

Improving Power Quality in a Nigerian Distribution Feeder Using PV-D-STATCOM: Modeling and Simulation in DIgSILENT



F. P. Gbigbidje, E. U. Ubeku, R. A. Omughele, J. O. Olomo, J. Alele

Department of Electrical and Electronic Engineering, Delta State University, Abraka, Oleh Campus, Delta State, Nigeria.



ABSTRACT: This study investigates the integration of photovoltaic-based Distribution Static Compensators (PV D-STATCOMs) to improve voltage stability, reduce losses, and mitigate harmonics in an 11 kV distribution feeder in Ughelli, Nigeria, operated by the Benin Electricity Distribution Company (BEDC). The feeder was modeled in DIgSILENT PowerFactory using actual network data under normal, medium, and heavy loading, as well as dynamic and harmonic conditions. The PV D-STATCOM was configured to supply active power while providing dynamic reactive power support in response to varying loads. Results showed that the minimum voltage under heavy loading improved from 0.637 p.u. to 0.992 p.u., while real power losses decreased by up to 91.4%, primarily driven by active power injection. Total Harmonic Distortion (THD) at critical nodes reduced from 19.9% to about 12.5%. During sudden load increases of up to 700%, the compensators maintained voltages close to 1.0 p.u., demonstrating strong dynamic voltage support. This study confirms that PV inverters can perform dual functions, delivering renewable energy and providing grid support. The integration of PV D-STATCOM offers a cost-effective solution to enhance voltage stability, reduce technical losses, and improve power quality in Nigerian distribution networks. These results indicate that PV D-STATCOMs can complement existing grid infrastructure, contributing to improved reliability and resilience in developing country power systems.

Keywords: PV-DSTATCOM, Voltage Stability, Power Loss Reduction, DIgSILENT PowerFactory, Nigerian Distribution Network.

[Received Oct. 23, 2025; Revised Jan. 25, 2026; Accepted Feb. 07, 2026]

Print ISSN: 0189-9546 | Online ISSN: 2437-2110

I. INTRODUCTION

Electrical power systems consist of three main segments: generation, transmission and distribution. While generation produces electricity and transmission conveys bulk power over long distances, the distribution network delivers electricity directly to end-users, including residential, commercial, and industrial consumers (Idrus et al., 2022). In many developing countries, including Nigeria, distribution networks represent the most vulnerable stage of the supply chain. This is due to high technical losses, poor voltage regulation, and susceptibility to power quality issues.

Reports indicate that approximately 13% of generated energy in distribution systems is lost, largely due to high resistance-to-reactance (R/X) ratios that aggravate voltage drops and increase power losses (Ramadan et al., 2019). These challenges reduce network efficiency, raise operational costs, and compromise service reliability. Addressing them requires advanced reactive power compensation technologies capable of operating effectively under variable loading conditions and in the presence of non-linear loads (Elsayed et al., 2019; Amin et al., 2019).

Conventional compensation methods, such as fixed or switched capacitor banks, are limited in flexibility and response speed. Modern solutions, such as Distributed Flexible AC Transmission System (D-FACTS) devices, especially the Distribution Static Compensator (D-STATCOM), offer rapid dynamic injection or absorption of reactive power to stabilize voltages and improve power quality (Idrus et al., 2022). However, conventional D-STATCOM deployment often involves high installation costs and separate infrastructure, which may be financially challenging for utilities in developing regions.

Numerous studies have explored the application of Distributed Static Compensators (D-STATCOMs) to address power quality challenges in distribution networks, including voltage sag, harmonic distortion, and power losses. Kumar et al. (2024) developed a grid-tied photovoltaic (PV) system integrated with a D-STATCOM, reporting reductions in harmonic distortion and voltage sag at the Point of Common Coupling (PCC). However, this work was limited to simulations on simplified test networks, lacking consideration of real-life network variability. Similarly, Patil (2021) introduced a hybrid JCF-LA optimization model to determine the optimal placement and sizing of D-STATCOM devices

while considering economic costs and voltage stability. Despite these strengths, this study did not incorporate renewable energy sources as active providers of reactive power.

Varma and Siavashi (2018) proposed the innovative PV-STATCOM concept, in which PV inverters support reactive power compensation at night and supply both active and reactive power during daylight hours. While this approach demonstrated improvements in voltage regulation, it did not explicitly analyze real-time coordination of active and reactive power under dynamic loading conditions. Other researchers focused on optimization strategies: Grover-Silva et al. (2017) employed a Second-Order Cone Program (SOCP) to optimally size and place grid-connected battery systems. Shaheen et al. (2023) combined PV-STATCOM operation with the Hunter-Prey Optimization (HPO) algorithm, resulting in significant improvements in voltage profiles and reductions in energy losses. Nonetheless, these studies primarily used standard IEEE 14-, 33-, 69-, or 83-bus test systems. While widely accepted in academia, these models do not fully reflect the operational complexities and unique constraints of real distribution networks, particularly in rural or semi-urban Nigerian contexts.

Additional notable contributions include Ismail et al. (2022), who utilized the Chu-Beasley genetic algorithm to optimize the placement and sizing of D-STATCOM devices on an IEEE 33-bus system, leading to lower annual operational costs. Gangil et al. (2021) applied differential evolution algorithms, achieving better placement outcomes compared to particle swarm optimization. Yuvaraj and Devalalaji (2015) addressed load variation challenges using the bat algorithm, while Isha and Jagatheeswari (2021) implemented a fuzzy-lightning search algorithm, improving voltage stability and reducing system losses. Singh et al. (2021) examined voltage control in distribution systems through reactive power dispatch. Their study emphasized the importance of maintaining a stable voltage profile.

An emerging solution is the use of photovoltaic (PV) inverters configured as dual-function PV D-STATCOMs. These devices can supply active power during daylight hours while dynamically providing reactive power support by utilizing available inverter headroom. While previous studies have explored aspects of this concept, most have been conducted on idealized IEEE test feeders, without accounting for the operational complexity of real-life Nigerian distribution networks. Furthermore, there is limited evidence on how PV D-STATCOMs perform under varying loading conditions, sudden demand fluctuations, and harmonic distortion in such practical environments.

This study addresses these gaps by modeling and simulating PV D-STATCOM integration on an actual 11 kV distribution feeder in Ughelli, Nigeria, operated under the Benin Electricity Distribution Company (BEDC). Using DIgSILENT PowerFactory and actual utility data, the work evaluates the impact of PV D-STATCOMs on voltage stability, power loss reduction, and harmonic mitigation.

The novelty lies in applying the PV D-STATCOM concept to a real feeder with zone-based placement optimization. By testing performance under both steady-state and dynamic conditions, this study provides practical insights for power

quality improvement in Nigerian and similar developing country networks. Finally, the remainder of this paper is organized as follows: Section II presents the materials and methods used for the modeling and simulation of the PV D-STATCOM system. Section III discusses the results and analysis of the simulation outcomes, while Section IV concludes the study with key findings and recommendations for future work.

II. MATERIALS AND METHOD

This study adopted a structured, simulation-based methodology to assess the performance of photovoltaic-based Distribution Static Compensators (PV D-STATCOMs). The primary objectives were to improve voltage stability, reduce power losses, and mitigate harmonic distortion in a real-life Nigerian distribution feeder. This approach combined actual network data with detailed digital modeling in DIgSILENT PowerFactory, enabling realistic representation of system operating conditions. The methodology encompassed data acquisition, feeder characterization, network modeling, load flow analysis, and the integration of PV D-STATCOMs under various operating scenarios. By simulating both steady-state and dynamic events, this method provided a comprehensive framework for evaluating the technical benefits of PV D-STATCOM deployment in practical distribution network environments.

A. Study Design and Scope

This study employed a simulation-based methodology to evaluate strategies for improving voltage regulation and reducing power losses in the real-life 11 kV Isoko Road Feeder, located in Ughelli, Delta State, Nigeria. The focus was on integrating photovoltaic-based Distribution Static Compensators (PV D-STATCOMs), configured to supply active power and dynamically inject reactive power in response to network demand.

Using operational data obtained from the Benin Electricity Distribution Company (BEDC), the feeder was modeled and analyzed in DIgSILENT PowerFactory. This research process included data acquisition and validation, detailed network modeling, simulation of load flow under normal, medium, and heavy loading conditions and PV D-STATCOM integration. The feeder's topology, represented in Figure 1, provided a realistic foundation for testing the compensator's effectiveness under practical conditions.

This structured approach ensured that the analysis addressed specific challenges of Nigerian distribution systems while also generating insights applicable to broader power system planning and optimization.

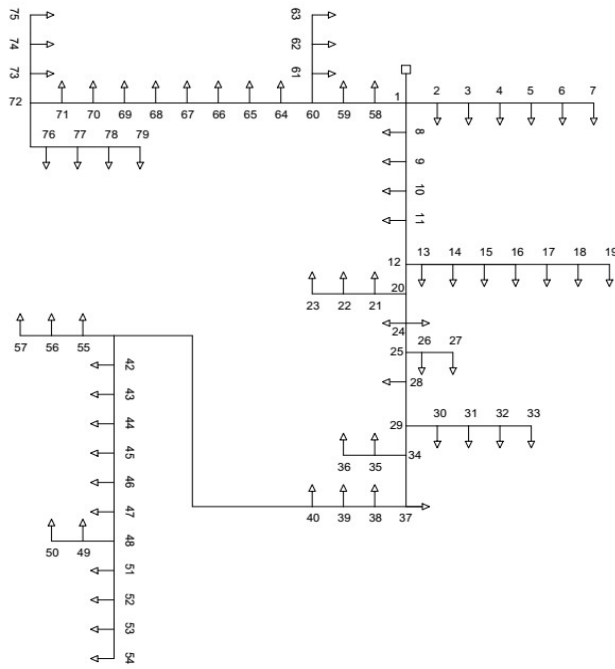


Figure 1 Single-line diagram of the 11 kV Isoko Road Feeder

B. Data Collection and Network Characterization

Accurate and validated data were central to the reliability of this study's modeling. Operational data were obtained directly from BEDC, covering real and reactive power demand at seventy distribution transformers, each rated between 50 kVA and 500 kVA. Additional information included feeder segment lengths, conductor types; All Aluminium Conductor (AAC) on the 11 kV feeder and Aluminium Conductor Steel Reinforced (ACSR) on the upstream 33 kV lines and corresponding impedance values.

Field consultations with BEDC engineers and local technicians provided practical insights into recurring voltage drops, overloading patterns, and maintenance challenges. Using ZWCAD 2025, a single-line diagram incorporating node-by-node loading and transformer data was drafted; the feeder's topology is illustrated in Figure 1. By integrating field measurements with operational data, the digital model closely reflected actual network characteristics, ensuring realistic simulation and credible analysis of PV D-STATCOM performance.

C. Case Study Location and System Overview

The Isoko Road Feeder is a radial 11 kV distribution network originating from the OTOVWODO U16 Injection Substation, which itself receives power from the Ughelli Transmission Station through a 132/33 kV step-down transformer. At OTOVWODO, voltage is further reduced from 33 kV to 11 kV by a single 15 MVA transformer. Spanning approximately 22.24 km, the feeder serves a mix of residential, commercial, and institutional consumers, including facilities such as Zenith Bank, First Bank, and DAGIRI Primary School.

The network comprises several branches that extend to high-demand areas like Agwadodo, Student Villa, Usman Usman, and Yakazib Guest Inn. It was chosen for this study due to its known voltage regulation challenges, its operational importance within the urban grid of Ughelli, and the availability of detailed operational data from BEDC. These factors ensured this study's findings remain practically relevant for real-world planning and power quality improvement strategies.

D. Network Modeling in DIgSILENT PowerFactory

The feeder was digitally modeled using DIgSILENT PowerFactory version 15.1.7, which is widely applied for power system analysis. The single-line diagram drafted in ZWCAD 2025 was imported and extended to include calculation nodes as busbars, transformers configured with actual step-down ratios, feeder lines represented by real impedance data, and load elements corresponding to measured demand at each distribution transformer.

To validate the model, simulated no-load and full-load voltages at key buses were compared with BEDC's field measurements. This verification confirmed that the digital representation accurately matched real system behavior, providing confidence in the reliability of subsequent simulations involving PV D-STATCOM integration and performance assessment.

E. Load Flow Analysis and Theoretical Foundation

The load flow analysis was conducted using the Newton-Raphson iterative method, selected for its quadratic convergence properties which are well-suited for radial distribution networks like the Isoko Road Feeder. The method iteratively solves the power mismatch equations until the solution converges within a specified tolerance, as detailed in standard power system analysis texts (Grainger and Stevenson, 1994). Within PowerFactory, the Jacobian matrix linking incremental changes in voltage and angle to real and reactive power was generated automatically, enabling efficient computation.

Using this method provided a detailed view of steady-state node voltages, system losses, and the potential benefits of integrating compensation devices, forming the analytical foundation for evaluating network performance improvements. The Newton-Raphson method iteratively solves a set of nonlinear algebraic equations representing the power balance at each bus. Its implementation in PowerFactory allows for efficient analysis of radial distribution systems such as the 11 kV Isoko Road Feeder.

F. Modeling Components and Reference Data

To ensure technical accuracy and realism, the simulation model included standard PowerFactory components representing real-life equipment: busbars for node voltage calculations; external grids modeled as voltage-controlled sources simulating upstream supply; transformers matching actual system voltage ratios and impedance; and PV system elements configured for dual active/reactive power operation.

The Station Controller played a key role by dynamically adjusting reactive power output to maintain target voltage

levels, emulating real-world automatic voltage regulation strategies. The entire simulation process was supported by detailed data on transformer capacities, bus loads, conductor types, and line impedances, ensuring the model accurately reflected the actual distribution feeder’s characteristics.

G. PV D-STATCOM Integration and Simulation Strategy

The core innovation in this study lies in simulating PV-based D-STATCOMs as multi-functional devices capable of injecting both active and reactive power. Within the PowerFactory environment, the PV system element was configured to supply active power according to system demand. Simultaneously, reactive power support was managed dynamically using the Station Controller operating in 'Voltage Setpoint Adaptation' mode.

Recognizing the load diversity typical of real-life distribution networks, the feeder was divided into three operational zones to optimize PV D-STATCOM placement. This zoning strategy was quantitatively defined based on distance from the source of supply and load clustering. Specifically, zones were delineated to group high-load clusters, ensuring that the impact of voltage drops could be analyzed as branches extended further from the injection substation. Figure 2 illustrates Network topology of the Isoko Road Feeder divided into three operational zones.

Simulation scenarios included three loading conditions: normal loading (Load Factor = 1.0), medium loading (LF = 0.8), and heavy loading (LF = 1.5). Each scenario was simulated first without and then with PV D-STATCOM integration to evaluate improvements in voltage profiles and reductions in active power losses. Additionally, a dynamic load increase event was simulated at a critical node to assess the compensator’s ability to stabilize voltage during sudden demand spikes.

Harmonic analysis was also performed by injecting a harmonic current source into the model to study how the PV D-STATCOM’s reactive power capability could mitigate voltage distortion. Together, these simulations provided a comprehensive evaluation of the compensator’s performance under steady-state and dynamic conditions.

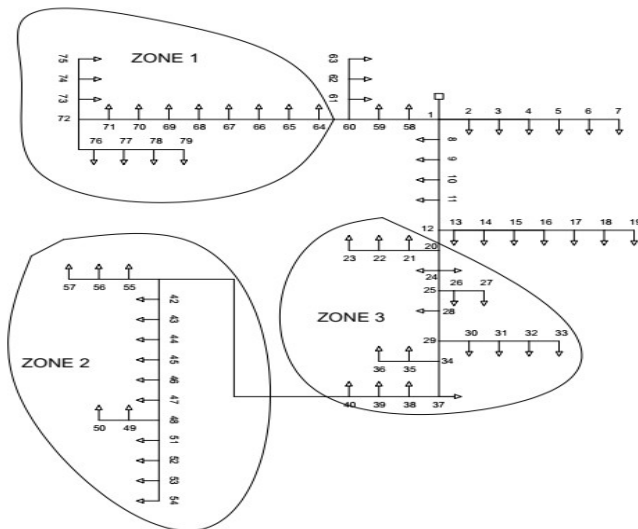


Figure 2 Network topology of the Isoko Road Feeder divided into three operational zones

III. RESULTS AND DISCUSSION

The simulations carried out on the 11 kV Isoko Road Feeder generated performance indicators reflecting behavior under normal, medium, and heavy loading, as well as during dynamic events and harmonic injection scenarios. This analysis focused on four major aspects: voltage profile improvement, power loss reduction, feeder response to sudden load changes, and mitigation of harmonic distortion. Each result is presented and immediately discussed to highlight its technical implications for real-life network performance.

A. Voltage Profile before PV D-STATCOM Integration

The Ughelli distribution network’s voltage profiles were simulated under normal loading (LF = 1.0), medium loading (LF = 0.8), and heavy loading (LF = 1.5). Under heavy loading, the lowest node voltage was about 0.637 p.u. at Node 54. Under normal loading, the minimum voltage increased to 0.810 p.u., while medium loading produced about 0.857 p.u. Voltage decline was most noticeable at the feeder’s end nodes as shown in Figure 3. These results show that the feeder’s voltage profile was highly sensitive to loading, with voltages dropping well below statutory limits under heavy demand. This behavior is consistent with Kumar et al. (2024) and Varma & Siavashi (2018), who observed similar voltage depression in feeders without adequate reactive support. This simulation highlights the vulnerability of real operating conditions, confirming the need for advanced compensation strategies.

B. Voltage Profile After PV D-STATCOM Integration

After integrating three PV D-STATCOM units at Nodes 79, 54, and 25, voltage levels improved across all loading conditions. Under heavy loading (LF = 1.5), the lowest voltage rose from 0.637 p.u. to about 0.992 p.u. For normal loading, the minimum increased to about 0.994 p.u., keeping all buses within acceptable limits as shown in Figure 4. These improvements demonstrate the effectiveness of PV D-STATCOMs in stabilizing voltages within statutory limits. Compared to Kumar et al. (2024) and Varma and Siavashi (2018), who reported lower recovery margins on IEEE test feeders, this study achieved greater enhancement because device placement was based on real feeder data and operational zone analysis. The dual active/reactive capability ensured voltage support even during peak loading, aligning with Varma and Siavashi (2018), but extending it to a real Nigerian feeder with practical relevance

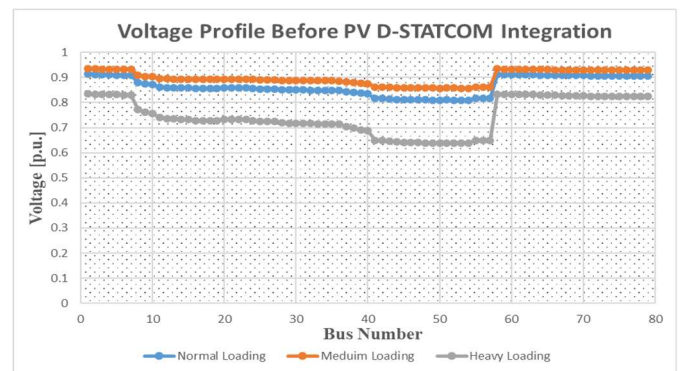


Figure 3 Simulated voltage profiles under normal, medium, and heavy loading before PV D-STATCOM integration

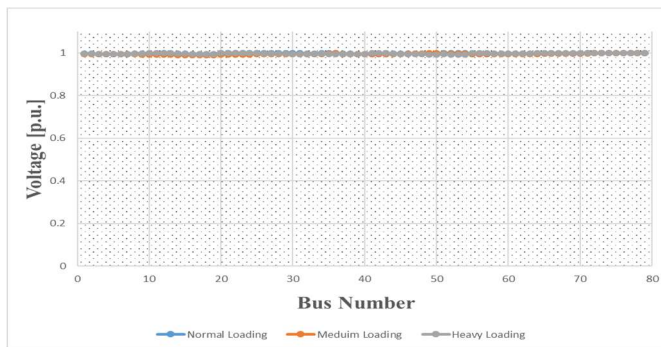


Figure 4 Simulated voltage profiles under normal, medium, and heavy loading after PV D-STATCOM integration.

C. Power Loss Analysis

Total real power losses were calculated under normal, medium, and heavy loading before and after PV D-STATCOM integration. Losses were about 0.91 MW under normal loading and increased to 3.02 MW under heavy loading. After integration of PV D-STATCOM, they reduced significantly to 0.21 MW and 0.26 MW, respectively. The detailed comparison is shown in Table 1, which highlights notable reductions across the feeder. Real power losses under heavy loading dropped from 3.02 MW to about 0.26 MW, representing a 91.4% reduction. This efficiency gain is higher than improvements reported in Shaheen et al. (2023), where D-STATCOM placement on IEEE test feeders achieved lower percentages due to the absence of dynamic active-reactive coordination. The substantial reduction in losses (up to 91.4%) is primarily driven by the significant local active power injection (3.0 MW) from the PV system, which drastically reduces current flow from the upstream substation. The reactive power compensation component further optimizes the reduction by correcting the power factor and minimizing I²R losses.

Table 1 Power Loss Reduction Detail

Loading Condition	Real Power loss in MW		
	Before PV-D-STATCOM	After PV-D-STATCOM	Percentage Reduction
Normal	0.91	0.21	76.9%
Medium	0.54	0.18	66.7%
Heavy	3.02	0.26	91.4%

Table 2 Comparison of Voltage Change at Node 79 before and after PV D-STATCOM Integration

Loading at node 79	Without PV D-STATCOM		With PV D-STATCOM Constant Injection of 1.5 MW and 0.4 MVar		With PV D-STATCOM Dynamic Injection at constant active power of 1.5 MW with changing reactive power injection.		
	Voltage Before in p.u.	Voltage After in p.u.	Voltage Before in p.u.	Voltage After in p.u.	Voltage Before in p.u.	Voltage After in p.u.	Reactive Power Injection in MVar
50%	0.91	0.91	1.0	1.001	1.0	1.0	0.3
100%	0.91	0.90	1.0	0.998	1.0	1.0	0.4
200%	0.91	0.90	1.0	0.996	1.0	1.0	0.6
300%	0.91	0.90	1.0	0.994	1.0	1.0	0.8
400%	0.91	0.90	1.0	0.992	1.0	1.0	0.9
500%	0.91	0.89	1.0	0.990	1.0	1.0	1.1
600%	0.91	0.89	1.0	0.990	1.0	1.0	1.3
700%	0.91	0.89	1.0	0.990	1.0	1.0	1.5

D. Load Change

Node 79 was selected for this dynamic analysis because it represents the tail-end of the feeder, furthest from the injection substation. In radial distribution networks, tail-end nodes experience the most severe voltage drops and are most vulnerable to load fluctuations, making this the critical worst-case location for testing the compensator's performance. The modeling assumption for this simulation was that the load at the target bus (Node 79) varied dynamically while all other network loads remained constant at their base values. This isolation allows for a specific assessment of the compensator's transient response.

A load ramp event was simulated at Node 79 under normal loading, with demand increased up to 700%. Before PV D-STATCOM integration, node voltage fell from about 0.91 p.u. to 0.89 p.u. at peak load as shown in Figure 5. After PV D-STATCOM integration, two scenarios were evaluated. In the constant injection case (1.5 MW active and 0.4 MVar reactive), voltage stayed within 1.0–0.990 p.u. In the dynamic injection case, reactive support adapted from 0.3 MVar at 50% load to 1.5 MVar at 700%, keeping voltage nearly constant at 1.0 p.u. For example, at 100% load increase, voltage before integration dropped to 0.90 p.u., while dynamic compensation kept it near 1.0 p.u. as shown in Figure 6. The full voltage response at Node 79 under varying loading conditions before and after PV D-STATCOM integration is shown in Table 2. These results confirm that PV D-STATCOMs provide strong dynamic support during demand spikes. Both constant and dynamic modes stabilized the feeder, with the dynamic strategy more effective. This sustained stability is more robust than the results in Yuvaraj et al. (2015) and Isha and Jagatheeswari (2021), where voltage support under load variation was achieved but lacked integrated active-reactive coordination.

Here, the Station Controller's "Voltage Setpoint Adaptation" allowed instantaneous adjustment of reactive output, a capability not fully explored in IEEE test-feeder studies.

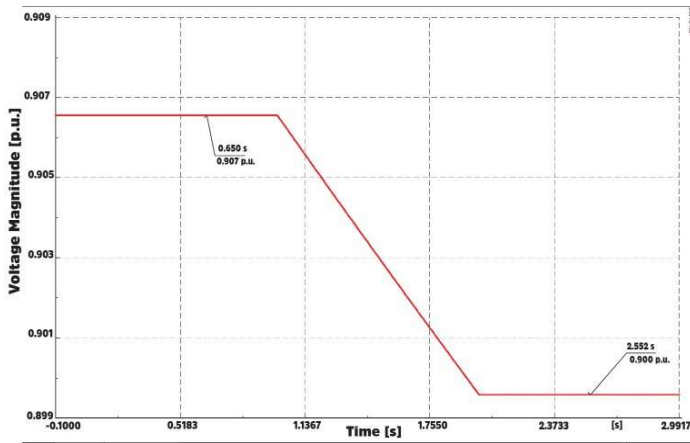


Figure 5 Voltage response at Node 79 during load increase before PV D-STATCOM integration

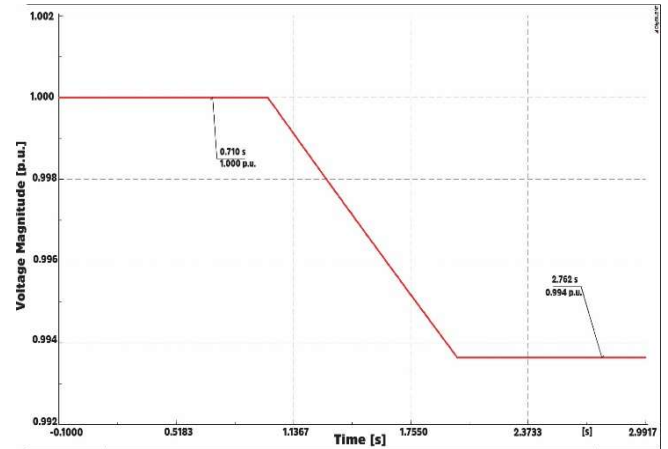


Figure 6 Voltage response at Node 79 during load increase after PV D-STATCOM integration

E. Harmonic Distortion Analysis

Harmonic current injections were simulated at Node 55 to evaluate waveform distortion. Table 3 presents the harmonic order, magnitude, and phase angles used in the simulation. The 5th harmonic was injected at 80% of the fundamental current, the 7th at 50%, the 11th at 30%, and the 13th at 40%. Without compensation, the Total Harmonic Distortion (THD) at Node 55 rose to 19.9%, exceeding limits as shown in Table 4 and Figure 7. After PV D-STATCOM integration, operating in reactive power control mode, THD decreased significantly.

Table 3 Harmonic Current Injection at Node 55

Harmonic Order	$I_{\text{harmonic}}/I_{\text{Fundamental}}$	Angle
5	80.	0
7	50.	0
11	30.	0
13	40.	0

Table 4 Simulation data output showing the percentage magnitude of individual harmonic orders at Node 55 before PV D-STATCOM integration.

Harmonics Rated Frequency	IS_55 Harmonic Distortion in %
5.0000	7.6635
7.0000	7.0166
11.0000	8.0148
13.0000	14.9271

Table 5 Simulation data output showing reduced percentage magnitudes of harmonic orders at Node 55 after PV D-STATCOM integration

Harmonics Rated Frequency	IS_55 Harmonic Distortion in %
5.0000	5.4391
7.0000	5.0101
11.0000	5.8405
13.0000	11.1054

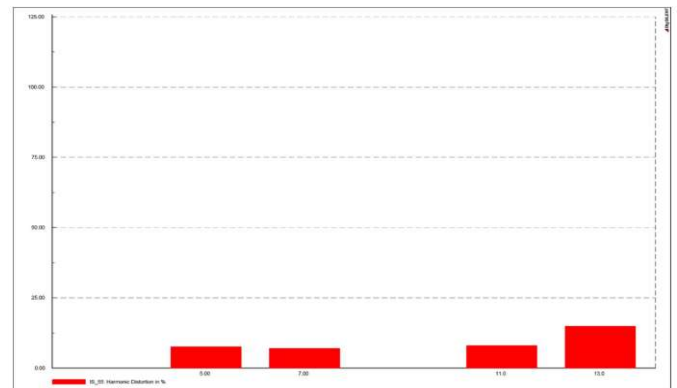


Figure 7 Harmonic spectrum at Node 55 before PV D-STATCOM integration

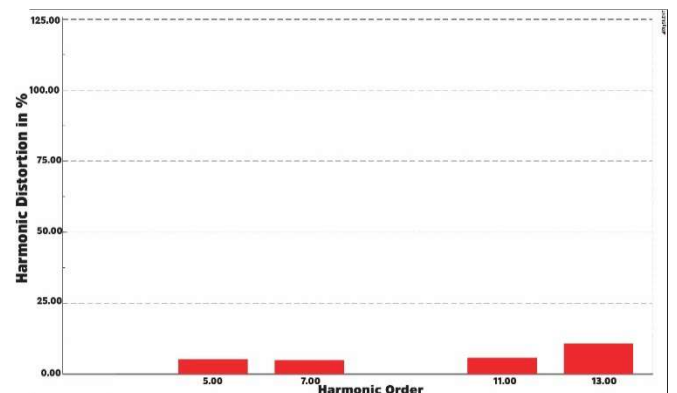


Figure 8 Harmonic spectrum at Node 55 after PV D-STATCOM integration

With 1.5 MW active power, reactive support (4–8 MVar) reduced THD from 19.9% to 12.5%. Simultaneously, node voltage improved from 0.97 p.u. to over 1.06 p.u. as shown in Table 5 and Figure 8. Tables 6, 7 and 8 summarize the effect of PV D-STATCOM on THD under three configurations: constant active power, zero active power, and varying both active and reactive power. This result shows that PV D-STATCOMs are effective not only for voltage regulation and power loss reduction but also for mitigating harmonic distortion. The THD reduction from 19.9% to 12.5% is stronger than reported by Kumar et al. (2024), who studied PV-based mitigation on simplified models. The greater effectiveness here is due to adaptive reactive power control, which scaled support in proportion to distortion severity, ensuring superior performance under real operational conditions.

It is important to clarify the modeling mechanism used. No specific active harmonic filtering control loop was developed for this study; instead, the standard Station Controller provided in the DIgSILENT PowerFactory library was utilized. As noted in the software documentation, the Station Controller acts on sources to control the reactive power flow according to the desired characteristic. In this case, maintaining the voltage level at the busbar. By injecting reactive power to support the voltage magnitude, the controller effectively improves the grid stiffness at the Point of Common Coupling (PCC). This physical improvement in the voltage profile indirectly mitigates the harmonic distortion (THD), as confirmed by the simulation results.

Table 6 PV D-STATCOM effect on THD at constant active power and varying reactive power injection at Node 55

Active Power Injection in MW	Reactive Power Injection in MVar	THD Before in %	THD After in %	Voltage After in p.u.
1.5	4	19.9	14.6	0.97
1.5	4.5	19.9	14.2	0.98
1.5	5	19.9	13.9	1
1.5	5.5	19.9	13.7	1.01
1.5	6	19.9	13.4	1.02
1.5	6.5	19.9	13.2	1.03
1.5	7	19.9	12.9	1.04
1.5	7.5	19.9	12.7	1.05
1.5	8	19.9	12.5	1.06

Table 7 PV D-STATCOM effect on THD at zero active power and varying reactive power injection at Node 55

Active Power Injection in MW	Reactive Power Injection in MVar	THD Before in %	THD After in %	Voltage After in p.u.
0	1	19.9	18.4	0.84
0	2	19.9	17.3	0.88
0	3	19.9	16.3	0.91
0	4	19.9	15.5	0.94
0	5	19.9	14.8	0.96
0	6	19.9	14.2	0.99
0	7	19.9	13.6	1.01
0	8	19.9	13.1	1.03
0	9	19.9	12.7	1.05
0	10	19.9	12.3	1.07

Table 8 PV D-STATCOM effect on THD at varying active power and reactive power injection at Node 55

Active Power Injection in MW	Reactive Power Injection in MVar	THD Before in %	THD After in %	Voltage After in p.u.
0.5	0.5	19.9	18.6	0.84
0.5	1	19.9	17.9	0.86
1	1	19.9	18.7	0.87
1	1.5	19.9	16.9	0.89
1.5	1.5	19.9	16.6	0.9
2	1.5	19.9	16.2	0.91
2	2	19.9	15.8	0.93
2	2.5	19.9	15.4	0.94
2.5	2.5	19.9	15.1	0.95
3	3	19.9	14.5	0.98
4	4	19.9	13.4	1.02
5	5	19.9	12.5	1.06

IV. CONCLUSION

This study modeled the integration of PV D-STATCOMs on a real 11 kV feeder in Ughelli, Nigeria, utilizing actual utility data in DIgSILENT PowerFactory. Unlike prior studies reliant on idealized IEEE test systems, this research evaluated performance under realistic operational constraints, including heavy loading and dynamic disturbances. The results demonstrated significant technical improvements. Minimum node voltages under heavy loading rose from 0.637 p.u. to 0.992 p.u., ensuring statutory compliance, while active power losses decreased by up to 91.4% primarily due to local power injection. Additionally, the system-maintained voltage stability during 700% load ramps and reduced Total Harmonic Distortion (THD) from 19.9% to 12.5%, confirming the device's capability to improve grid stiffness. Practically, these findings demonstrate that Nigerian utility operators, such as

BEDC, can leverage existing solar PV infrastructure to provide ancillary grid services, reducing the need for separate, capital-intensive capacitor bank installations. This dual-function approach validates that PV inverters can serve as cost-effective tools for addressing persistent undervoltage and power quality challenges in developing networks.

However, it is important to acknowledge that these results are based on the simulation of a specific radial 11 kV feeder. The performance of PV D-STATCOMs in other network topologies may vary depending on inverter capability limits and specific feeder characteristics. Future research should extend this work by benchmarking PV D-STATCOMs against other compensation devices, such as Dynamic Voltage Restorers (DVRs) and Battery Energy Storage Systems (BESS), and by employing metaheuristic optimization to refine placement strategies for broader application.

AUTHOR CONTRIBUTIONS

F. P. Gbigidje conceived the concept, developed the PV D-STATCOM model, performed the simulations, and drafted the manuscript. **E. U. Ubeku** supervised the research, validated the methodology, and reviewed the work for technical accuracy. **R. A. Omughele** assisted with data collection from BEDC and model configuration. **J. O. Olomo** verified the simulation results, harmonic analysis, and power loss computations. **J. Alele** handled the manuscript structuring, figure presentation, and formatting compliance. All authors read and approved the final manuscript.

ACKNOWLEDGEMENT

The authors gratefully acknowledge the Benin Electricity Distribution Company (BEDC) for providing the necessary network data and the Department of Electrical and Electronic Engineering, Delta State University, Abraka, Oleh Campus, for the technical resources used in this research.

REFERENCES

Amin, A.; S. Kamel; A. Selim and L. Nasrat. (2019). Optimal placement of distribution static compensators in radial distribution systems using hybrid analytical-coyote optimization technique. *IEEE 21st International Middle East Power Systems Conference (MEPCON)*, pp. 1–9. <https://doi.org/10.1109/MEPCON47431.2019.9007924>.

Elsayed, A. M.; M. Mishref and S. M. Farrag. (2019). Optimal allocation and control of fixed and switched capacitor banks on distribution systems using Grasshopper Optimisation Algorithm with power loss sensitivity and rough set theory. *IET Generation, Transmission & Distribution*, 13(17), 3863–3878. <https://doi.org/10.1049/iet-gtd.2018.5494>.

Gangil, G.; S. K. Goyal; A. Saraswat; A. Soni and M. Srivastava. (2021). Power quality improvement using DSTATCOM in distribution network. *International Conference on Control, Automation, Power and Signal Process (CAPS)*, pp. 1–6. <https://doi.org/10.1109/CAPS52117.2021.9730717>

Grainger, J. J. and Stevenson, W. D. (1994). *Power System Analysis*. New York: McGraw-Hill.

Grover-Silva, E.; R. Girard and G. Kariniotakis. (2018). Optimal sizing and placement of distribution grid-connected battery systems through an SOCP optimal power flow algorithm. *Applied Energy*, 219, 385–393. <https://doi.org/10.1016/j.apenergy.2017.09.008>.

Idrus, F.; I. Musirin; M. Kamari; A. Rahim; A. V. Kumar; M. H. Mansor; M. M. Othman and M. H. Hussain. (2022). Integrated multi-verse evolutionary programming and evolutionary programming-based techniques for optimal placement of D-STATCOM installation. *Mathematical Statistician and Engineering Applications*, 71(3s2), 986–1001. <https://philstat.org.ph>.

Isha, G. and Jagatheeswari, P. (2021). Optimal allocation of DSTATCOM and PV array in distribution system employing fuzzy-lightning search algorithm. *Automatika*, 62(3–4), 339–352. <https://doi.org/10.1080/00051144.2021.1963080>.

Ismail, B.; N. I. Wahab; M. L. Othman; M. A. Radzi; K. Naidu and M. N. Naain. (2022). The optimal location and sizing of single and multiple STATCOM using analytical approaches under high loading occasion. *Journal of Engineering Science and Technology*, 17(6), 3973–3988. <https://jestec.taylors.edu.my/Vol>.

Kumar, S.; R. K. Bindal and A. Gupta. (2024). Power quality investigation of a grid-tied hybrid energy system using a D-STATCOM control and Grasshopper Optimization Technique. *Results in Control and Optimization*, 14, 100368. <https://doi.org/10.1016/j.rico.2023.100368>.

Patil, V. (2021). D-STATCOM optimal placement and sizing in the distribution system with JCF-LA approach. *Journal of Computational Mechanics Power System and Control*, 4(1), 8–16. <https://doi.org/10.46253/jcmps.v4i1.a2>.

Ramadan, A; M. Ebeed and S. Kamel. (2019). Performance assessment of a realistic Egyptian distribution network including PV penetration with DSTATCOM. *IEEE International Conference on Innovative Trends in Computer Engineering (ITCE)*, pp. 1–6. <https://doi.org/10.1109/ITCE.2019.08646473>.

Shaheen, A. M.; R. A. El-Sehiemy; A. Ginidi; A. M. Elsayed and S. F. Al-Gahtani. (2023). Optimal allocation of PV-STATCOM devices in distribution systems for energy losses minimization and voltage profile improvement via Hunter-Prey-Based Algorithm. *Energies*, 16(6), 2790. <https://doi.org/10.3390/en16062790>.

Singh, M.; J. Negi and S.S. Rawat. (2021). Voltage control in distribution system with reactive power dispatch. *International Journal of Engineering Research & Science (IJOER)*, 7(1), 5–11. <https://doi.org/10.5281/zenodo.4587627>.

Varma, R. K. and Siavashi, E. M. (2018). PV-STATCOM: A new smart inverter for voltage control in distribution systems. *IEEE Transactions on Sustainable Energy*, 9(4), 1681–1691. <https://doi.org/10.1109/TSTE.2018.2808601>.

Yuvaraj, T.; K. Ravi and K. Devabalaji. (2015). DSTATCOM allocation in distribution networks considering load variations using bat algorithm. *Ain Shams Engineering Journal*, 8(3), 391–403. <https://doi.org/10.1016/j.asej.2015.08.006>