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Voltage Regulation Performance of Centralized and Decentralized Solar PV in Weak Radial Distribution Networks: A Multi-Voltage Case Study of the Zaria System

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Abstract. The increasing penetration of solar photovoltaic (PV) systems presents both opportunities and operational challenges for weak radial distribution networks, where voltage regulation is often constrained by long feeder lengths and limited control infrastructure. This paper presents a simulation-based comparative assessment of centralized and decentralized solar PV integration in the Zaria Area distribution network, Nigeria. A detailed utility-based network model was developed in PSS®SINCAL, and steady-state load flow analyses were conducted under three scenarios: base-case operation, centralized PV integration via a 50 MW plant connected at the transmission–distribution interface, and decentralized PV deployment distributed across selected medium and low-voltage buses. Voltage profiles were evaluated at the 33 kV, 11 kV, and 0.415 kV levels. The results show that centralized PV integration improves upstream voltage conditions and reduces overall undervoltage severity but offers limited support at electrically remote feeder ends. In contrast, decentralized PV deployment provides superior end-of-line voltage improvement across all voltage levels due to localized generation and reduced feeder loading. These findings demonstrate that, for weak radial distribution networks, decentralized PV integration is more effective for improving customer-side voltage quality, while centralized PV remains advantageous for bulk power injection and upstream voltage support. The study provides practical planning insights for distribution utilities considering high PV penetration under weak grid conditions.

Key words. Centralized and decentralized solar PV, Weak distribution networks, Voltage profile improvement, Distribution system planning, PSS®SINCAL simulation

1. Introduction

The accelerated deployment of solar photovoltaic (PV) generation is fundamentally transforming power distribution systems globally. Traditionally passive distribution networks, designed for unidirectional power flow, are increasingly required to accommodate inverter-dominated and spatially dispersed generation sources. High PV penetration introduces significant technical challenges, including voltage magnitude deviations, reverse power flow, feeder congestion, and protection coordination issues particularly in radial networks with high resistance-to-reactance ratios [1-3].

These challenges are especially severe in weak distribution networks, which are typified by long radial feeders, limited voltage regulation infrastructure, aged assets, and low short-circuit capacity. In such systems, voltage regulation is already problematic under base-case loading conditions, with chronic end-of-line undervoltage and elevated technical losses being common [4,5]. The integration of PV in weak grids can therefore either improve or degrade voltage performance depending on the integration architecture, penetration level, and point of connection [6,7].

A key planning dilemma in this context is the choice between centralized, utility-scale PV integration at transmission or sub-transmission levels, and decentralized PV deployment embedded within distribution feeders. Centralized PV plants offer economies of scale and coordinated system-level control, and they can contribute to bulk power support and upstream voltage regulation [8,9]. However, their influence on downstream voltage profiles is often attenuated by distribution transformer impedance and feeder length, limiting their effectiveness in alleviating

end-of-line voltage problems in weak radial networks [10].

In contrast, decentralized PV systems connected at medium-voltage (MV) and low-voltage (LV) levels have the potential to provide localized voltage support, reduce feeder currents, and improve voltage profiles at electrically weak buses [2,11]. Strategic placement of distributed PV near load centers can significantly reduce voltage drops and technical losses [12]. Nevertheless, uncoordinated decentralized deployment may introduce new operational challenges, including local overvoltage, reverse power flow, increased tap-changer operations, and protection miscoordination, particularly in networks with limited monitoring and automation [13,14].

While numerous studies have examined the impacts of centralized and decentralized PV integration, much of the existing literature is based on benchmark test feeders or well-instrumented networks in developed power systems [1,3,15]. Consequently, the applicability of these findings to developing-country distribution networks where weak grid conditions, informal network expansions, load asymmetry, and constrained regulatory frameworks prevail remains limited. Studies focusing on Sub-Saharan Africa, and Nigeria in particular, have primarily investigated optimal PV sizing and placement [12], volt–var optimization [16], or transmission-level voltage support [9], with relatively few offering a quantitative, multi-voltage comparative assessment of centralized and decentralized PV architectures using real utility feeders.

Nigeria's power distribution networks exemplify this research gap. Persistent undervoltage at MV and LV feeder ends, high technical losses, and delayed network reinforcement have driven increasing interest in solar PV as both an energy supply and a voltage support mechanism [5,12,16,17]. However, utilities lack empirical, system-level evidence to guide strategic decisions on whether centralized PV or decentralized PV delivers superior voltage regulation benefits under realistic weak-grid conditions.

This paper addresses this gap through a simulation-based comparative analysis of centralized and decentralized solar PV integration in the Zaria Area distribution network, a real utility system operated by Kaduna Electricity Distribution Company (Kaduna DisCo), Nigeria. Using a detailed, utility-validated model developed in PSS®SINCAL, the study evaluates voltage profile performance at the 33 kV, 11 kV, and 0.415 kV levels under three scenarios: (i) base-case operation, (ii) centralized PV integration via a 50 MW solar plant connected at the 132 kV interface, and (iii) decentralized PV deployment optimally located at electrically weak MV and LV buses.

By directly comparing these PV integration strategies within the same weak radial network, this study provides practical planning insights for distribution utilities, clarifying the relative effectiveness of centralized versus decentralized PV in mitigating voltage violations across multiple voltage levels in developing-country power systems. The novelty of this work lies in the use of a real weak distribution network to perform a controlled, like-for-like comparison of centralized and decentralized PV integration, combined with a multi-voltage-level assessment of voltage performance.

This study introduces a sensitivity-based PV allocation method, multi-voltage performance evaluation, and consistent like-for-like penetration comparison, which extend previous works beyond benchmark feeder analysis.

Unlike many existing studies based on benchmark feeders, this study provides system-wide insights into how PV spatial deployment influences voltage regulation across 33 kV, 11 kV, and low-voltage networks under realistic weak-grid conditions.

2. Review of Related Works

Voltage regulation constraints are widely acknowledged as a dominant limitation to PV hosting capacity in radial distribution networks, particularly those with weak grid characteristics. Early analytical and simulation-based studies established that voltage impacts of distributed generation in radial feeders are highly dependent on feeder characteristics and generator location [18-20]. As PV penetration increases, voltage deviations become nonlinear and highly location-dependent, often violating statutory limits before thermal constraints are reached [21,22].

Subsequent review studies consolidated these findings, highlighting that weak distribution networks characterized by long feeder lengths, limited voltage control resources, and reduced short-circuit strength are especially vulnerable to voltage regulation problems under fluctuating PV output [23]. Empirical investigations demonstrated that conventional voltage regulation assets, such as fixed capacitor banks and mechanical tap changers, are often insufficient to cope with fast PV variability, particularly in aging or under-reinforced networks [24,25].

In developing-country contexts, voltage regulation challenges are compounded by asymmetric loading, informal network extensions, and limited real-time system visibility. Studies focusing on African and South-Asian networks report persistent end-of-line undervoltage even under base-case operation, leaving little voltage headroom for PV integration [26-28]. These characteristics make weak radial networks an especially critical case for evaluating PV integration strategies.

Centralized, utility-scale PV plants connected at transmission or sub-transmission levels have been widely studied for their system-level benefits. Research has shown that large PV plants can improve voltage profiles at high-voltage buses and reduce loading on upstream transmission and primary substation assets, particularly when inverter-based reactive power support is enabled [29-31]. Grid-code-compliant solar plants

have also been demonstrated to contribute to voltage ride-through and steady-state voltage support under high renewable penetration scenarios [32]. Detailed feeder-level studies under high PV penetration further confirm that the influence of PV on voltage profiles depends strongly on feeder topology, loading pattern, and the electrical distance between the PV source and load centres [33].

However, several studies highlight the spatial limitation of centralized PV benefits. Distribution-level analyses reveal that voltage support provided at grid-supply points is significantly attenuated along radial feeders due to transformer impedance and feeder resistance [20]. As a result, downstream MV and LV buses where electrically remote MV and LV buses may experience limited improvement because upstream support is attenuated by feeder impedance [20].

Comparative investigations further indicate that centralized PV may inadvertently exacerbate voltage regulation challenges in weak networks by increasing reverse power flow into upstream transformers during low-load periods [34]. These findings have led several authors to conclude that centralized PV, while valuable for bulk generation, is not a sufficient standalone solution for resolving distribution-level voltage degradation in weak radial networks [35,36].

Decentralized PV integration, involving the connection of generation directly to MV and LV feeders, has been extensively analysed as an alternative voltage regulation approach. Numerous studies demonstrate that distributed PV can provide effective localized voltage support by reducing feeder current flows and compensating voltage drops near load centres [37-39].

Optimal placement and sizing studies show that PV systems located at electrically weak buses yield disproportionately high voltage improvement compared to installations near substations [39,40]. Coordinated voltage control strategies combining PV inverter volt–var control with existing regulators have been shown to significantly reduce voltage deviations and regulator wear [41,42]. Related inverter-control studies further demonstrate that optimal inverter reactive-power dispatch can improve voltage regulation in distribution systems with high PV penetration [43].

In weak and developing-country networks, decentralized PV has been increasingly promoted as a pragmatic voltage mitigation measure. Case studies from Nigeria, India, and Brazil report measurable improvements in feeder voltage profiles and loss reduction following PV deployment at strategic MV and LV nodes [44]. Nevertheless, uncoordinated decentralized PV penetration introduces new operational challenges, including overvoltage, protection miscoordination, and excessive tap-changer operations, particularly in networks lacking advanced monitoring and automation [45-47].

Despite extensive individual investigations of centralized and decentralized PV, direct comparative studies remain limited. Early comparative analyses suggested that decentralized PV outperforms centralized PV in improving distribution-level voltage profiles due to its proximity to loads, while centralized PV offers superior bulk power contributions and operational simplicity [48].

Later studies expanded this comparison by incorporating loss reduction, hosting capacity, and voltage compliance metrics, generally concluding that decentralized PV provides greater voltage benefits in radial feeders with high impedance [49,50]. However, most of these studies relied on benchmark IEEE test feeders or assumed strong grid conditions, limiting their applicability to weak networks [51].

Only a small subset of studies explicitly considers weak grid characteristics such as low fault levels, long feeders, and inadequate voltage regulation infrastructure. Even fewer conduct multi-voltage comparative assessments spanning transmission interfaces, MV feeders, and LV networks using real utility data [52]. Consequently, distribution utilities in developing countries lack clear, evidence-based guidance on when centralized or decentralized PV offers superior voltage regulation performance under realistic system constraints.

3. Methodology

This research adopts a quantitative, simulation-based approach to assess the impact of solar PV integration on the operational performance of the Zaria distribution network. The methodology progresses from network data acquisition and base-case modelling to PV integration analysis. The physical topology of the Zaria distribution system was digitised in the PSS®SINCAL environment, with buses defined for all substations and feeder tapping points. Distribution lines were modelled using their actual route lengths and corresponding electrical parameters. The network configuration reflects the predominantly radial structure with limited interconnections, as derived from available geospatial and utility data. The model includes a single infeed supplying the downstream 33/11 kV and 11/0.415 kV distribution networks, detailed feeder impedances, and the associated connected loads at each voltage level.

The total PV penetration level of 50 MW was adopted from the proposed utility-scale integration plan for the study area of Zaria and represents the maximum hosting capacity scenario used to evaluate network performance.

For the centralized configuration, the entire 50 MW PV capacity was connected at the 33 kV source bus which aligns with the highest voltage strength for assessing the impact of bulk power injection on network performance.

For the decentralized configuration, the total PV capacity (50 MW) was distributed across multiple buses using a sensitivity-informed allocation strategy. Buses exhibiting significant voltage drops were prioritized for PV integration. The proportional allocation of 15 MW, 15

MW, 15 MW, and 5 MW was distributed across selected 33 kV and 11 kV buses which reflects the combined influence of Bus-specific hosting capacity and voltage sensitivity

This allocation ensures that PV generation is strategically deployed to enhance voltage support and improve overall system performance in the weak distribution network.

3.1 Load Flow Analysis Framework

Steady-state load flow analysis was carried out using the Newton–Raphson (NR) method, owing to its quadratic convergence characteristics and robustness for large and weakly meshed distribution systems. The NR method was employed to:

(1) Evaluate bus voltage magnitudes and phase angles

(2) Determine real and reactive power flows

(3) Calculate active power losses

(4) Identify electrically weak buses exhibiting voltage violations

The complex power injected at bus *i* is expressed as

$$S_i = P_i + jQ_i \tag{1}$$

and can be related to bus voltages through the network admittance matrix as

$$S_i = P_i + jQ_i = V_i \sum_{n=1}^{N} Y_{in} V_n \tag{2}$$

Where V_i and V_n are the voltage magnitudes at buses *i* and *n*, respectively, and Y_{in} is the element of the bus admittance matrix.

Separating (2) into real and reactive power components yields

$$P_i = V_i \sum_{n=1}^{N} |Y_{in}| V_n \cos(\delta_i - \delta_n - \theta_{in}) \tag{3}$$

$$Qi = V_i \sum_{n=1}^{N} |Y_{in}| V_n \sin(\delta_i - \delta_n - \theta_{in}) \tag{4}$$

where δ_i and δ_n are voltage phase angles, and θ_{in} is the admittance angle between buses *i* and *n*.

3.2 Modelling of Distribution Losses with PV Integration

The total active power loss in the distribution network is calculated as the sum of feeder losses, expressed as

$$P_{loss} = \sum_{i=1}^{k} [I_i]^2 \times R_i \tag{5}$$

For buses with PV integration, the line current is influenced by the net real power exchange, resulting in the loss expression

$$P_{loss} = \sum_{i=1}^{k} [I_i]^2 \times R_i = \sum_{i=1}^{k} \frac{(P_{load,i} - P_{PV,i})^2 + Q^2_{load,i}}{V_i^2} \tag{6}$$

This formulation explicitly captures the reduction or increases in feeder currents due to local PV generation.

3.3 Solar PV Integration Modelling

Solar PV systems were modelled as inverter-based generators operating at unity power factor, consistent with common grid-code requirements for utility-scale and distributed PV systems.

The net real power injection at a bus *i* with PV integration is given by $P_{load,i} - P_{PV,i}$

$$= V_i \sum_{n=1}^{N} |Y_{in}| V_n \cos(\delta_i - \delta_n - \theta_{in}) \tag{7}$$

All PV units are modelled as inverter-based generators operating at unity power factor, providing only active power injection ($Q_{PV} = 0$) . Reactive power control strategies such as Volt–Var (V–Q) regulation are not considered in this study to isolate the impact of PV placement on voltage profile performance.

Thus, the reactive power balance at the PV bus reduces to

$$-P_{PV,i} = V_i \sum_{n=1}^{N} |Y_{in}| V_n \sin(\delta_i - \delta_n - \theta_{in}) \tag{8}$$

In weak radial distribution networks, high PV penetration at unity power factor can lead to voltage rise, as additional real power is injected without reactive power absorption. When

$P_{PV} < P_{load}$, feeder currents are reduced and losses decrease

$P_{PV} > P_{load}$ reverse power flow occurs, pushing excess power upstream toward the substation

This behaviour is explicitly captured in the loss and voltage analysis.

3.4 Load Modelling

To accurately represent voltage sensitivity in weak distribution networks, a voltage- and frequency-dependent ZIP load model was adopted, particularly for the decentralized PV scenario.

The real and reactive power consumption of the ZIP load model is expressed as

$$P_{ZIP} = P_0 \left(\eta Z \left(\frac{V}{V_0} \right)^2 + \eta I \left(\frac{V}{V_0} \right)^1 + \eta P \left(\frac{V}{V_0} \right)^0 \right) \tag{9}$$

$$Q_{ZIP} = Q_0 \left(\gamma Z \left(\frac{V}{V_0} \right)^2 + \gamma I \left(\frac{V}{V_0} \right)^1 + \gamma P \left(\frac{V}{V_0} \right)^0 \right) \tag{10}$$

where:

P_0, Q_0 are nominal real and reactive power at rated voltage and frequency

V is the actual bus voltage

V_0 is the rated voltage

η and γ are weighting coefficients for constant impedance (Z), constant current (I), and constant power (P) components

To capture frequency variations, the ZIP model was extended as

$$P_{ZIP} = P_0 \mid \eta Z\left(\frac{V}{V_0}\right)^2 + \eta I\left(\frac{V}{V_0}\right)^1 + \eta P \mid (1 + K_{pf} + \Delta f) \quad (11)$$

$$Q_{ZIP} = Q_0 \mid \gamma Z\left(\frac{V}{V_0}\right)^2 + \gamma I\left(\frac{V}{V_0}\right)^1 + \gamma P \mid (1 + K_{qf} + \Delta f) \quad (12)$$

where Δf represents frequency deviation, and Kpf, Kqf are frequency sensitivity coefficients for real and reactive power, respectively. The validity of the simulation results is ensured with a validated power system analysis tool (PSS®SINCAL), modelling based on real utility network data, base-case verification, and consistent simulation conditions across all scenarios.

4. Results

A base-case load flow analysis without PV integration was initially performed to validate the Zaria distribution network model and to identify voltage-critical buses, particularly at the remote ends of long radial feeders. Two PV integration architectures were subsequently analysed. In the centralized configuration, a utility-scale PV plant of 50 MW was connected at the 33 kV main bus supplying the network and modelled as an inverter-based generator operating at unity power factor. In the decentralized configuration, PV systems were connected directly to selected 33 kV and 11 kV buses, prioritising electrically weak locations identified in the base-case results, with the total installed capacity chosen to be comparable to the centralized case. Steady-state load flow simulations were carried out for the base-case, centralized, and decentralized scenarios under identical operating conditions, and the impact of each integration strategy was evaluated through comparative analysis of voltage profiles at 33 kV, 11 kV, and low-voltage levels. The load flow simulations were carried out under a steady-state operating condition representative of average network loading. The same load level was maintained across all scenarios to ensure a consistent and fair comparison of voltage profile performance.

4.1 Voltage Profiles

Power flow studies analysed the voltage profile across the distribution network under normal operating conditions. Table 1 presents the permissible voltage limits specified by the Nigerian Grid Code, serving as a benchmark for evaluating the adequacy of voltage profiles obtained under the different PV integration scenarios.

Table 1. Voltage control ranges by nigeria grid code version 2.

Voltage level	Minimum voltage kV (pu)	Maximum voltage kV (pu)
33 kV	31.02 (0.94)	34.98 (1.06)
11 kV	10.45 (0.95)	11.55 (1.05)
0.415 kV	0.394 (0.95)	0.436 (1.05)

4.2 Result Discussion

The voltage profile analysis evaluates the impact of large-scale centralized solar PV integration and compares its performance with decentralized PV deployment across the Zaria Area distribution network. The centralized scenario considers a 50 MW solar PV plant connected at the 132/33 kV Zaria substation, providing bulk power injection at the transmission-distribution interface, while the decentralized scenario distributes PV units across selected 33 kV and 11 kV buses with high voltage drop identified through load flow simulation.

Under centralized PV integration, voltage regulation is noticeably improved relative to the base case across all voltage levels. At the 33 kV network (Figure 1), the minimum end-of-line voltage increases from 89.5% in the base variant to 92.8%, representing a 3.3% improvement. The voltage profile remains consistently higher along the feeder. However, despite this improvement, end-of-feeder voltages remain close to statutory limits, suggesting limited support for electrically remote sections.

At the 11 kV level (Figure 2), centralized integration mitigates severe undervoltage conditions observed in the base case, where the voltage drops to 86.3%. With centralized PV, the minimum voltage improves to 89.2%, reducing the magnitude of voltage deviation by 2.9%. Similar trends are observed at the 0.415 kV level (Figure 3), where the minimum voltage increases from 85.5% to 88.8%. Although centralized PV significantly improves overall voltage profiles, persistent undervoltage at medium voltage and low voltage feeder ends highlights the influence of feeder impedance and radial topology, which constrain the downstream reach of centrally provided voltage support.

A direct comparison between centralized and decentralized configurations further clarifies these effects. At the 33 kV level (Figure 4), centralized integration offers stable voltage conditions near the source but experiences a steep decline toward feeder ends, reaching approximately 92.8%. In contrast, decentralized PV integration improves the minimum voltage to about 94.7%, providing superior support at critical remote

nodes, albeit with elevated voltages at upstream buses that may require careful operational control.

At the 11 kV and 0.415 kV levels (Figures 5 and 6), decentralized integration consistently outperforms the centralized approach. Decentralized PV maintains final voltages around 94.5% at 11 kV and 93.5% at 0.415 kV, compared to critically low values of approximately 89.0% and 88.5% under centralized integration. The localized active power injection in the decentralized scenario effectively reduces feeder loading and voltage drops, particularly in long, weak feeders.

Overall, centralized PV integration provides effective upstream voltage support and system-level stability, while decentralized PV deployment demonstrates superior voltage regulation at MV and LV levels. For weak distribution networks with long radial feeders, decentralized PV integration is more effective in maintaining voltages within acceptable limits and improving end-user power quality, whereas centralized PV remains advantageous for bulk power injection and upstream voltage control.

Percentage improvement is calculated relative to the base case minimum voltage

$$\text{Improvement (\%)} = \frac{V_{min,case} - V_{min,base}}{V_{min,base}} \times 100$$

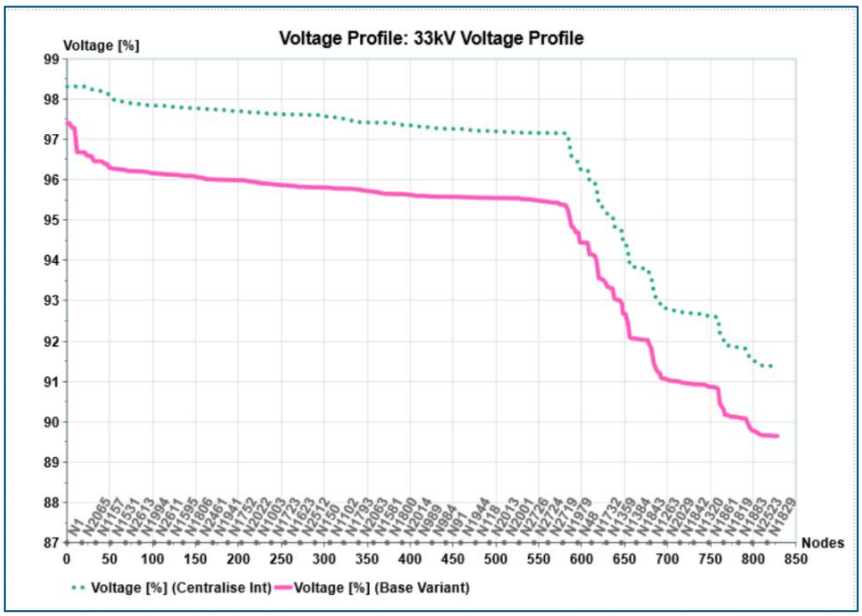


Figure 1. Base voltage profile and centralised solar PV integration of 33 kV network.

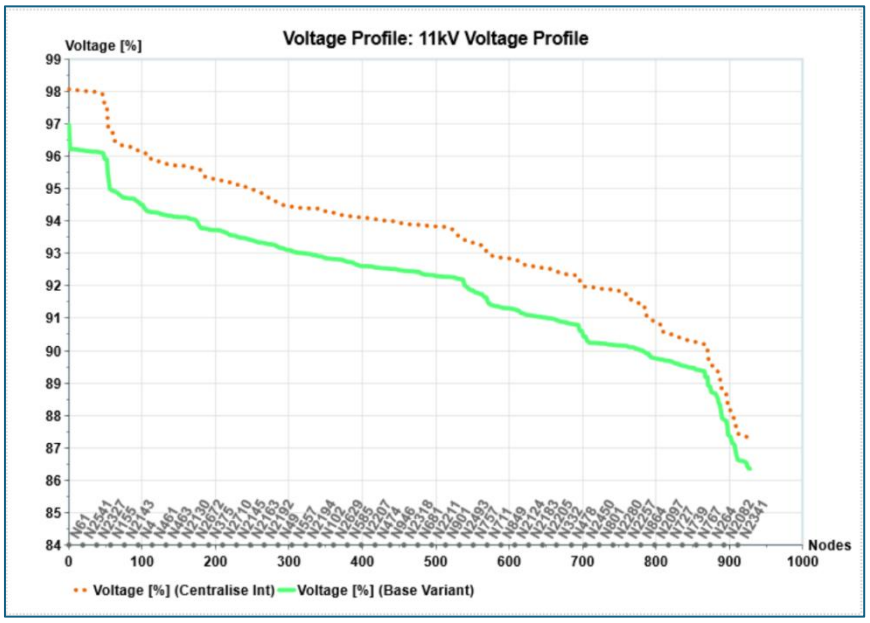


Figure 2. Base voltage profile and centralised solar PV integration of 11 kV network.

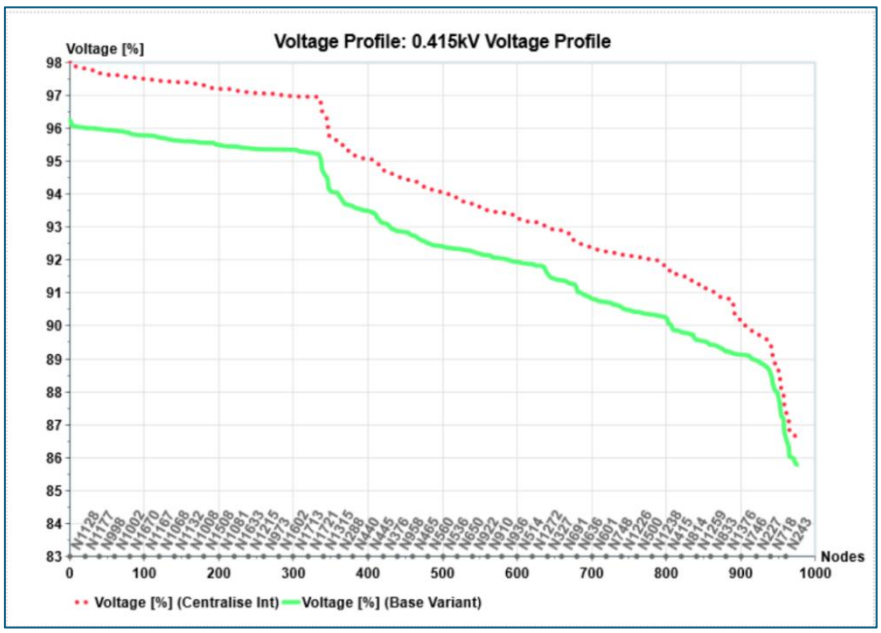


Figure 3. Base voltage profile and centralised solar PV integration of 0.415 kV network.

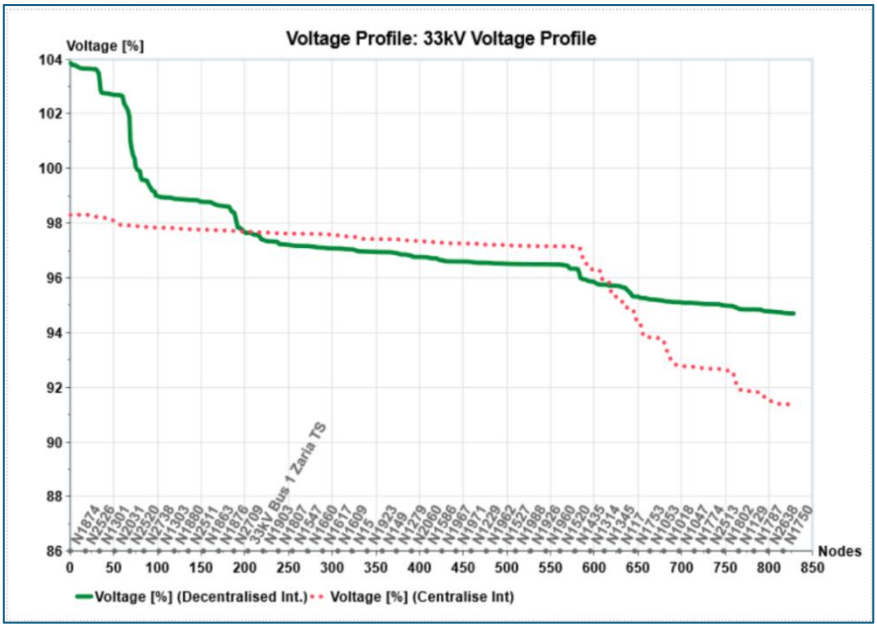


Figure 4. A graph of centralized and decentralized solar PV_33 kV voltage profile Zaria area network.

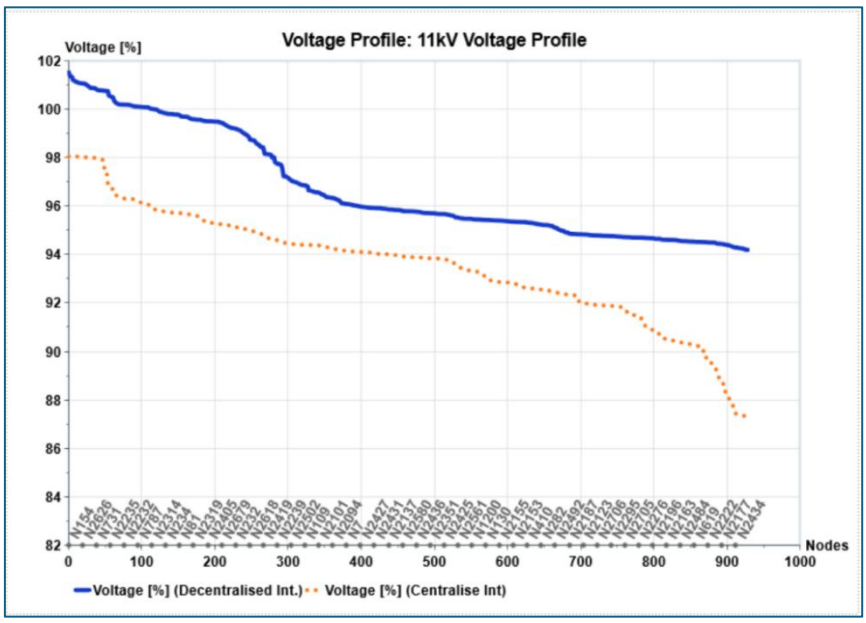


Figure 5. A graph of centralized and decentralized solar PV 11 kV voltage profile Zaria area network.

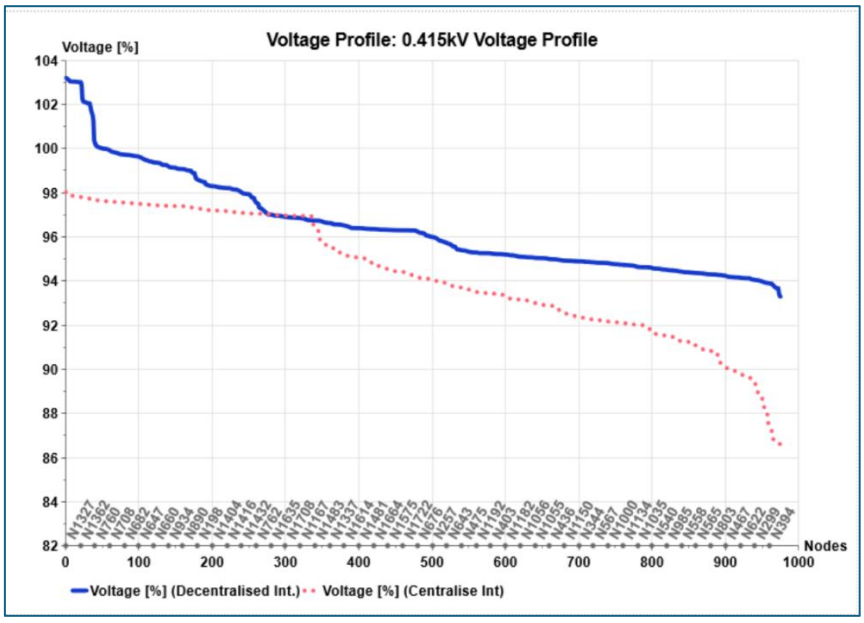


Figure 6. A graph of centralized and decentralized solar PV_0.415 kV voltage profile Zaria area network.

Table 2. Minimum voltage comparison under different PV integration scenarios.

Voltage level	Base case minimum voltage (%)	Centralized PV minimum voltage (%)	Decentralized PV minimum voltage (%)	Percentage improvement (Decentralized vs Base)
33 kV	89.5	92.8	94.7	+5.81%
11 kV	86.3	89.2	94.5	+9.50%
0.415 kV	85.5	88.8	93.5	+9.36%

Table 2 provides a quantitative comparison of minimum voltage levels under base-case, centralized, and decentralized PV integration, highlighting the relative improvement in voltage performance achieved through each integration architecture across multiple voltage levels.

Decentralized PV integration performs better because injecting power close to load centres directly reduces feeder current and voltage drop along long, high-impedance radial feeders, thereby improving end-of-line voltages. In contrast, centralized PV mainly raises upstream voltages, with limited downstream

impact due to feeder impedance. This explains why the decentralized scenarios consistently achieve higher minimum voltages at the 33 kV, 11 kV, and 0.415 kV levels in the results. In addition to voltage profile improvement, decentralized PV integration demonstrated superior performance in reducing aggregate voltage deviation and increasing voltage compliance across all voltage levels, indicating a more uniform and stable voltage distribution compared to the centralized configuration.

5. Conclusion

This study presented a detailed simulation-based comparison of centralized and decentralized solar PV integration in the Zaria Area distribution network, with the objective of determining their relative effectiveness in improving voltage regulation across multiple voltage levels. Centralized integration of a 50 MW PV plant improved overall voltage profiles compared to the base case, confirming that bulk power injection at the transmission–distribution interface can elevate upstream voltages and mitigate system-wide undervoltage conditions. Quantitatively, minimum operating voltages increased from 89.5% to 92.8% at 33 kV, from 86.3% to 89.2% at 11 kV, and from 85.5% to 88.8% at 0.415 kV. However, persistent undervoltage at feeder extremities remained evident, highlighting the limited downstream reach of centralized voltage support in weak radial networks with high feeder impedance.

In contrast, decentralized PV deployment at electrically weak medium- and low-voltage buses consistently delivered superior voltage regulation at feeder ends. The decentralized configuration improved minimum voltages to approximately 94.7% at 33 kV, 94.5% at 11 kV, and 93.5% at 0.415 kV, demonstrating the effectiveness of localized active-power injection in reducing feeder currents and voltage drops along long radial lines. These results indicate that, for weak and distribution-dominated power systems, decentralized PV siting close to high-drop nodes offers the most effective means of enhancing customer-side voltage quality, while centralized PV remains valuable for upstream voltage support and bulk generation.

While PV integration also affects thermal loading, feeder current limits, system losses, and reverse power flow, this study deliberately focuses on voltage profile performance as the primary constraint in weak radial networks; these additional impacts are reserved for future investigation.

Future work should extend this analysis to include inverter reactive-power control capabilities, feeder unbalance, protection coordination, and power-quality constraints, in order to develop comprehensive PV integration guidelines for utility distribution networks operating under realistic weak-grid conditions.

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Author Contribution

[Shater Sylvester Apeshi]: Participated in collecting, assessing, and interpreting the data. Developed and planned the study, performed simulation, and interpreted results. Edited and refined the manuscript with a focus on critical intellectual contributions.

[Ogbuefi Uche C]: Provided substantial intellectual input during the drafting and revision of the manuscript.

Conflicts of Interest

The authors declare that they have no financial conflicts of interest.

Generative AI Statement

The authors declare that no generative artificial intelligence technologies were used in the preparation of this manuscript.

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