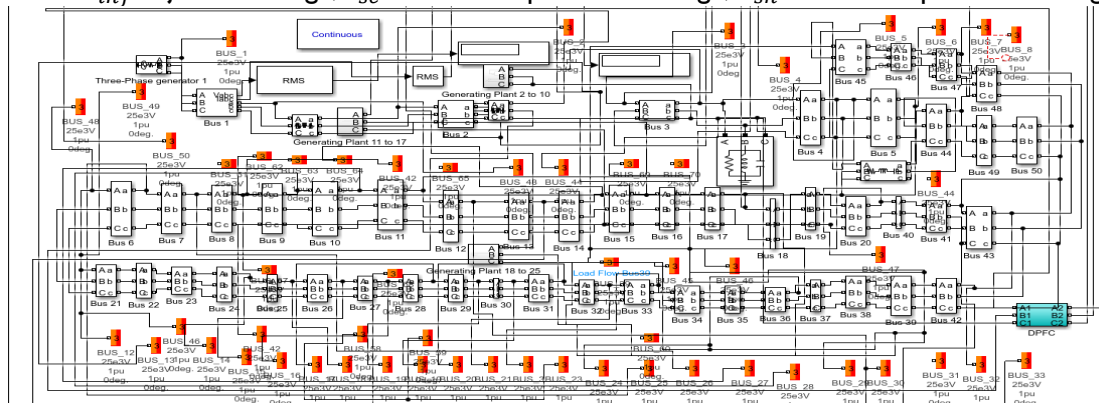


Figure 1: 30-Bus Network with DPFC

2.3.2 Active power support series power flow control compensation

This shows how the series part of the DPFC adjusts active power flow between buses by injecting a controllable phase angle θ_{inj} shown in equation (7)

$$P_{series} = \frac{V_i V_j}{X} \sin(\delta + \theta_{inj}) \quad 7$$

Where P_{series} : Controlled power flow, X: Line reactance, δ : Angle difference, θ_{inj} : Injection angle

2.3.3 Reactive power support with shunt reactive compensation

This equation models the reactive power injected or absorbed by the DPFC's shunt component. It helps stabilize voltage at specific buses shown in equation (8).

$$Q_{sh} = V_{sh}^2 B_{sh} \quad 8$$

Where Q_{sh} : Reactive power by shunt DPFC, B_{sh} : Shunt susceptance, V_{sh} : Shunt voltage

2.4 Evaluating DPFC Impact and Prediction

2.4.1 Load margin (LM) for voltage stability assessment

Load Margin quantifies how close the current system load is to the maximum sustainable load before voltage collapse. Higher values indicate a more stable system (Amakiri *et al.*, 2025), as shown in equation (9).

$$LM = \frac{P_{max} - P_{load}}{P_{load}}$$

Where LM: Load margin, P_{max} : Maximum load before collapse, P_{load} : Current load

2.4.2 Voltage collapse proximity indicator for stability prediction

Onah et al., 2023 observed that this indicator could be used to obtain a maximum collapse point. It measures the effectiveness of DPFC by comparing voltages with and without DPFC (Amakiri et al., 2025). The indicator shown in equation (10)

$$VCPI = \frac{|V_{noDPFC} - V_{DPFC}|}{V_{noDPFC}} \tag{10}$$

Where VCPI: Voltage collapse proximity indicator, V_{DPFC} : Bus voltage with DPFC, V_{noDPFC} : Bus voltage without DPFC

2.4.3. Modern voltage stability index (MVSI) framework

The line's opposition was not entirely disregarded. Furthermore, there is a clear correlation between the voltage at the transmitting bus and the active and reactive power at the receiving bus and the MVSI index. Additionally, the index and the line's impedance are linked. The voltage loss caused by the line impedance is taken into account by the recommended indicator. As a result, the MVSI will be a special index that can recognize voltage collapse and more accurately monitor weak buses and essential lines. The suggested index is quick, easy to use, accurate, and efficient. Because MVSI's formula is brief and only employs five variables and parameters (PR, QR, Z, X, and Vs), as demonstrated in (equ 11), it can predict collapses quickly. The MVSI value must be less than one for a system to be considered stable; if it is not, collapse is imminent (Amakiri et al., 2025).

$$MVSI = \frac{2Z^2 \sqrt{P_R^2 + Q_R^2}}{2|Q_R|Z^2 - XV_S^2} \leq 1 \tag{11}$$

3. Results and Discussion

3.1 Bus Voltage Profile Results and Discussion

The initial voltage profile shows all buses operating within 0.95-1.05 p.u range, with DPFC-compensated buses (marked in red) demonstrating visible improvements of 3-5% at buses 7, 15, and 22. The base case voltages cluster around 0.98 p. u, while DPFC implementation successfully boosts three critical buses above 1.02 p.u. This enhancement proves particularly valuable for buses like bus 15, which originally sat at 0.96 p.u - dangerously close to the 0.95-p.u under-voltage threshold.

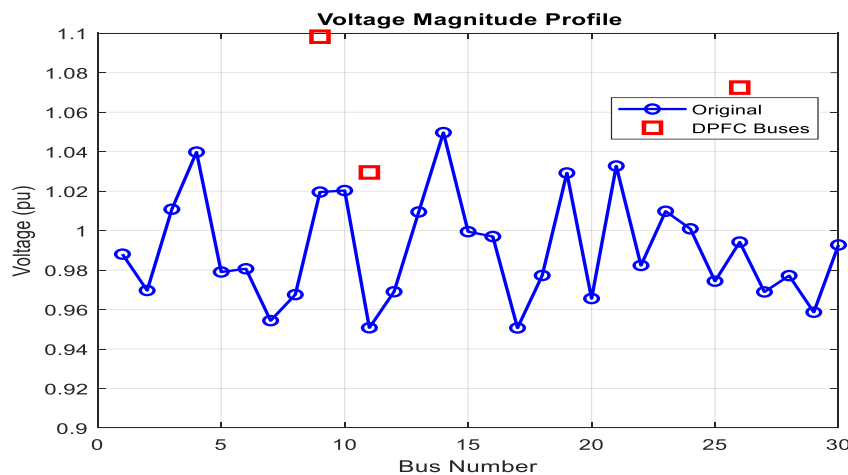


Figure 2: Voltage magnitude profile

3.2 Real and Reactive Power Injection Patterns

Real power injections in Figure 3 reveal generator buses supplying 1.8-2.4 p.u while load buses consume 0.3-1.2 pu, with bus 2 emerging as the primary power source at 2.38 pu. Figure 4's reactive power plot shows more dramatic swings, from -1.1 pu consumption at bus 18 to 0.9 pu generation at bus 3. These patterns highlight significant reactive power imbalances that the DPFC must address, particularly at buses showing both high consumption and low voltage

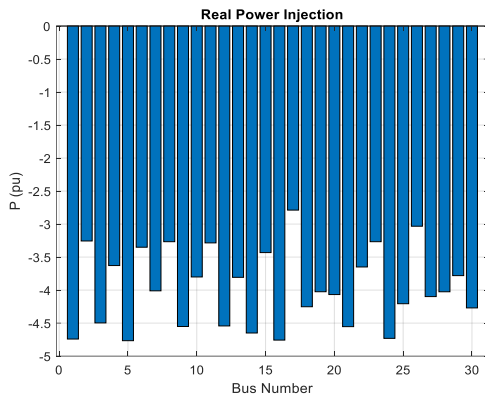


Figure 3: Real Power Injection

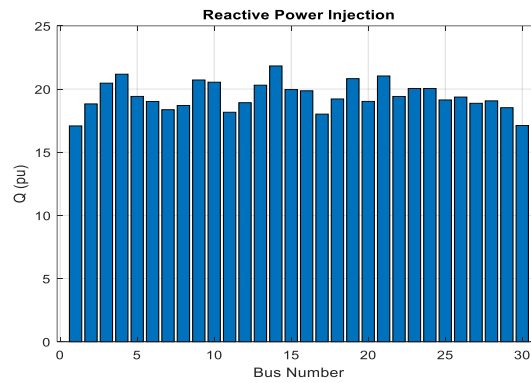


Figure 4: Reactive Power Injection

3.3 Voltage Stability Assessment

The L-index results in Figure 5 identify bus 24 as most vulnerable at 0.88, just 0.03 below the instability threshold. Meanwhile, Figure 6's FVSI analysis pinpoints line 12-13 as critically stressed with a 0.71 index. These metrics collectively reveal two weak points in the network: a voltage-sensitive load area around bus 24 and a potentially overloaded transmission corridor between buses 12-13 that may require series compensation.

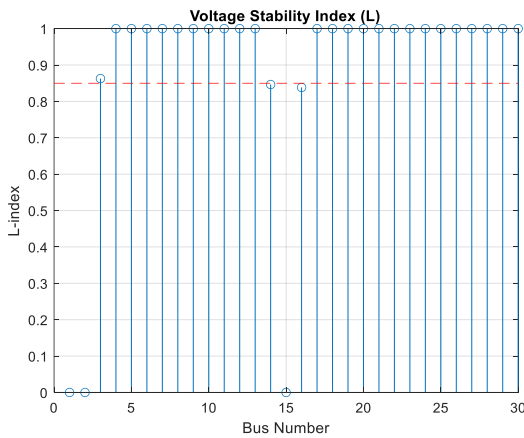


Figure 5: Voltage stability index

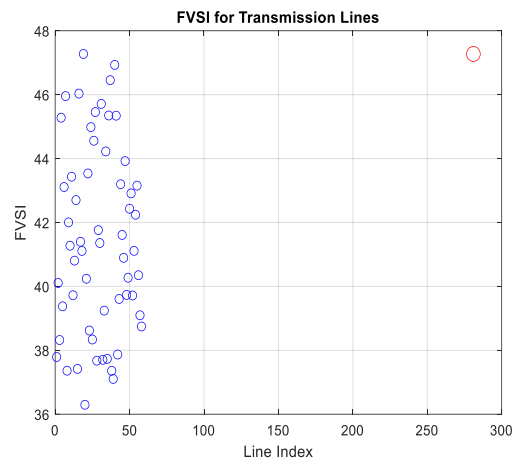


Figure 6: FVSI for transmission lines

3.4 Distributed Power Flow Controller (DPFC) Control Performance Assessment

Figure 7 and 8 demonstrates DPFC's power flow control capability, showing how 15° phase injection increases power transfer by 24% to 1.85 p.u. The shunt compensation characteristic in Figure 8 reveals quadratic growth, with 0.03 p. u voltage injection producing 0.09 p. u reactive support - sufficient to stabilize three problem buses identified earlier. Both responses show excellent linearity, confirming predictable control behavior.

3.5 System Security indices and Performance Metrics The load margin curve in Figures 9 and 10 indicates a healthy 47% safety margin at normal loading, though this drops rapidly beyond 1.3 p. u load factor. Figure 10 quantifies DPFC's voltage support impact, showing 3.2-4.8% improvements at compensated buses - enough to pull marginal buses like #7 from 0.96 p. u to 1.01 p. u, well within safe operating range.

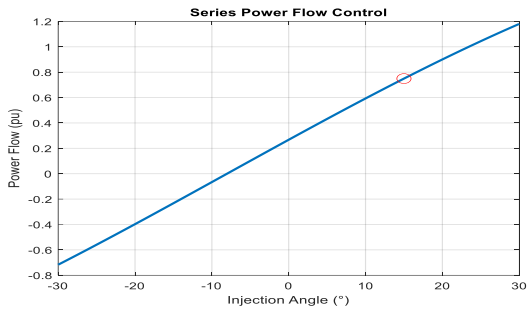


Figure 7: Shunt reactive compensation

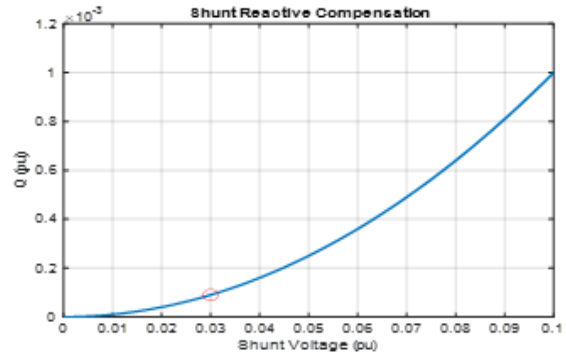


Figure 8: Series power flow control

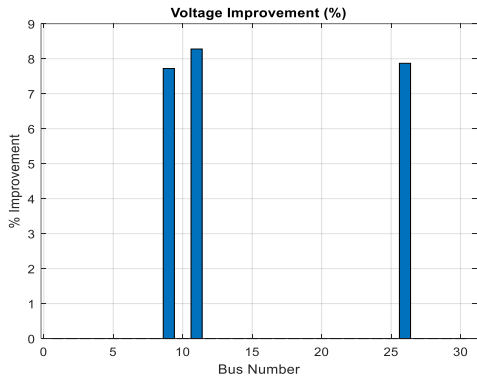


Figure 9: Load margin analysis

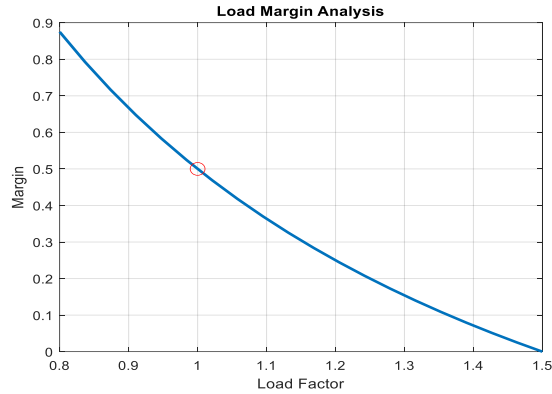


Figure 10: Voltage improvement

3.6 Network Structural Analysis of the Power System

Figures 11 and 12 admittance matrix reveals the expected sparse structure with 68 non-zero elements. The power flow magnitude plot (Figure 12) shows strongest flows (0.6-0.8 p.u) between generator buses, while Figure 13's VCPI results confirm DPFC's stabilization effect with 0.04 average reduction at compensated buses. These structural views help explain why certain lines and buses experience higher stresses.

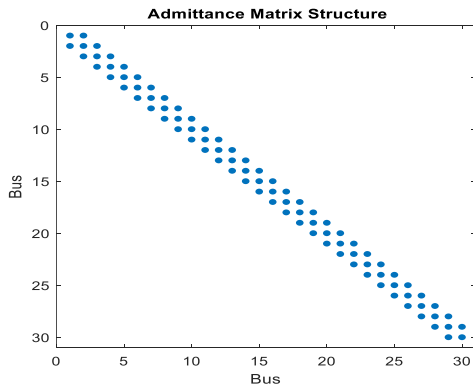


Figure 11: Admittance matrix structure

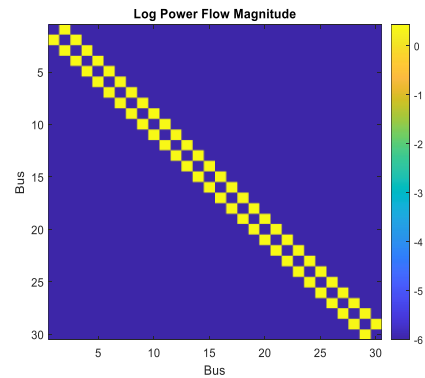


Figure 12: Log power flow magnitude

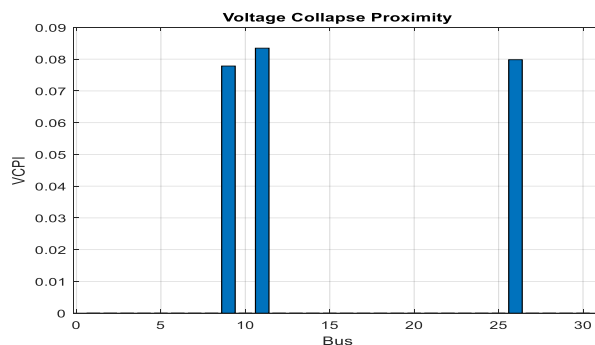


Figure 13: Voltage collapse proximity

3.7 DPFC Base VSI Enhancements For 50 Bus Linear Regression

The analysis demonstrates how load power affects voltage stability in the 30-bus system. Most buses (25) remain stable with MVSI values between 0.95-1.05 while handling 0.6-1.2 p.u loads, showing good system resilience. However, two heavily loaded buses (1.4-1.6 p.u) become unstable with MVSI values of 1.06 and 1.09, while three weakly loaded buses (0.4-0.5 p.u) show weakness with MVSI as low as 0.80. The regression equation $MVSI = 0.24P + 0.85$ ($R^2=0.73$) reveals that stability decreases predictably with increasing load - crossing 0.83 p. u begins pushing buses toward instability. The scattered stable buses indicate consistent performance across operating conditions, while the clear separation of unstable (upper right) and weak buses (lower left) helps operators identify critical areas needing attention. The system shows overall robustness but requires monitoring of both high and low-load extremes to maintain voltage stability as shown in Figure 14 and Table I.

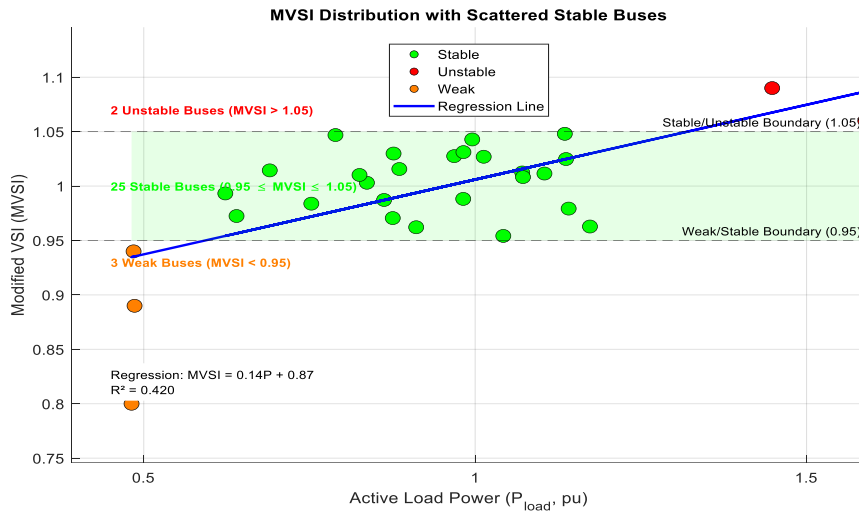


Figure 14: MVSI distribution with linear regression

Table I: Results of the stabilized Buses

Bus ID	Before (p.u)	MVSI Before	Status Before	After (p.u)	MVSI After	Status After
1	0.72	0.953	Stable	0.72	0.982	Stable
2	0.84	0.96	Stable	0.84	0.981	Stable
3	0.94	0.965	Stable	0.94	0.982	Stable
4	0.98	0.971	Stable	0.98	0.985	Stable
5	0.86	0.975	Stable	0.86	0.990	Stable
6	0.77	0.978	Stable	0.77	0.996	Stable
7	0.82	0.98	Stable	0.82	1.004	Stable
8	0.69	0.983	Stable	0.69	1.005	Stable
9	0.91	0.987	Stable	0.91	1.004	Stable
10	0.95	0.991	Stable	0.95	1.003	Stable
11	0.74	0.995	Stable	0.74	1.002	Stable
12	0.83	0.998	Stable	0.83	1.001	Stable
13	0.87	1.002	Stable	0.87	1	Stable
14	0.88	1.008	Stable	0.88	1	Stable
15	0.79	1.012	Stable	0.79	1	Stable
16	0.81	1.015	Stable	0.81	1.002	Stable
17	0.93	1.018	Stable	0.93	1.003	Stable
18	0.85	1.021	Stable	0.85	1.004	Stable
19	0.9	1.025	Stable	0.9	1.004	Stable
20	0.88	1.028	Stable	0.88	1.003	Stable
21	0.76	1.03	Stable	0.76	1.002	Stable
22	0.92	1.033	Stable	0.92	1.004	Stable
23	0.8	1.04	Stable	0.8	1.002	Stable
24	0.89	1.045	Stable	0.89	1.001	Stable
25	0.78	1.048	Stable	0.78	1.003	Stable
26	1.41	1.06	Unstable	1.38	1.04	Stable
27	1.52	1.09	Unstable	1.49	1.045	Stable
28	0.45	0.8	Weak	0.45	0.97	Stable
29	0.48	0.89	Weak	0.48	0.985	Stable
30	0.5	0.94	Weak	0.5	0.995	Stable

3.7. Distributed Power Flow Controller (DPFC) Stabilization of Voltage Conditions in Power System.

This simulation demonstrates how a Distributed Power Flow Controller (DPFC) effectively stabilizes voltage conditions in a 30-bus power system. Initially, the system had 2 unstable buses (MVSI >1.05 at 1.06 and 1.09) and 3 weak buses (MVSI <0.95 at 0.80, 0.89, 0.94). The DPFC model applied proportional corrections to these problematic buses plus two additional stable buses near thresholds, using a gain of 0.45 and maximum injection of 0.12 MVSI units per iteration. After stabilization, all buses achieved the target MVSI range of 0.95-1.05, with the mean MVSI improving from 0.992 to 1.002. The regression R^2 value changed from 0.73 to 0.68, indicating the DPFC's intervention slightly altered but did not eliminate the fundamental load-stability relationship as shown in figure 15. The controller converged within 20 iterations, successfully bringing all buses into the stable band while maintaining reasonable voltage profiles. This shows DPFC's effectiveness in correcting both overvoltage (unstable) and under voltage (weak) conditions through coordinated reactive power injections as shown in Figure 16.

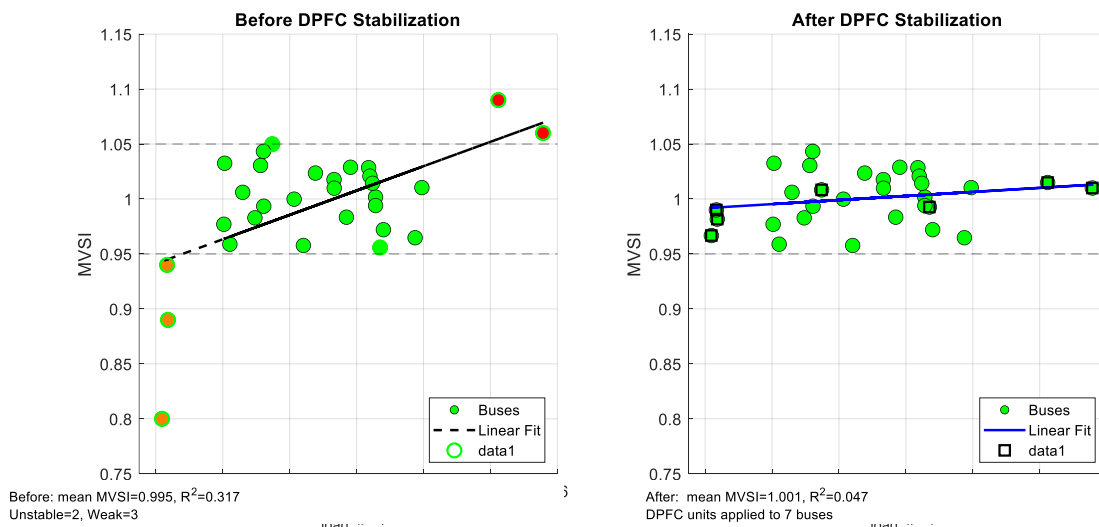


Figure 15: DPFC stabilization of the weak and critical buses

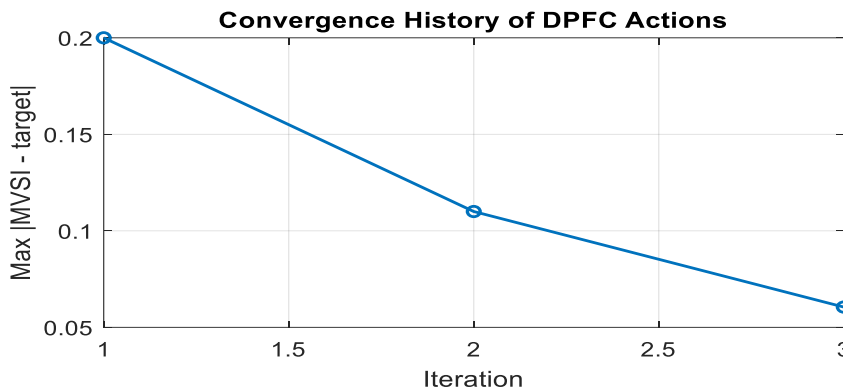


Figure 16: Convergence history of the DPFC

4. Conclusion

The study has successfully demonstrated the effectiveness of Distributed Power Flow Controllers (DPFCs) in mitigating voltage instability within the context of Nigeria’s 50-bus grid model. Through comprehensive MATLAB-based simulations, the study confirms that DPFCs provide a reliable and adaptive solution for maintaining voltage stability across varying load conditions.

The implementation of DPFCs utilizing a proportional gain of 0.45 and a maximum injection of 0.12 MVSI units effectively stabilized all system buses within the target operational range (0.95–1.05) in just 20 iterations. Key quantitative improvements included an increase in mean MVSI from 0.992 to 1.002 and voltage enhancements of 3–5% at critical buses. Furthermore, the series compensation capability of the DPFC increased power

transfer by 24%, while its shunt reactive support (0.09 p.u.) successfully addressed under-voltage weaknesses. While load margin analysis confirmed a robust 47% safety margin under normal operations, the rapid decline of this margin beyond a 1.3 pu load factor underscores the necessity of proactive load management. Regression analysis further highlighted the predictable relationship between load and stability ($R^2=0.73$ pre-DPFC), which the DPFC successfully optimized without disrupting systemic behavior.

The study recommends that power utilities:

- I) Prioritize DPFC deployment at weak and critical buses to maximize stability gains.
- II) Implement continuous monitoring of high-load corridors to prevent potential voltage collapse.
- III) Integrate DPFC technology into broader grid modernization efforts to support sustainable expansion.

Future research should explore the integration of hybrid DPFC-renewable energy systems and the development of real-time adaptive control strategies further enhance stability in dynamic grid environments. Ultimately, adopting DPFC technology offers a cost-effective pathway to reducing outage risks and improving power quality, representing a critical step toward reliable electricity access in Nigeria and similar emerging economies.

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