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Voltage Profile Improvement in Renewable-Integrated Distribution Grids using the Voltage Deviation Index for Optimal DG Placement

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Abstract

This paper investigates voltage profile improvement in an 11 kV/0.415 kV distribution network using the Voltage Deviation Index (VDI) as the objective criterion for optimal placement of distributed generation (DG). A 33-bus representation of the Enugu distribution network is modeled and analyzed in ETAP. Baseline load flow results identify the weakest buses by VDI. A renewable-integrated DG (PV + BESS + synchronous generator units in the modeled hybrid mix) is placed at the bus with maximum VDI (Bus512), and the system is reanalyzed. Results show a substantial reduction in the maximum VDI from 2.8636% (baseline) to 0.0091% (with DG at Bus512), corresponding to a 99.68% improvement in maximum deviation. The study demonstrates that a simple, direct power quality metric like VDI can be an effective and computationally lightweight objective for DG siting to rapidly improve voltage profiles in distribution networks with high renewable penetration.

Keywords: *Voltage profile improvement; Voltage Deviation Index (VDI); Distributed Generation (DG); Optimal placement; Renewable energy; Power quality; Distribution grids, ETAP*

INTRODUCTION

An electric power system is comprised of three fundamentally different segments: generation, transmission, and distribution. Among these, the distribution system is the most significant one as it is the system which ensures the delivery of power to the customers directly. Distribution networks are characterized by long radial feeders, unbalanced loads, high (R/X) ratios, and a large number of customer demand patterns. On the other hand, transmission networks require low (R/X) ratios to transfer large amounts of power. These features make them more vulnerable to fluctuations, dips, and voltage shifts, especially at feeder termini (Khare *et al.*, 2021). In case the voltage profile is not monitored, it may deteriorate power quality, cause equipment to break, increase losses, and even make the system unstable.

As more and more people install renewable distributed generation (DG) such as wind and solar photovoltaic (PV) systems, voltage stability issues in distribution networks have become a major concern. The use of renewable distributed generation has, among other things, the benefit of reducing line losses, supplying electricity closer to the place where it is needed, and being a clean source of energy. However, the power injected is fluctuating because renewables are not always reliable, which makes bus voltages unpredictable. Previously, normal distribution networks had only one responsibility - to deliver power from substations to houses and businesses. However, distributed renewable energy can enable the power to flow in both directions. If this change in the system of operations is not properly managed, it could lead to unstable profiles and poor voltage control (Saxena *et al.*, 2024).

The energy distribution network that uses renewables has to maintain its voltage at the right level. This means that a power system is able to keep bus voltages within the safe range for the most part and with only a few difficulties (Anthony and Arunachalam, 2025). In a case where the problem is not solved, the voltage can continue to drop to the point where the system fails entirely or partially. Distribution networks with high (R/X) ratios and long feeders are more difficult to keep the voltage at a steady level. It is very important to have the voltage profiles optimized in order that people always experience a good quality of service.

Scientists and scholars have invented and used Voltage Deviation Indices (VDI) to evaluate the extent of deviation of a voltage from its nominal value. They are straightforward ways of giving information about the extent of the voltage deviation from the standard. VDI makes it possible to locate the areas where the voltage is extremely low and to measure the electrical power quality. VDI assists the utilities in diagnosing problems through the identification of weak areas that show the largest voltage changes. This comprises locating the proper place(s) where DG units should be installed and making certain they are the appropriate size (Vidyasagar *et al.*, 2016). VDI provides customers with a systematic method to optimize voltage profiles and offers them an insight into the current situation.

Among other things, the Electrical Transient Analyser Program (ETAP) and recent advances in modelling software have significantly simplified the process of studying and analyzing voltage profiles in renewable energy systems. ETAP affords convenient ways for carrying out power flow calculations and optimal dispatch of distributed resources in both planning and operational scenarios (Mehtre and Dubey, 2024). Utilities may determine the effects of integration scenarios on the voltage profiles through simulation of baseline scenarios without distributed generation (DG), followed by comparison with scenarios that have renewable DG and reactive power adjustment. This lets them know the measures to be taken to increase the voltage and stabilize the system when the sources of renewable energy vary.

This paper is solely focused on the enhancement of voltage profiles in distribution networks utilizing renewable energy sources. A hypothetical 33-bus distribution network is considered as a test system to demonstrate the working of the method. The investigation firstly examines the regular voltage profile of the network and utilizes the Voltage Deviation Index (VDI) to identify the risk buses. It also surveys the influence of renewable distributed generation (DG) installation on the voltage level and the beneficial effects of proper scaling of DG on the voltage profile. The study demonstrates that VDI-based strategies can lead to the enhancement of voltage profiles while safeguarding the system's operational performance and reliability, as evidenced by the comparison of the baseline and refined cases. The current study deepens our understanding of renewable energy integration by demonstrating that it is not only necessary but also feasible to achieve voltage optimization through the judicious use of power quality indicators and modern analytical approaches.

Literature Review

Voltage stability issues have been at the center of attention of power system publications for decades. The authors of these publications understand this issue as one that mostly refers to the power system's ability to hold voltage within limits at all points of the network during and after both typical operation and disturbance situations (Anthony and Arunachalam, 2025). Power quality in the area of voltage levels is of great importance to consumers, as they may suffer damage to their appliances from such a source of energy or, in the worst cases, a complete blackout situation can occur (Justin *et al.*, 2021). Hence, voltage profile is the term used to describe the map of voltage levels throughout the electrical network, and its enhancement is the fundamental requirement of a continuous and the most efficient electric energy supply (Anthony, 2025).

The impact of renewable energy sources' penetration is so tremendous that the voltage dynamics of the traditional power networks have been changed beyond recognition by solar PV systems, wind turbines, and small-scale distributed generation (Adegoke *et al.*, 2024). Unlike normal synchronous generators such as diesel or nuclear, renewable sources are in the form of intermittent, weather-dependent, and grid-connected through power electronic interfaces. These features cause voltage fluctuations, reverse power flow, and reactive power problems that endanger the safety of the system. Inadequate controllable reactive power in a renewable energy-based system can result in weak bus voltages and unstable profiles, especially in distribution networks (Mirza and Jain, 2025).

In the literature, numerous suggestions have been made to overcome these problems. One of the extensively researched methods is the optimal location and the determination of the correct size of the reactive power devices, such as shunt capacitor, static VAR compensator, and STATCOM that supply voltages directly at the critical buses. Besides these, the literature also presents solutions such as the introduction of On-Load Tap Changers (OLTC) in transformers for the dynamic regulation of the voltages and the installation of distributed generation units at the most suitable nodes of the network to lower the voltage drop (Source 9). Current research also points to the significance of advanced optimization methods like Particle Swarm Optimization (PSO), Genetic Algorithms (GA), and Artificial Bee Colony (ABC), for ascertaining the most effective arrangement of these gadgets in order to achieve voltage stability improvement (Ismail *et al.*, 2020).

Voltage Deviation Indices (VDI) have turned into indispensable instruments for locating the buses with the minimum voltage magnitude and measuring the intensity of power quality problems. The VDI delivers a numeric indication which is directly linked to power quality standards, thus providing a roadmap for system engineers in strengthening system weak points which breach compliance. For systems integrating renewables, employment of VDI is imperative as it allows operators to grasp & alleviate the fluctuation in voltage caused by renewable intermittency and high system loading (Danish *et al.*, 2019).

Different back-up tools like ETAP, PowerWorld, and MATLAB/Simulink have been the first choice of researchers in the study of voltage stability and profile enhancements. To a great extent, ETAP provides a set of strong power flow analysis, contingency analysis, and stability modules that make it suitable for practical and real-time studies. ETAP mock-ups can also be valuable in demonstrating the efficacy of renewable integration strategies and reactive power compensation techniques in elevating system voltage profiles (Alturki and Marouani, 2024).

The existing progress is accompanied by literature gaps, especially when it comes to using only VDI as the main objective function for DG placement and sizing to obtain maximized profile enhancement. The majority of papers are based on a decisive factor that is an intricate stability index or loss reduction, while they dedicate little attention to the simple and straightforward power quality metric such as VDI for the coordinated control of DG. These voids highlight the imperative of research targeted at voltage profile improvement in a renewable-integrated system, particularly through ETAP based simulation, where profile correction can not only be extensively considered but also from a power quality perspective (Haider *et al.*, 2021).

METHODOLOGY

Network Architecture

The network one line diagram of the Enugu Distribution network is presented in Fig.1.

Load Flow Analysis of Enugu Distribution Network

The foundation of voltage stability assessment lies in accurate steady-state analysis of the network, which is achieved through load flow studies. In this research, the Electrical Transient Analyzer Program (ETAP) was utilized to perform the load flow calculations on the modeled 33-bus distribution system. The Newton-Raphson (NR) iterative method was selected for its fast convergence, high accuracy, and reliability, particularly in analysing complex systems with variable generation and compensation devices.

Mathematical Formulation of the Newton-Raphson Method

The primary objective of a load flow study is to determine the bus voltages (both magnitudes and phase angles) in a power system network under steady-state operating conditions. These voltages are obtained by solving a set of non-linear algebraic equations derived from the power balance at each bus.

At any bus i in an n-bus system, the injected complex power S_i is expressed as:

$$S_\mathrm{i} = P_\mathrm{i} + jQ_\mathrm{i} = V_\mathrm{i} I_i^*$$

where:
P_i = real power injected at bus i
Q_i = reactive power injected at bus i
V_i = voltage at bus i (complex quantity)
I_i* = complex conjugate of current at bus i

The current at bus i is given by:

$$I_\mathrm{i} = \Sigma_\mathrm{k}{}^\mathrm{n} Y_\mathrm{ik} V_\mathrm{k}$$

where Y_{ik} represents the element of the bus admittance matrix (Y-bus).

Substituting for I_i:

$$S_i = V_i \Sigma_k{}^n Y_{ik}{}^* V_k{}^*$$

Expanding this gives the expressions for real and reactive powers:

$$P_\mathrm{i} = \Sigma_\mathrm{k}{}^\mathrm{n} |V_\mathrm{i}||V_\mathrm{k}||Y_\mathrm{ik}| \cos(\theta_\mathrm{ik} + \delta_\mathrm{k} - \delta_\mathrm{i}))$$

$$Q_\mathrm{i} = -\Sigma_\mathrm{k}{}^\mathrm{n} |V_\mathrm{i}||V_\mathrm{k}||Y_\mathrm{ik}| \sin(\theta_\mathrm{ik} + \delta_\mathrm{k} - \delta_\mathrm{i}))$$

where:

$|V_i|$, $|V_k|$ = voltage magnitudes of buses i and k
δ_i, δ_k = voltage phase angles of buses i and k
$|Y_{ik}|$ = magnitude of Y-bus element between buses i and k
θ_{ik} = angle of Y_{ik}

The mismatch between the specified and calculated powers at each bus is given by:

$$\Delta P_\mathrm{i} = P_\mathrm{i}(spec) - P_\mathrm{i}(calc)$$

$$\Delta Q_\mathrm{i} = Q_\mathrm{i}(spec) - Q_\mathrm{i}(calc)$$

These mismatches are then arranged in vector form as:

$$[\Delta P \;\; \Delta Q]^T = [P(spec) - P(calc) \; Q(spec) - Q(calc)]^T$$

The Newton–Raphson (NR) method linearizes these non-linear equations around the current operating point using a first-order Taylor series expansion:

$$[\Delta P \;\; \Delta Q]^T = [J^1 \, J^2; \, J^3 \, J^4][\Delta\delta \;\; \Delta|V|]^T$$

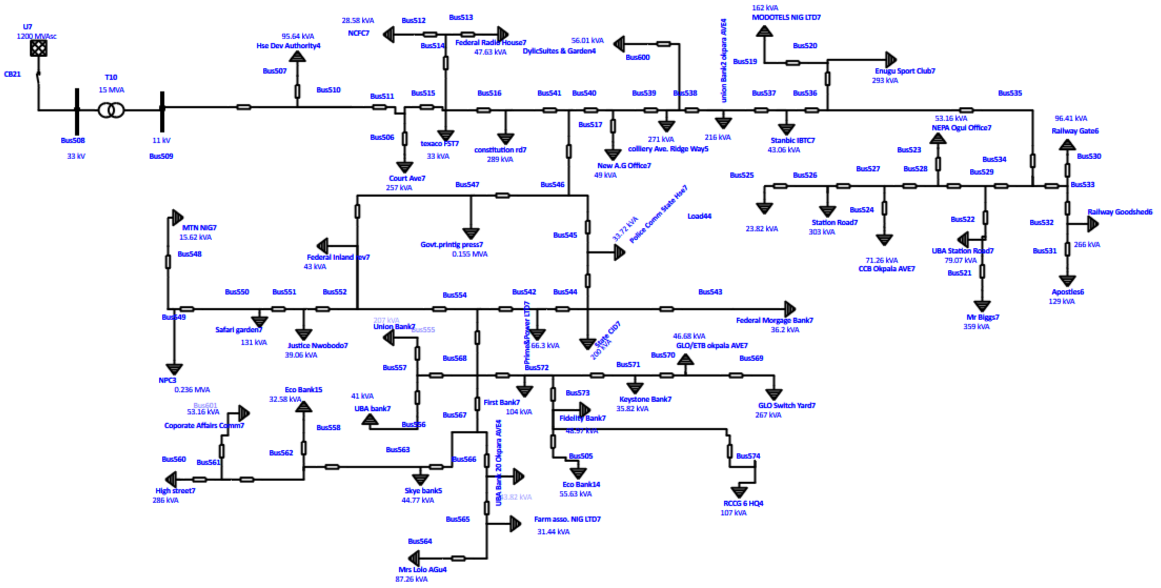

Fig. 1: Network one line diagram of the Enugu Distribution network.

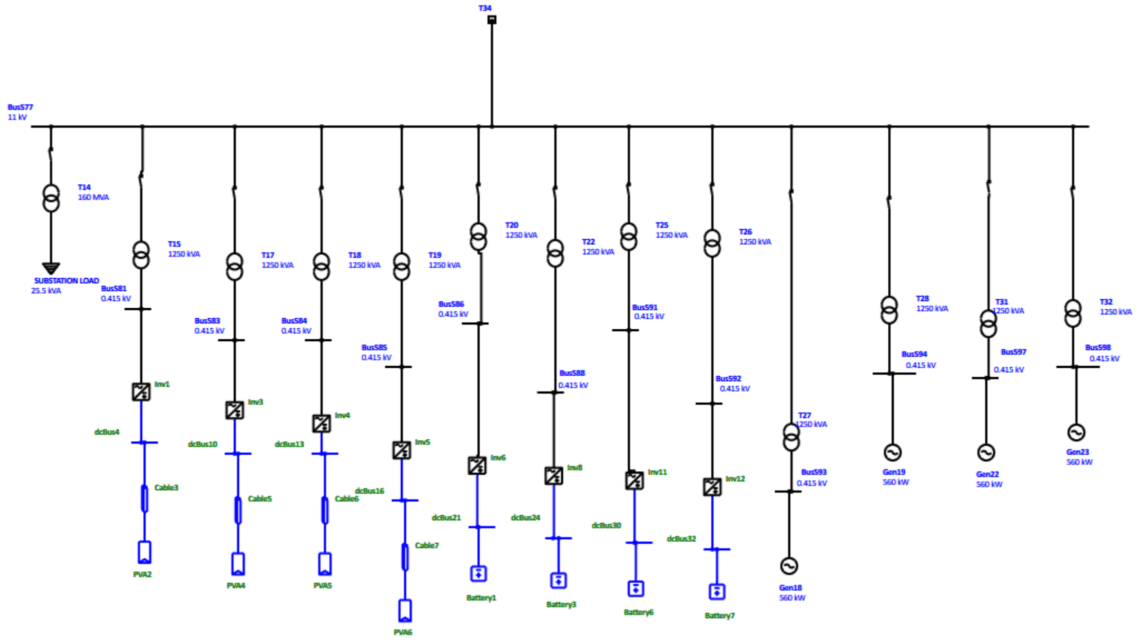

Fig. 2: Single-line diagram of the renewable-integrated distribution network modeled in ETAP.

where J_1, J_2, J_3, J_4 are the elements of the Jacobian matrix, representing the partial derivatives of power with respect to voltage magnitudes and angles:

$$J^1 = \frac{\partial P}{\partial \delta},\ J^2 = \frac{\partial P}{\partial |V|},\ J^3 = \frac{\partial Q}{\partial \delta},\ J^4 = \frac{\partial Q}{\partial |V|}$$

At each iteration, the correction terms $\Delta\delta$ and $\Delta|V|$ are computed as:

$$[\Delta\delta \ \ \Delta|V|]^T = \ [J^1\, J^2;\, J^3\, J^4]^{-1}[\Delta P \ \ \Delta Q]^T$$

The new estimates of bus voltage magnitudes and phase angles are updated as:

$$\delta(new) = \ \delta(old) + \ \Delta\delta$$

$$|V|(new) = \ |V|(old) + \ \Delta|V|$$

These iterations continue until the mismatches ΔP and ΔQ fall below a specified convergence tolerance, typically 10^{-4} or 10^{-6} per unit. Once convergence is achieved, the bus voltages and line flows can be computed, and the steady-state operating condition of the power system is determined.

Representation of Renewable Energy Sources and Distributed Generation

Fig. 2 shows a distributed generation (DG) network that feeds the 11 kV Bus 77 through a 160 MVA step-up transformer (T14). The network includes several 0.415 kV generation units linked through 1250 kVA transformers (T15–T32). These units are made up of solar PV systems (PV1–PV5), battery storage systems (Battery1–Battery7), and synchronous generators (Gen1–Gen3). Each PV and battery unit connects through an inverter (Inv1–Inv6) and a DC bus link for power conversion and grid synchronization. The synchronous generators connect directly to the 0.415 kV buses (Bus53, Bus54, and Bus57) to supply both active and reactive power. All DG units deliver power to the 0.415 kV buses, which then feed the 11 kV Bus 77 through step-up transformers. This setup forms a grid-connected distributed generation system that supports voltage stability, improves reliability, and helps meet local load demand.

RESULTS

The Enugu Distribution network one line diagram load flow result is presented in Fig. 3, and voltage profile for Enugu Distribution network without distributed generation is tabulated in Table 1.

Voltage Profile Analysis: Quantifying Performance with the Voltage Deviation Index (VDI)

Voltage Profile Analysis is the fundamental diagnostic procedure in power system engineering. Executed primarily through a Load Flow Study (utilizing methods like Newton-Raphson), this analysis determines the voltage magnitude (V) and phase angle δ at every bus under specified operating conditions, thereby establishing the crucial baseline voltage profile for the distribution grid and assessing power quality. The analysis centrally relies on the Voltage Deviation Index (VDI) to quantify system performance. The (VDI) provides a clear numerical measure of the percentage difference between the actual bus voltage (V_i) and the system's nominal rated voltage (V_{rated}). A higher (VDI) value directly signifies a greater divergence from the ideal voltage magnitude, indicating poorer power quality and a higher risk of non-compliance with regulatory standards. VDI is critical for two reasons: First, the bus exhibiting the maximum VDI is instantly identified as the electrically weakest bus and becomes the primary target for voltage support strategies. Second, the VDI acts as the core performance metric for validation, as the success of DG integration and compensation is quantitatively proven by a significant reduction in the maximum system-wide VDI, thereby ensuring the entire voltage profile is safely within operational bounds.

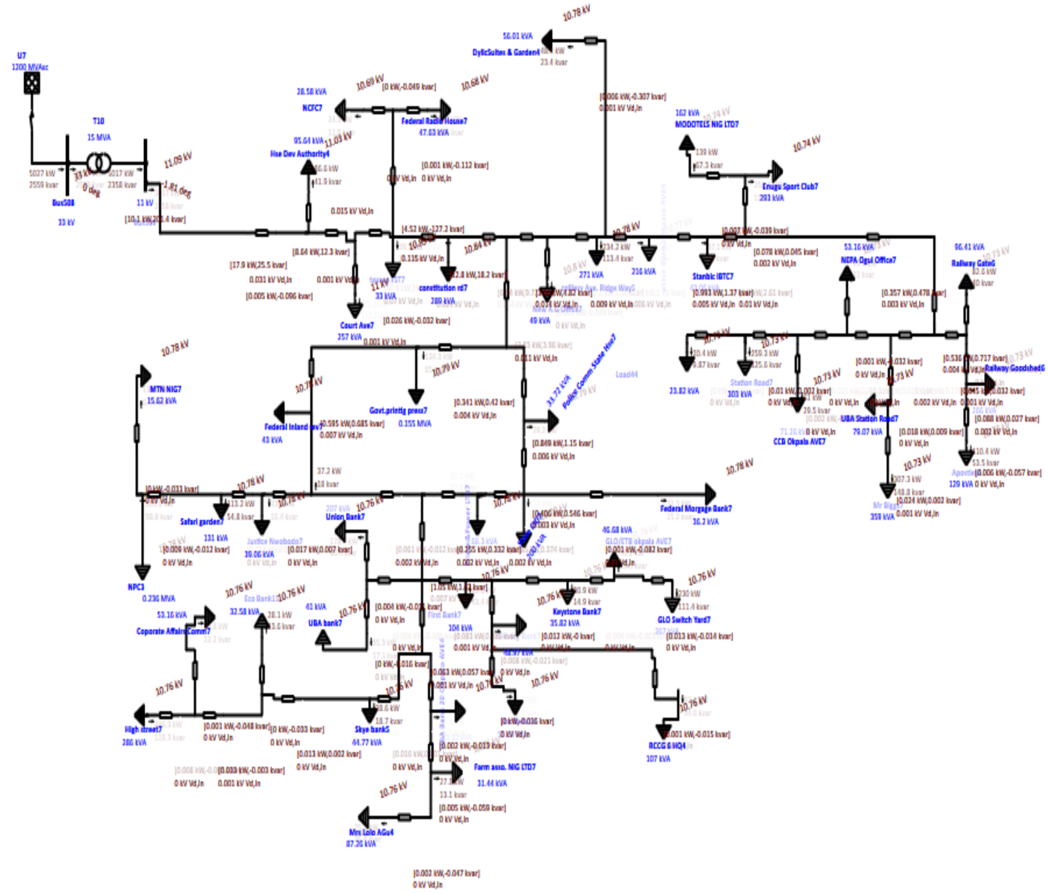

Fig. 3: Enugu Distribution network one line diagram load flow result.

The baseline load flow (no DG) shows a non-uniform voltage profile across the network. The minimum voltage recorded is 10.685 kV at Bus512, Bus513 and Bus514 (Fig. 4).

$$VDI_i = \frac{|V_i - V_{rated}|}{V_{rated}} \times 100$$

VDI_i = Voltage Deviation index at bus i

V_i = Actual voltage at bus i

V_{rated} = Rated nominal voltage

The baseline load flow (no DG) shows a non-uniform voltage profile across the network. The minimum voltage recorded is 10.685 kV at Bus512, Bus513 and Bus514, corresponding to a maximum VDI of 2.8636% (calculated as $(11 - 10.685)/11 \times 100$). Table 2 in the draft contains the full list of bus voltages and associated VDIs for the baseline system. The VDI distribution highlights that the tail-end buses of the radial feeder are the electrically weakest points and therefore logical candidates for voltage support.

Baseline maximum VDI: 2.8636363364% at Bus512/513/514.

Table 1: Voltage Profile for Enugu Distribution network without distributed generation.

Bus ID	Norminal KV	Voltage	Bus ID	Norminal KV	Voltage	Bus ID	Norminal KV	Voltage	Bus ID	Norminal KV	Voltage
Bus512	11	10.685	Bus519	11	10.739	Bus567	11	10.763	Bus544	11	10.785
Bus513	11	10.685	Bus520	11	10.74	Bus571	11	10.763	Bus545	11	10.79
Bus514	11	10.685	Bus536	11	10.743	Bus572	11	10.763	Bus547	11	10.793
Bus531	11	10.725	Bus537	11	10.76	Bus555	11	10.765	Bus517	11	10.795
Bus532	11	10.726	Bus559	11	10.76	Bus556	11	10.765	Bus540	11	10.795
Bus521	11	10.727	Bus560	11	10.76	Bus557	11	10.765	Bus546	11	10.799
Bus524	11	10.727	Bus561	11	10.76	Bus568	11	10.765	Bus541	11	10.819
Bus525	11	10.727	Bus569	11	10.761	Bus538	11	10.77	Bus516	11	10.843
Bus526	11	10.727	Bus505	11	10.762	Bus554	11	10.777	Bus515	11	10.885
Bus527	11	10.727	Bus558	11	10.762	Bus600	11	10.778	Bus506	11	11.004
Bus522	11	10.728	Bus562	11	10.762	Bus548	11	10.779	Bus511	11	11.006
Bus523	11	10.728	Bus564	11	10.762	Bus549	11	10.779	Bus507	11	11.032
Bus528	11	10.728	Bus565	11	10.762	Bus550	11	10.779	Bus510	11	11.033
Bus529	11	10.729	Bus570	11	10.762	Bus539	11	10.78	Bus509	11	11.087
Bus530	11	10.73	Bus573	11	10.762	Bus551	11	10.78	Bus508	33	33
Bus533	11	10.73	Bus574	11	10.762	Bus542	11	10.781			
Bus534	11	10.732	Bus563	11	10.763	Bus552	11	10.781			
Bus535	11	10.738	Bus566	11	10.763	Bus543	11	10.785			

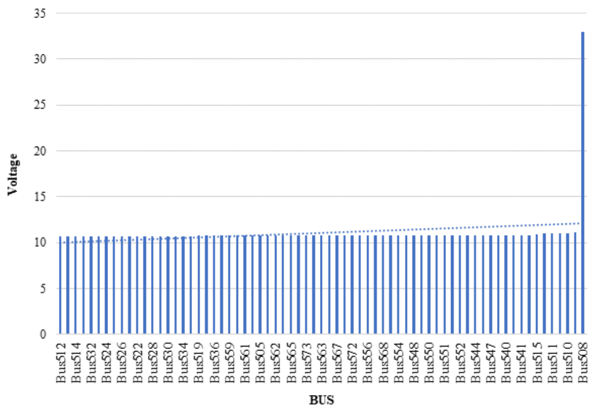

Fig. 4: Voltage profile graphical representation.

The load flow results presented in Table 2 (Voltage Profile for Enugu Distribution network without distributed generation) and the corresponding calculated Voltage Deviation Index (VDI) clearly indicate a non-uniform voltage profile across the network. The minimum voltage magnitude recorded in the system is 10.685kV at buses Bus512, Bus513, and Bus514. This translates to a maximum VDI of 2.864 (Fig. 5). This value falls within the ± 5% standard typically mandated by utility regulators for distribution networks. However, the VDI identifies these buses, located at the electrical extremities of the feeder, as the weakest nodes in the system, reflecting the inherent limitations of a long radial distribution feeder. The analysis using the VDI successfully quantifies the severity of voltage degradation across the network and provides the baseline data against which the effectiveness of the stabilization strategies (DG integration and reactive power compensation) will be measured.

Voltage Profile Improvement Strategy: Placement and Sizing of DG Units for Optimal Voltage Regulation

The strategic placement and precise sizing of Distributed Generation (DG) units are paramount for achieving optimal voltage regulation in renewable-integrated distribution grids.

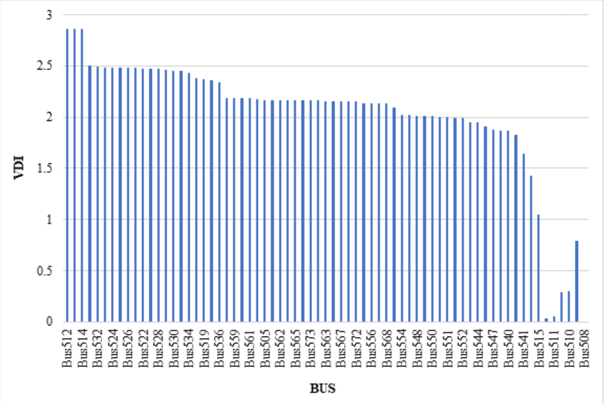

Fig. 5: Performance indices for evaluating voltage profile (Voltage Deviation Index).

Poorly located or improperly sized DG can worsen voltage issues, leading to voltage rise, increased losses, and equipment stress. The goal is to determine the ideal location (bus) and capacity $\left(\frac{kW}{kVar}\right)$ that maximizes voltage profile improvement.

DG placement at Bus512 (Maximum-VDI rule) and post-interconnection results

Applying the Maximum-VDI rule, a DG cluster representing the modeled renewable mix (PV + BESS + synchronous DG as encoded in the ETAP model) was connected at Bus512, and a new load flow was run. The post-interconnection voltages for the affected buses show that Bus512, Bus513 and Bus514 are raised to approximately 11.001 kV each.

Post-DG VDI at formerly weakest buses:

$$\mathrm{VDI}_{\mathrm{Bus512}} = \frac{|11-11.001|}{11} \times 100\% \approx 0.0090909\%$$

Thus, the maximum system VDI is reduced from 2.863636364% to 0.009090909%.

Quantitative improvement

Table 2: Voltage Profile and VDI for Enugu Distribution Network without Distributed Generation.

Bus ID	Norminal KV	Voltage	VDI	Bus ID	Norminal KV	Voltage	VDI	Bus ID	Norminal KV	Voltage	VDI
Bus512	11	10.685	2.863636364	Bus560	11	10.76	2.181818182	Bus548	11	10.779	2.009090909
Bus513	11	10.685	2.863636364	Bus561	11	10.76	2.181818182	Bus549	11	10.779	2.009090909
Bus514	11	10.685	2.863636364	Bus569	11	10.761	2.172727273	Bus550	11	10.779	2.009090909
Bus531	11	10.725	2.5	Bus505	11	10.762	2.163636364	Bus539	11	10.78	2
Bus532	11	10.726	2.490909091	Bus558	11	10.762	2.163636364	Bus551	11	10.78	2
Bus521	11	10.727	2.481818182	Bus562	11	10.762	2.163636364	Bus542	11	10.781	1.990909091
Bus524	11	10.727	2.481818182	Bus564	11	10.762	2.163636364	Bus552	11	10.781	1.990909091
Bus525	11	10.727	2.481818182	Bus565	11	10.762	2.163636364	Bus543	11	10.785	1.954545455
Bus526	11	10.727	2.481818182	Bus570	11	10.762	2.163636364	Bus544	11	10.785	1.954545455
Bus527	11	10.727	2.481818182	Bus573	11	10.762	2.163636364	Bus545	11	10.79	1.909090909
Bus522	11	10.728	2.472727273	Bus574	11	10.762	2.163636364	Bus547	11	10.793	1.881818182
Bus523	11	10.728	2.472727273	Bus563	11	10.763	2.154545455	Bus517	11	10.795	1.863636364
Bus528	11	10.728	2.472727273	Bus566	11	10.763	2.154545455	Bus540	11	10.795	1.863636364
Bus529	11	10.729	2.463636364	Bus567	11	10.763	2.154545455	Bus546	11	10.799	1.827272727
Bus530	11	10.73	2.454545455	Bus571	11	10.763	2.154545455	Bus541	11	10.819	1.645454545
Bus533	11	10.73	2.454545455	Bus572	11	10.763	2.154545455	Bus516	11	10.843	1.427272727
Bus534	11	10.732	2.436363636	Bus555	11	10.765	2.136363636	Bus515	11	10.885	1.045454545
Bus535	11	10.738	2.381818182	Bus556	11	10.765	2.136363636	Bus506	11	11.004	0.036363636
Bus519	11	10.739	2.372727273	Bus557	11	10.765	2.136363636	Bus511	11	11.006	0.054545455
Bus520	11	10.74	2.363636364	Bus568	11	10.765	2.136363636	Bus507	11	11.032	0.290909091
Bus536	11	10.743	2.336363636	Bus538	11	10.77	2.090909091	Bus510	11	11.033	0.3
Bus537	11	10.76	2.181818182	Bus554	11	10.777	2.027272727	Bus509	11	11.087	0.790909091
Bus559	11	10.76	2.181818182	Bus600	11	10.778	2.018181818	Bus508	33	33	0

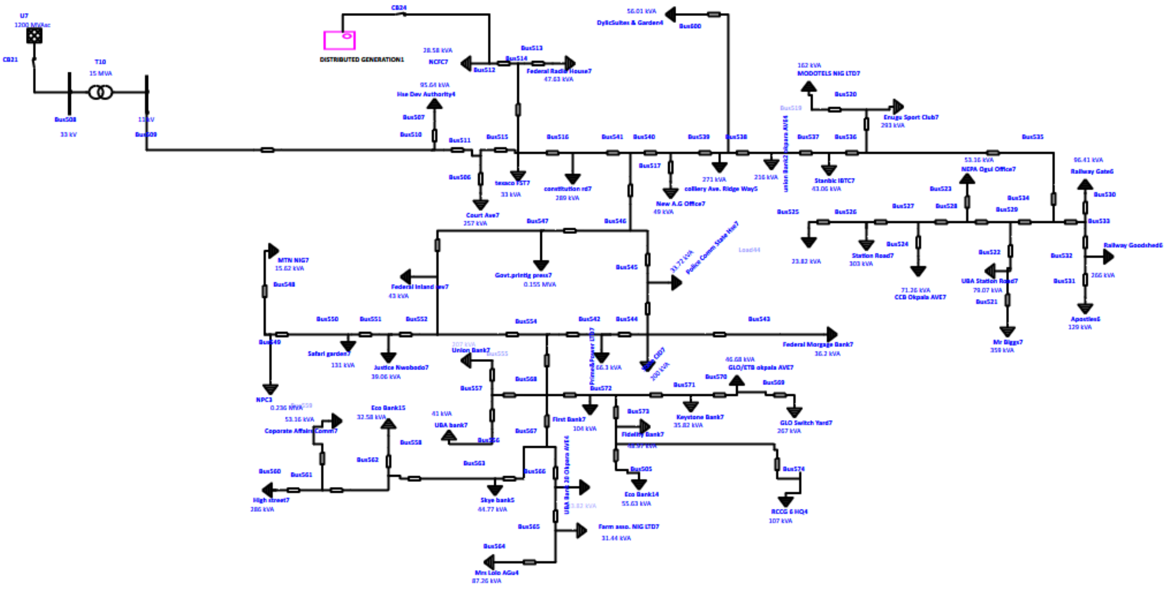

Fig. 6: Distributed generation connected to BUS 512.

- Absolute reduction in maximum VDI: $2.863636364\% - 0.009090909\% = 2.854545455\%$.
- Relative improvement in maximum VDI: $\frac{2.854545455}{2.863636364} \times 100\% \approx 99.68\%$.

This shows that placing the DG at the bus identified by the VDI criterion achieved a near-complete correction of the largest voltage deviation measured in the baseline system. Based on the baseline analysis (Table 2), the bus exhibiting the maximum VDI is 2.864% at Bus512, Bus513, and Bus514. To maximize the benefit of the DG injection where it is most needed, Bus512 is selected as the optimal location for the initial DG placement, as this point represents the deepest voltage sag in the uncompensated system (Fig. 6 and Fig. 7). This choice ensures that the injected power most effectively counteracts the maximum voltage drop.

The optimal placement strategy employed is based on the ***Maximum VDI Rule***. This rule dictates that the Distributed Generation (DG) unit must be installed at the bus exhibiting the highest Voltage Deviation Index. As VDI is a direct measure of voltage sag, placing the DG at this VDI_{max} bus (Bus512) ensures that the injected power directly addresses the most severe voltage violation, thereby maximizing the resultant voltage profile improvement across the entire feeder. The Maximum VDI Bus is the electrically weakest bus in terms of current power quality, making it the most logical and effective place to install your voltage support device (DG). The load flow results of the interconnected

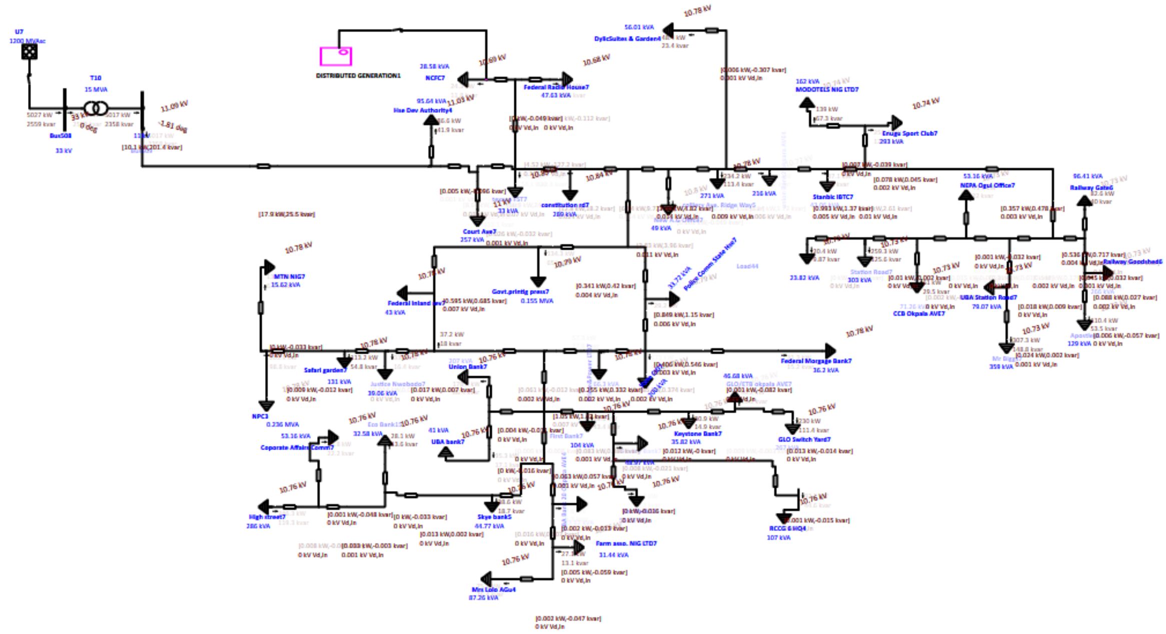

Fig. 7: Load flow of the interconnected network with DG connected on BUS 512.

Table 1: Voltage Profile for Enugu Distribution network without distributed generation.

Bus ID	Norminal KV	Voltage	Bus ID	Norminal KV	Voltage	Bus ID	Norminal KV	Voltage	Bus ID	Norminal KV	Voltage
Bus579	0.415	0.415	Bus523	11	10.728	Bus573	11	10.762	Bus543	11	10.785
Bus581	0.415	0.415	Bus528	11	10.728	Bus574	11	10.762	Bus544	11	10.785
Bus583	0.415	0.415	Bus529	11	10.729	Bus563	11	10.763	Bus545	11	10.79
Bus584	0.415	0.415	Bus530	11	10.73	Bus566	11	10.763	Bus547	11	10.793
Bus585	0.415	0.415	Bus533	11	10.73	Bus567	11	10.763	Bus517	11	10.795
Bus586	0.415	0.415	Bus534	11	10.732	Bus571	11	10.763	Bus540	11	10.795
Bus588	0.415	0.415	Bus535	11	10.738	Bus572	11	10.763	Bus546	11	10.8
Bus591	0.415	0.415	Bus519	11	10.739	Bus555	11	10.765	Bus541	11	10.819
Bus592	0.415	0.415	Bus520	11	10.74	Bus556	11	10.765	Bus516	11	10.843
Bus593	0.415	0.415	Bus536	11	10.743	Bus557	11	10.765	Bus515	11	10.885
Bus594	0.415	0.415	Bus559	11	10.76	Bus568	11	10.765	Bus512	11	11.001
Bus597	0.415	0.415	Bus560	11	10.76	Bus538	11	10.77	Bus513	11	11.001
Bus598	0.415	0.415	Bus537	11	10.761	Bus554	11	10.777	Bus514	11	11.001
Bus531	11	10.725	Bus561	11	10.761	Bus600	11	10.778	Bus577	11	11.001
Bus532	11	10.726	Bus569	11	10.761	Bus548	11	10.779	Bus506	11	11.003
Bus521	11	10.727	Bus505	11	10.762	Bus549	11	10.779	Bus511	11	11.005
Bus524	11	10.727	Bus558	11	10.762	Bus550	11	10.779	Bus507	11	11.03
Bus525	11	10.727	Bus562	11	10.762	Bus539	11	10.78	Bus510	11	11.031
Bus526	11	10.727	Bus564	11	10.762	Bus551	11	10.78	Bus509	11	11.085
Bus527	11	10.727	Bus565	11	10.762	Bus542	11	10.781	Bus508	33	33
Bus522	11	10.728	Bus570	11	10.762	Bus552	11	10.781			

system with DG connected on BUS 512 are presented in Table 3.

CONCLUSION

The simulation results confirm that placing distributed generation (DG) at the point of maximum voltage deviation provides the most direct and effective improvement to voltage profiles in distribution networks. Since the Voltage Deviation Index (VDI) explicitly measures deviation from nominal voltage, optimizing with respect to this index directly enhances customer-visible power quality rather than indirectly targeting losses or efficiency metrics. In this study, ETAP was used to model an 11 kV/0.415 kV distribution network, and the Maximum-VDI rule successfully identified Bus 512 as the optimal DG location. Integrating a renewable-based DG mix at that bus improved the voltage profile significantly, reducing the system's maximum VDI from 2.8636 % to 0.0091 %, representing a 99.68 % reduction in the worst-case deviation. These results demonstrate that VDI is a simple, reliable, and computationally efficient performance index for guiding DG siting and reactive support planning in renewable-integrated distribution systems. To further enhance system reliability and sustainability, it is recommended that network planners adopt VDI-based placement methods, ensure inverter reactive power capability, integrate energy storage for continuity, coordinate protection and operational policies, and employ multi-objective planning approaches that balance voltage regulation with loss minimization.

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Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/ or falsification, double publication and/or submission, and redundancy has been completely observed by the authors.

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