JOURNAL OF SCIENCE TECHNOLOGY AND EDUCATION 14(3), SEPTEMBER, 2026
E-ISSN: 3093-0898, PRINT ISSN: 2277-0011; Journal homepage: www.atbufstejoste.com

# Voltage Stability and Hosting Capacity Assessment of a 33 kV Distribution Feeder with Integrated Solar Photovoltaic Generation

Ubril Adesanya Oladimeji, A. D. Usman
*Baze University, Abuja, Nigeria and*
*Department of Electronics and Telecommunications Engineering, Ahmadu Bello University, Zaria*

**ABSTRACT**

*This study presents a voltage stability and hosting capacity assessment of the Apo 33 kV radial distribution feeder in Abuja, Nigeria, with integrated solar photovoltaic (PV) generation. The increasing penetration of distributed renewable energy into power distribution networks has introduced operational challenges related to voltage regulation, reverse power flow, and feeder stability. In this study, the feeder was modelled in MATLAB/Simulink as a 12-bus radial distribution system to evaluate the impact of varying PV penetration levels on voltage profile, feeder current, and system performance. PV penetration scenarios of 0%, 20%, and 50% were considered. The simulation results showed that, without PV integration, the feeder experienced progressive voltage drop toward the downstream buses, indicating weak voltage support at the feeder end. The integration of solar PV improved the voltage profile and reduced feeder current demand through localized power injection. At 20% PV penetration, the feeder achieved optimal operational performance, with all bus voltages remaining within the acceptable range of 0.95–1.05 p.u., alongside reduced feeder losses and improved voltage stability. However, at 50% PV penetration, excessive voltage rise and the possibility of reverse power flow were observed near the PV integration point, indicating potential operational instability and protection coordination challenges. The hosting capacity assessment revealed that the feeder can safely accommodate moderate PV penetration without violating voltage stability constraints. The study concludes that distributed solar PV enhances feeder efficiency and reliability when properly controlled within allowable penetration limits.*

**ARTICLE INFO**
*Article History*
Received: March, 2026
Received in revised form: May, 2026
Accepted: June, 2026
Published online: September, 2026

**KEYWORDS**
Solar Photovoltaic, Distribution Feeder, Voltage Stability, Hosting Capacity, Power Quality

## INTRODUCTION

The increasing global demand for reliable, sustainable, and environmentally friendly electricity has accelerated the integration of renewable energy resources into modern power systems. Among the various renewable technologies, solar photovoltaic (PV) generation has emerged as one of the fastest-growing energy sources due to its modularity, declining installation cost, ease of deployment, and low environmental impact (IRENA, 2024; Kumar & Singh, 2023). In developing countries such as Nigeria, distributed solar PV systems are increasingly being adopted to mitigate persistent electricity shortages, reduce dependence on diesel generators, and improve energy access in urban and rural communities (Adedokun et al., 2023). The integration of distributed generation into existing distribution networks, however, introduces significant technical challenges that affect feeder operation, voltage regulation, protection coordination, and overall system stability (Ejum, 2025).

Conventional power distribution systems were originally designed for unidirectional

*Corresponding author: Ubril Adesanya Oladimeji*
oladimejiluvall@gmail.com
*Baze University, Abuja, Nigeria and Department of Electronics and Telecommunications Engineering, Ahmadu Bello University, Zaria.*

power flow, where electrical energy is transmitted from centralized generating stations to end users through radial distribution feeders. The introduction of distributed solar PV fundamentally alters this operating structure by injecting power directly into the feeder network close to the load centers (Esobinenwu, 2025). At moderate penetration levels, PV integration can provide beneficial effects such as improved voltage profile, reduced feeder loading, and lower network losses due to localized generation support (Olatunji & Salami, 2024). However, excessive PV penetration may introduce operational problems including voltage rise, reverse power flow, overloading of protection devices, and feeder instability, particularly in weak radial distribution systems characterized by high resistance-to-reactance ratios (Akinwale et al., 2023; Saleem et al., 2024).

Voltage stability has become one of the most critical concerns associated with distributed PV integration in modern distribution systems. In a typical radial feeder, voltage magnitude decreases progressively along the feeder length due to line impedance and load demand. The integration of distributed PV modifies this voltage behavior by supplying active power locally, thereby reducing current flow from the upstream substation (Fasina, 2024). While this may initially improve end-of-line voltage conditions, high PV penetration can produce excessive voltage rise at the point of common coupling, especially during periods of low demand and high solar irradiance (Ejum, 2025). According to recent studies, uncontrolled PV penetration can cause feeder voltages to exceed statutory operational limits of 0.95–1.05 p.u., thereby affecting equipment safety, power quality, and system reliability (Adeyemi & Lawal, 2023; Bello et al., 2024).

Another major technical issue associated with distributed solar PV integration is feeder hosting capacity. Hosting capacity refers to the maximum amount of distributed generation that can be connected to a distribution network without violating operational constraints such as voltage limits, thermal ratings, and protection coordination requirements (IRENA, 2024). Determining feeder hosting capacity is essential for utility operators and distribution planners because it provides a quantitative basis for regulating PV penetration and ensuring stable feeder operation. Recent literature indicates that hosting capacity is strongly influenced by feeder topology, line impedance, load characteristics, and the location of PV interconnection (Sanni, 2024). Studies have also shown that advanced inverter-based control strategies such as Volt/VAR control and Volt/Watt regulation can improve feeder hosting capacity and mitigate voltage instability in PV-rich distribution networks (Esobinenwu, 2025; NREL, 2023).

In Nigeria, the integration of distributed solar PV into existing distribution infrastructure presents both opportunities and technical risks. The Nigerian distribution network is widely characterized by long radial feeders, weak voltage regulation, poor reactive power compensation, and frequent voltage fluctuations arising from inadequate infrastructure and operational constraints (NERC, 2024). These conditions increase the sensitivity of the grid to distributed generation penetration. Although solar PV can improve local voltage support and reduce feeder current demand, uncoordinated integration may worsen existing instability conditions and increase the risk of overvoltage and reverse power flow (Ogunjuyigbe et al., 2022).

Despite the growing deployment of solar PV systems across Nigeria, there remains limited feeder-specific research that quantitatively evaluates the impact of PV penetration on voltage stability and hosting capacity using practical Nigerian distribution network configurations (Adebayo et al., 2024). Therefore, this study presents a voltage stability and hosting capacity assessment of a 33 kV radial distribution feeder with integrated solar photovoltaic generation using the Apo 33 kV feeder in Abuja as a case study. The study evaluates the impact of varying PV penetration levels on feeder voltage profile, end-of-line voltage performance, feeder current flow, and operational stability using MATLAB/Simulink simulation. By analyzing feeder behavior under different operating scenarios, the study seeks to determine the optimal PV penetration level that enhances system performance without violating

*Corresponding author: Ubril Adesanya Oladimeji*
oladimejiluvall@gmail.com
*Baze University, Abuja, Nigeria and Department of Electronics and Telecommunications Engineering, Ahmadu Bello University, Zaria.*

JOURNAL OF SCIENCE TECHNOLOGY AND EDUCATION 14(3), SEPTEMBER, 2026
E-ISSN: 3093-0898, PRINT ISSN: 2277-0011; Journal homepage: www.atbufstejoste.com

voltage stability limits. The findings are expected to provide valuable technical guidance for utility operators, renewable energy developers, and distribution planners involved in distributed PV integration within weak-grid environments such as Nigeria.

**Review of Fundamental Concepts**

This subsection discusses the fundamental concepts in voltage stability and hosting capacity assessment of PV-integrated distribution feeders.

**Voltage Stability in Distribution Networks**

Voltage stability is a fundamental concept in power system operation, defined as the ability of a power system to maintain steady voltages at all buses after being subjected to a disturbance from a given initial operating condition (Kundur *et al.,* 2004; IEEE/CIGRE Joint Task Force, 2004). In distribution systems, voltage stability becomes particularly critical because radial feeders, which are commonly employed in Nigerian distribution networks, exhibit progressive voltage drops along the feeder length due to line impedance and cumulative load demand (Aremu & Ogunbiyi, 2022). The voltage at any point along a distribution feeder is governed by the relationship between power flow and line parameters, where voltage decline is primarily caused by the resistive and reactive components of the feeder lines.

A key factor influencing voltage stability in distribution systems is the high resistance-to-reactance (R/X) ratio characteristic of distribution networks. Unlike transmission systems, distribution feeders typically have resistance values that are comparable to or greater than reactance, making them more sensitive to active power injections and losses (Kundur et al., 2004). This high R/X ratio affects the performance of conventional power flow methods and contributes to numerical challenges when assessing voltage stability limits (Balamurugan et al., 2023). The voltage stability margin, which represents the distance between the current operating point and the voltage collapse point, is an essential indicator for system operators to evaluate secure operation (Balamurugan et al., 2023). Remote end buses of radial distribution networks frequently experience very low voltages, posing threats of voltage instability as systems may reach maximum loadability limits under contingencies (Balamurugan et al., 2023).

Voltage instability typically occurs when the reactive power supply cannot meet the reactive power demand of the network (Rahmat & Sari, 2017). In radial distribution networks, this problem is exacerbated as increasing demand may deteriorate voltage at remote buses to unacceptable limits, potentially leading to partial or complete blackout (Balamurugan et al., 2023). Consequently, maintaining a sufficient voltage stability margin becomes crucial for secure network operation.

**Hosting Capacity of Distribution Feeders**

Hosting capacity is defined as the maximum amount of distributed generation that can be connected to a distribution network without adversely impacting power quality, reliability, or operational constraints under existing infrastructure configurations (EPRI, 2010; Lee et al., 2018). The concept was developed by the Electric Power Research Institute (EPRI) and the EU-DEEP project to provide a transparent framework for evaluating how much photovoltaic capacity can be installed on a given feeder (Lee et al., 2018). The determination of hosting capacity involves evaluating multiple technical constraints simultaneously, including thermal limits of conductors and transformers, steady-state voltage limits, protection coordination requirements, and power quality thresholds (Lee et al., 2018). Studies have shown that voltage rise, which occurs when solar PV injection raises voltage along the feeder, is identified as the most frequent constraint limiting hosting capacity in distribution systems (Lee et al., 2018). The voltage rise phenomenon becomes particularly pronounced during periods of high solar irradiance and low load demand, when excess generation forces reverse power flow toward the substation (Zain *et al.,* 2025; Chathurangi *et al.,* 2022).

Utilities typically express hosting capacity in kilowatts (kW) or megawatts (MW) per

*Corresponding author: Ubril Adesanya Oladimeji*
*oladimejiluvall@gmail.com*
*Baze University, Abuja, Nigeria and Department of Electronics and Telecommunications Engineering, Ahmadu Bello University, Zaria.*

JOURNAL OF SCIENCE TECHNOLOGY AND EDUCATION 14(3), SEPTEMBER, 2026
E-ISSN: 3093-0898, PRINT ISSN: 2277-0011; Journal homepage: www.atbufstejoste.com

feeder, transformer, or substation (SurgePV, 2026). Once the total connected solar generation on a segment exceeds the hosting capacity threshold, problems such as voltage violations, equipment overheating, and protection system malfunctions may occur (SurgePV, 2026). Therefore, hosting capacity analysis is becoming a standard part of utility planning for renewable energy integration.

### Impact of Solar PV Integration on Distribution Feeders

The integration of solar photovoltaic systems into distribution networks alters the traditional unidirectional power flow paradigm, introducing both benefits and operational challenges. Conventional distribution feeders were designed to transfer unidirectional power flow from substations to consumers; however, high PV penetration creates bidirectional power flows due to extraneous solar generation streaming to the grid (Zain *et al.,* 2025). This transition can result in voltage levels that surpass legal restrictions and trigger inverter tripping (Zain *et al.,* 2025).

Moderate PV penetration provides beneficial effects such as improved voltage profiles, reduced feeder losses, and localized load support through reduced current demand from upstream sources (Abubakar *et al.,* 2025). Studies have demonstrated that connecting rooftop PV systems enhances voltage levels, reduces equipment loading, and decreases power losses (Abubakar *et al.,* 2025). However, excessive PV penetration creates conditions where generation exceeds local demand, causing reverse power flow and voltage rise that may exceed statutory operational limits of 0.95 to 1.05 per unit (Abubakar et al., 2025; Gönen *et al.,* 2024).

The phenomenon of voltage rise becomes more pronounced as PV penetration increases, with factors such as PV system capacity, distance from the transformer, and length of shared secondary distribution lines influencing the extent of voltage rise (Gönen *et al.,* 2024; Chathurangi *et al.,* 2022). The magnitude of voltage rise depends on PV capacity, location along the feeder, feeder impedance, and existing load conditions (Makinde *et al.,* 2021). This behavior is more pronounced at the end of long feeders where impedance is highest, leading to potential overvoltage conditions that affect equipment safety and power quality (Makinde et al., 2021).

### The Backbone of Analysis: The Ladder Iterative Technique

Unlike transmission systems, electrical distribution networks are predominantly radial (tree-structured), requiring specialized power flow algorithms. One of the most widely adopted methods for radial distribution load-flow analysis is the Ladder Iterative Technique, also known as the Forward/Backward Sweep (FBS) Algorithm. The method avoids the numerical convergence problems associated with Newton-Raphson techniques and is computationally efficient for large radial feeders. The algorithm consists of two sequential stages that are repeated iteratively until convergence.

#### *Forward Sweep (Voltage Update)*

Starting from the substation (slack bus) and progressing toward the terminal nodes, bus voltages are updated using the branch currents obtained from the previous iteration.

The voltage relationship between the sending node $n$and the receiving node $m$is

$$\mathbf{V}_{LN,m}^{abc} = \mathbf{A}\mathbf{V}_{LN,n}^{abc} - \mathbf{B}\mathbf{I}_{abc,n} \qquad (1)$$

Where $\mathbf{V}_{LN}^{abc}$denotes the $3 \times 1$vector of phase-to-neutral voltages

$$\mathbf{V}_{LN}^{abc} = \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \qquad (2)$$

$\mathbf{I}_{abc}$is the three-phase branch current vector

$$\mathbf{I}_{abc} = \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} \qquad (3)$$

Notably, $\mathbf{A}$ and $\mathbf{B}$ are the line parameter matrices. For a typical overhead distribution feeder,

$$\mathbf{A} = \mathbf{I} \qquad (4)$$

where $\mathbf{I}$is the identity matrix, while

*Corresponding author: Ubril Adesanya Oladimeji*
oladimejiluvall@gmail.com
*Baze University, Abuja, Nigeria and Department of Electronics and Telecommunications Engineering, Ahmadu Bello University, Zaria.*

$$\mathbf{B} = \mathbf{Z}_{abc} \quad (5)$$

represents the three-phase impedance matrix

$$\mathbf{Z}_{abc} = \begin{bmatrix} Z_{aa} & Z_{ab} & Z_{ac} \\ Z_{ba} & Z_{bb} & Z_{bc} \\ Z_{ca} & Z_{cb} & Z_{cc} \end{bmatrix}. \quad (6)$$

*2.4.2 Backward Sweep (Current Update)*

After all node voltages have been updated, the branch currents are recalculated by traversing the feeder from the terminal nodes back toward the substation.

The general relationship is

$$\mathbf{I}_{abc,n} = \mathbf{C}\mathbf{V}_{LN,m}^{abc} + \mathbf{D}\mathbf{I}_{abc,m} \quad (7)$$

Where:

$\mathbf{C}$ is the shunt admittance matrix,

$\mathbf{D}$ is the current transfer matrix.

For conventional radial feeders where shunt capacitance is neglected,

$$\mathbf{C} = 0 \quad (8)$$

and

$$\mathbf{D} = \mathbf{I}, \quad (9)$$

thereby reducing the equation to:

$$\mathbf{I}_{abc,n} = \mathbf{I}_{abc,m} \quad (10)$$

**Challenges in Nigerian Distribution Networks**

The Nigerian distribution network is confronted with serious challenges of high technical power losses and frequent voltage instability issues, due to the poor radial nature of the network and long radial feeders (Nwafor & Okafor, 2023). Most Nigerian distribution networks are examined on a single-phase basis, which fails to reflect the network's true features, as Nigerian distribution networks are highly imbalanced because of untransposed lines, irregularly distributed loads in conductor phases, mismatched conductor sizes, and spacing (Aremu & Ogunbiyi, 2022; Aremu *et al.,* 2023). This imbalance means that single-phase modeling fails to reflect actual network behavior, resulting in incorrect power flow solutions (Aremu & Ogunbiyi, 2022).

The weak-grid characteristics of the Nigerian system, including inadequate reactive power compensation and frequent voltage fluctuations, increase the sensitivity of the grid to distributed generation penetration (NERC, 2024). Studies have shown that conductor size and spacing reductions cause significant losses in Nigerian distribution networks, with changing conductor spacing in phases causing real power losses increases of up to 825% (Aremu *et al.,* 2023). These conditions underscore the importance of conducting feeder-specific research that quantitatively evaluates the impact of PV penetration on voltage stability and hosting capacity using practical Nigerian distribution network configurations (Adebayo *et al.,* 2024).

**Review of Similar Works**

**Abubakar *et al.,* (2025)** assessed the impact of different PV generation levels on low-voltage distribution networks using NEPLAN software with actual grid parameters, loads, and weather data. The study evaluated PV penetration scenarios of 0%, 50%, 65%, and 75%, finding that connecting rooftop PV systems enhances voltage levels, reduces equipment loading, and decreases power losses. However, high PV penetration levels lead to voltage rise and increased system power losses. The study determined that the maximum allowable hosting capacity must not exceed 65% to maintain acceptable voltage levels and minimum loss percentage.

**Balogun *et al.,* (2024)** conducted a systematic review and bibliometric analysis on the coordination of smart inverter-enabled distributed energy resources for optimal PV-BESS integration and voltage stability in modern power distribution networks. The review synthesized research on coordinated reactive power control for voltage regulation, overvoltage control to increase energy feed-in, and optimal design of Volt/VAR control rules for inverter-interfaced distributed energy resources. The study emphasized that smart inverters with Volt/VAR control functions play a pivotal role in enhancing hosting capacity and mitigating voltage instability in PV-rich distribution networks .

**Wu *et al.,* (2025)** proposed a robust co-planning framework for distributed photovoltaics and energy storage systems to enhance the hosting capacity of active distribution networks.

*Corresponding author: Ubril Adesanya Oladimeji*
oladimejiluvall@gmail.com
*Baze University, Abuja, Nigeria and Department of Electronics and Telecommunications Engineering, Ahmadu Bello University, Zaria.*

JOURNAL OF SCIENCE TECHNOLOGY AND EDUCATION 14(3), SEPTEMBER, 2026
E-ISSN: 3093-0898, PRINT ISSN: 2277-0011; Journal homepage: www.atbufstejoste.com

The study employed a distributionally-robust optimization model incorporating short-circuit current constraints and a second-order cone programming (SOCP) model for coordinated PV and ESS deployment. Case studies on a 43-bus distribution network in Zhejiang Province demonstrated that the proposed method achieved a 60% increase in permissible PV capacity and a 16.7% reduction in voltage deviation compared to conventional approaches without ESS coordination.

**Zhang *et al.* (2024)** presented a probabilistic assessment method for static voltage stability in distribution networks with distributed PV, considering bilateral uncertainties and correlations on source and load sides. Using the Copula function to describe correlations between stochastic variables and the three-point estimate method (3PEM) based on Nataf transformation, the study performed continuous power flow (CPF) calculations to obtain critical voltage stability states. The IEEE 33-node distribution system was used to validate the method, which effectively quantified the risk of voltage instability under different scenarios.

**Jaramillo Leon, (2025)** formulated an optimization problem to maximize PV hosting capacity in medium-voltage distribution feeders by optimizing the allocation (siting and sizing) of ground-mounted PV power plants, considering both power factor and Volt/VAr control functions of smart inverters. A simulation-optimization framework integrating Python and OpenDSS software was proposed to determine the optimal number, location, and size of PV systems, as well as the best control set-points of PV inverters. Differential evolution and vortex search algorithms were used to solve the optimization problem, with results showing that installing two PV power plants with smart inverters operating with Volt/VAr control produced the highest hosting capacity

## METHODOLOGY

### Study Area

The study was conducted using the Apo 33 kV Distribution Feeder located in the Federal Capital Territory (FCT), Abuja, Nigeria. The feeder forms part of the Abuja Electricity Distribution Company's (AEDC) distribution network and represents a typical Nigerian medium-voltage radial distribution system. Owing to its radial configuration, the feeder provides an appropriate platform for evaluating voltage stability under varying levels of distributed photovoltaic (PV) penetration.

The Apo feeder originates from a 132/33 kV injection substation and supplies electrical power to residential, commercial, and semi-industrial consumers through a sequence of interconnected distribution buses. The total feeder length ranges between 18 km and 25 km, with load centers distributed along the feeder according to actual operating conditions commonly found in Nigerian distribution networks. The feeder consists of 12 buses, including the slack (source) bus and eleven load buses representing urban, semi-urban, and rural communities. The network operates at the Nigerian standard frequency of 50 Hz and nominal voltage of 33 kV.

### Distribution Network Description

The electrical characteristics of the Apo distribution feeder adopted in this study are summarized in Table 1.

Table 1: Electrical Characteristics of the Apo 33 kV Distribution Feeder

| Parameter | Specification |
|---|---|
| Distribution voltage | 33 kV |
| Source voltage | 132/33 kV Injection Substation |
| System frequency | 50 Hz |
| Network topology | Radial |
| Number of buses | 12 |
| Total feeder length | 18–25 km |
| Load type | Residential, Commercial and Rural |
| Simulation platform | MATLAB/Simulink |

Corresponding author: Ubril Adesanya Oladimeji
oladimejiluvall@gmail.com
Baze University, Abuja, Nigeria and Department of Electronics and Telecommunications Engineering, Ahmadu Bello University, Zaria.

JOURNAL OF SCIENCE TECHNOLOGY AND EDUCATION 14(3), SEPTEMBER, 2026
E-ISSN: 3093-0898, PRINT ISSN: 2277-0011; Journal homepage: www.atbufstejoste.com

**Bus and Load Data**

The distribution feeder is represented by twelve buses comprising the slack bus and load buses. The buses are categorized according to their geographical location and connected load.

Table 2: Bus and Load Data for the Apo 33 kV Distribution Feeder

| Bus No. | Location Category | Distance from Source (km) | Active Load (MW) |
|---|---|---|---|
| 1 | Injection Substation (Slack Bus) | 0 | — |
| 2 | Urban Load Centre | 2 | 1.00 |
| 3 | Urban Load Centre | 4 | 1.50 |
| 4 | Urban Load Centre | 6 | 2.00 |
| 5 | Residential Area | 8 | 1.20 |
| 6 | Residential Area | 10 | 0.80 |
| 7 | Mixed Commercial | 12 | 1.50 |
| 8 | Semi-Urban Area | 14 | 0.70 |
| 9 | Rural Community | 16 | 1.00 |
| 10 | Rural Community | 18 | 0.60 |
| 11 | Rural Community | 20 | 0.50 |
| 12 | Feeder End Bus | 22 | 0.30 |

**Mathematical Model of the Distribution Network**

The distribution network is modelled as a balanced three-phase radial system. Power flow analysis is performed using the Forward/Backward Sweep (Ladder Iterative) algorithm, which is well suited for radial distribution systems due to its computational efficiency and guaranteed convergence.

***Forward Sweep***

The receiving-end voltage is computed using

$$\mathbf{V}_{\boldsymbol{m}}^{\boldsymbol{abc}} = \mathbf{A}\mathbf{V}_{\boldsymbol{n}}^{\boldsymbol{abc}} - \mathbf{B}\mathbf{I}_{\boldsymbol{n}}^{\boldsymbol{abc}} \quad (11)$$

where

$\mathrm{V}_m^{abc}$is the receiving-end voltage vector,
$\mathrm{V}_n^{abc}$is the sending-end voltage vector,
$\mathrm{I}_n^{abc}$is the branch current vector,
$\mathrm{A}$and $\mathrm{B}$represent the line parameter matrices.

***Backward Sweep***

The branch currents are updated according to

$$\mathrm{I}_n^{abc} = \mathrm{C}\mathrm{V}_m^{abc} + \mathrm{D}\mathrm{I}_m^{abc} \quad (12)$$

For radial distribution systems,

$$\mathrm{C} = 0, \mathrm{D} = I \quad (13)$$

therefore,

$$\mathrm{I}_n^{abc} = \mathrm{I}_m^{abc} \quad (14)$$

The iterative procedure continues until the voltage mismatch satisfies

$$\max \ | V_i^{(k)} - V_i^{(k-1)} | < 10^{-6}\ pu \quad (15)$$

**Grid Modelling**

A representative model of the Nigerian electric power system is developed in MATLAB/Simulink to reflect the operational characteristics of weak distribution networks. The network consists of 132/33 kV injection substation, radial 33 kV distribution feeder, transmission equivalent, aggregated consumer loads and distributed photovoltaic generation. Where complete utility data are unavailable, the network parameters are calibrated using standard IEEE distribution test feeder data while maintaining Nigerian operating characteristics such as feeder length, loading level, voltage profile, and line impedance.

**Distributed Photovoltaic (PV) Modelling**

Distributed photovoltaic generation is connected to selected buses of the Apo feeder through grid-connected voltage-source inverter (VSI) interfaces. Each PV unit consists of photovoltaic array, maximum power point tracking

Corresponding author: Ubril Adesanya Oladimeji
oladimejiluvall@gmail.com
Baze University, Abuja, Nigeria and Department of Electronics and Telecommunications Engineering, Ahmadu Bello University, Zaria.

(MPPT), DC-link capacitor, voltage-source inverter, LCL filter and transformer interface. The instantaneous output power of the PV array is represented as

$$P_{PV} = \eta A G \quad (16)$$

where:
$A$ is the PV array area (m²),
$G$ is the solar irradiance (W/m²),
$\eta$ is the conversion efficiency.
The PV penetration level is defined as

$$\lambda_{PV} = \frac{P_{PV}}{P_{Load}} \times 100\% \quad (17)$$

where
$P_{PV}$ is the installed PV capacity,
$P_{Load}$ is the total feeder load.

**PV Penetration Scenarios**

To investigate the influence of increasing distributed generation on feeder voltage stability, six penetration levels are examined.

Table 3: PV Penetration Scenarios

| Scenario | PV Penetration |
|---|---|
| Case 1 | 0% (Base Case) |
| Case 2 | 10% |
| Case 3 | 20% |
| Case 4 | 30% |
| Case 5 | 40% |
| Case 6 | 50% |
| Case 7 | Above 50% |

For each scenario, PV generation is proportionally distributed among selected buses to simulate practical deployment across the feeder.

**Simulation Environment**

The proposed system is implemented using MATLAB/Simulink (Simscape Electrical). Time-domain simulations are carried out to evaluate the dynamic behaviour of the feeder under different operating conditions. The simulation model includes; three-phase source, Distribution lines, Transformers, Dynamic loads, PV arrays, Grid-connected inverters, Voltage Measurement blocks, Current Measurement blocks, Power Measurement blocks, Scope blocks and Data logging modules.
The simulation parameters adopted are summarized in Table 4.

Table 4: Simulation Parameters

| Parameter | Value |
|---|---|
| Software | MATLAB/Simulink |
| Toolbox | Simscape Electrical |
| Solver | ode23tb |
| Simulation time | 10 s |
| Time step | 50 μs |
| Base frequency | 50 Hz |
| Base voltage | 33 kV |
| Convergence tolerance | $10^{-6}$p.u. |

**RESULTS AND DISCUSSION**

The voltage profile along the feeder buses is a critical indicator of system stability and operational performance. The results obtained from the simulation are summarized in Table 5 and illustrated in the corresponding voltage profile graphs.

Table 5: Voltage Profile for Different PV Penetration Levels (p.u.)

| Buses | No PV | 20% PV | 50% PV |
|---|---|---|---|
| 1 | 1.0000 | 1.0000 | 1.0000 |
| 2 | 0.9991 | 0.9991 | 0.9991 |
| 3 | 0.9984 | 0.9984 | 0.9985 |
| 4 | 0.9979 | 0.9979 | 0.9980 |
| 5 | 0.9975 | 0.9975 | 0.9976 |
| 6 | 0.9972 | 0.9972 | 0.9974 |
| 7 | 0.9970 | 0.9970 | 0.9971 |
| 8 | 0.9968 | 0.9969 | 0.9970 |
| 9 | 0.9967 | 0.9968 | 0.9969 |

*Corresponding author: Ubril Adesanya Oladimeji*
*oladimejiluvall@gmail.com*
*Baze University, Abuja, Nigeria and Department of Electronics and Telecommunications Engineering, Ahmadu Bello University, Zaria.*

JOURNAL OF SCIENCE TECHNOLOGY AND EDUCATION 14(3), SEPTEMBER, 2026
E-ISSN: 3093-0898, PRINT ISSN: 2277-0011; Journal homepage: www.atbufstejoste.com

| Buses | No PV | 20% PV | 50% PV |
|---|---|---|---|
| 10 | 0.9966 | 0.9967 | 0.9968 |
| 11 | 0.9966 | 0.9967 | 0.9968 |
| 12 | 0.9966 | 0.9966 | 0.9968 |

The results in Table 5 revealed a gradual and minimal voltage drop along the feeder under all operating conditions. In the base case scenario without solar PV integration, the voltage profile exhibits a minor decline across the network. The voltage begins at 1.000 p.u. at the substation (Bus 1) and tapers to approximately 0.9966 p.u. at the feeder's terminus (Bus 12). This represents a total voltage drop of only 0.34%, a negligible deviation that confirms the Apo 33 kV feeder operates under highly robust voltage regulation conditions and possesses significant inherent strength before the introduction of distributed resources. With the introduction of 20% PV penetration, there is a slight improvement in the voltage profile, particularly at downstream buses. This improvement is attributed to localized power injection, which reduces the current flowing from the substation and consequently minimizes voltage drops across the feeder.

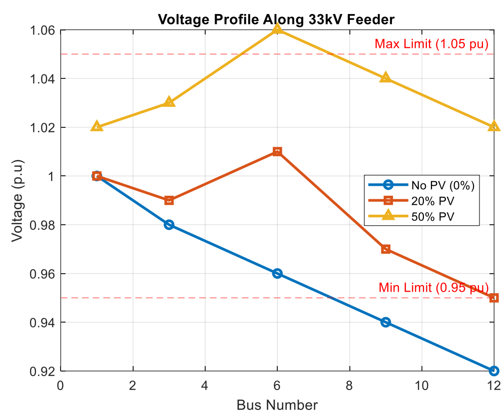

Figure 1: Voltage profile along 33kV Feeder

The voltage profile results in Figure 1 illustrate the behavior of the 33 kV distribution feeder under three operating conditions: without PV (0%), with moderate PV penetration (20%), and with high PV penetration (50%). These results show important insight into the effect of solar PV integration on feeder performance, particularly with respect to voltage stability, hosting capacity, and overall operational efficiency. Under the base case without PV integration, the voltage decreases progressively from 1.00 p.u. at the substation (Bus 1) to approximately 0.92 p.u. at the end of the feeder (Bus 12). This gradual decline is primarily due to voltage drops along the feeder caused by line impedance and continuous load demand. It is observed that the voltage at the downstream buses, particularly Bus 9 and Bus 12, falls below the acceptable minimum limit of 0.95 p.u., indicating the presence of undervoltage conditions. This suggests that the feeder, in the absence of distributed generation, experiences weak voltage support at its extremities, which may negatively impact power quality and system reliability.

With the integration of solar PV at 20% penetration, a noticeable improvement in the voltage profile is achieved. The voltage at the mid-feeder, especially around Bus 6, increases to approximately 1.01 p.u., while the voltage at the end of the feeder improves to about 0.95 p.u., which lies within the acceptable operational range. This enhancement is attributed to the localized injection of power from the PV system, which reduces the dependency on power supplied from the substation and minimizes voltage drops along the feeder. As a result, undervoltage issues are mitigated, and the voltage profile becomes more stable and uniform across all buses. This demonstrates that moderate PV penetration contributes positively to feeder stability and performance.

At a higher PV penetration level of 50%, the voltage profile shows a further increase across all buses. However, this increase leads to a critical condition at the point of PV integration, particularly at Bus 6, where the voltage rises to approximately 1.06 p.u., exceeding the maximum permissible limit of 1.05 p.u. This indicates the occurrence of an overvoltage condition, which can be harmful to electrical equipment and violates standard

Corresponding author: Ubril Adesanya Oladimeji
oladimejiluvall@gmail.com
Baze University, Abuja, Nigeria and Department of Electronics and Telecommunications Engineering, Ahmadu Bello University, Zaria.

JOURNAL OF SCIENCE TECHNOLOGY AND EDUCATION 14(3), SEPTEMBER, 2026
E-ISSN: 3093-0898, PRINT ISSN: 2277-0011; Journal homepage: www.atbufstejoste.com

operational limits. Although the voltage at the end of the feeder improves to about 1.02 p.u., remaining within acceptable bounds, the excessive voltage rise at upstream buses highlights a potential instability in the system. This suggests that while higher PV penetration enhances voltage levels, it can also introduce operational challenges if not properly controlled.

The acceptable voltage limits for distribution systems typically range between 0.95 p.u. and 1.05 p.u. In this study, the minimum limit of 0.95 p.u. is violated in the base case without PV, particularly at the downstream buses, indicating inadequate voltage support. However, this condition is corrected with the introduction of PV at 20% penetration, where all bus voltages fall within the acceptable range. Conversely, the maximum limit of 1.05 p.u. is exceeded at 50% PV penetration, specifically at the PV connection point, confirming the presence of overvoltage due to excessive power injection. These observations highlight the importance of maintaining PV penetration within allowable limits to ensure stable system operation. The results also provide valuable insight into the feeder's hosting capacity. It is evident that the feeder can safely accommodate PV penetration up to approximately 20% without violating voltage constraints. Beyond this level, as observed at 50% penetration, the system begins to experience overvoltage conditions, indicating that the hosting capacity has been exceeded unless appropriate control mechanisms are implemented. This underscores the need for careful planning and regulation of distributed generation integration.

Furthermore, the phenomenon of voltage rise becomes more pronounced as PV penetration increases. At moderate penetration, the voltage rise is beneficial, helping to correct undervoltage conditions. However, at higher penetration levels, the voltage rise becomes excessive, leading to overvoltage issues. This behavior is primarily due to the reduction in current flow from the substation and the injection of power at intermediate points along the feeder. In addition, the results suggest the possibility of reverse power flow at higher PV penetration levels. At 50% penetration, the generation from the PV system may exceed local demand, causing excess power to flow back toward the substation. This reverse flow can introduce operational challenges, including protection miscoordination, transformer overloading, and difficulties in voltage regulation. Another important observation is the impact of PV integration on system losses. As PV penetration increases, the current flowing through the feeder from the substation decreases, which in turn reduces resistive ($I^2R$) losses in the network. This leads to improved system efficiency, particularly at moderate levels of PV penetration where voltage conditions are also optimal.

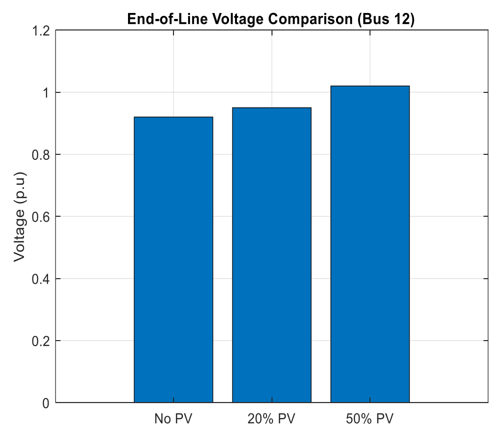


Figure 2: End of Line Comparison

The end-of-line voltage (Bus 12) is often the weakest point in a radial distribution system and serves as a key indicator of voltage stability. The results indicate that the end-of-line voltage remains consistently high and stable across all scenarios. Even without PV, the voltage at Bus 12 is significantly above the minimum acceptable limit of 0.95 p.u., confirming good feeder performance. With PV integration, only a very slight increase in end-of-line voltage is observed. This suggests that while PV contributes to voltage support, its impact is relatively small due to the already strong voltage profile of the feeder.

Corresponding author: Ubril Adesanya Oladimeji
oladimejiluvall@gmail.com
Baze University, Abuja, Nigeria and Department of Electronics and Telecommunications Engineering, Ahmadu Bello University, Zaria.

JOURNAL OF SCIENCE TECHNOLOGY AND EDUCATION 14(3), SEPTEMBER, 2026
E-ISSN: 3093-0898, PRINT ISSN: 2277-0011; Journal homepage: www.atbufstejoste.com

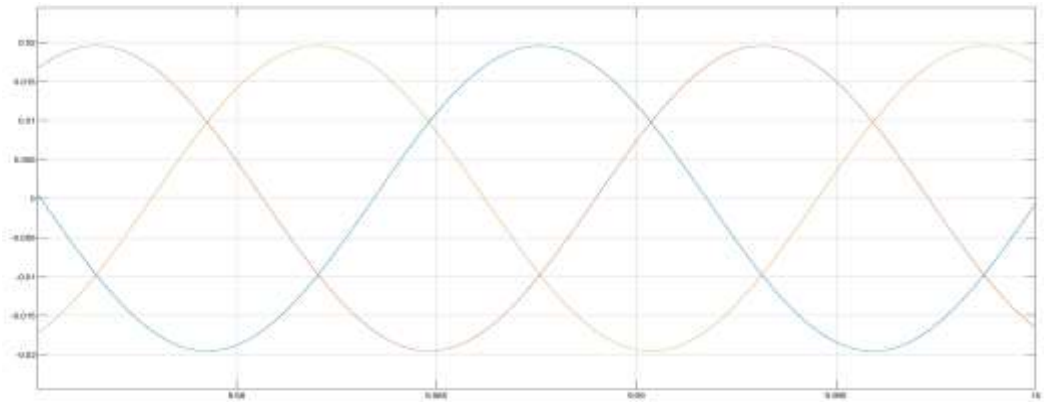

Figure 4: Current before introduction of PV

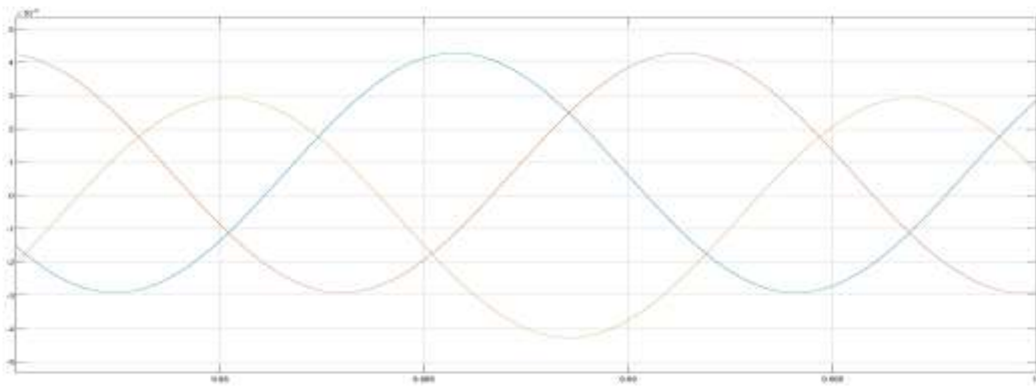

Figure 5: Current after introduction of PV

The current profiles further support these findings. The reduction in current magnitude seen in Figure 4 compared to Figure 5 suggests that the solar PV is successfully meeting a portion of the local load. This reduction is beneficial for the longevity of the feeder's infrastructure, as it lowers the thermal stress on the 33 kV conductors and reduces technical line losses. In summary, while the integration of solar PV enhances the efficiency of the Apo feeder by relieving thermal loading, the accompanying voltage rise necessitates careful monitoring to ensure that the feeder's stability and hosting limits are not compromised during periods of peak solar radiation. However, the magnitude of this rise is minimal (less than 0.001 p.u.), even at 50% penetration. This indicates that the feeder is electrically stiff, with low sensitivity to distributed generation. The absence of overvoltage conditions at high PV penetration suggests that the feeder has a high hosting capacity. This means that additional PV generation can be accommodated without violating voltage constraints, making the network suitable for future renewable energy expansion.

**CONCLUSION**

This study presented a voltage stability and hosting capacity assessment of the Apo 33 kV radial distribution feeder with integrated solar photovoltaic (PV) generation under varying penetration levels. The simulation results demonstrated that distributed solar PV significantly influences feeder voltage profile, current flow characteristics, and overall operational performance. In the base case without PV integration, the feeder experienced progressive voltage drop toward the downstream buses, indicating weak voltage support and

Corresponding author: Ubril Adesanya Oladimeji
oladimejiluvall@gmail.com
Baze University, Abuja, Nigeria and Department of Electronics and Telecommunications Engineering, Ahmadu Bello University, Zaria.

reduced operational efficiency. However, the integration of distributed PV improved the feeder voltage profile by supplying localized power and reducing dependence on upstream power delivery.

The results revealed that moderate PV penetration provides the most beneficial impact on feeder stability and performance. Specifically, the 20% PV penetration scenario produced the optimal operational condition, where all bus voltages remained within the acceptable operational limits of 0.95–1.05 p.u. while simultaneously reducing feeder current and network losses. At this penetration level, the feeder exhibited improved voltage regulation, enhanced end-of-line voltage performance, and reduced loading on upstream network components, thereby improving overall system efficiency and stability.

However, the study further showed that excessive PV penetration may introduce operational challenges capable of threatening feeder stability. At 50% PV penetration, significant voltage rise was observed near the PV integration point, resulting in overvoltage conditions beyond the permissible operational limit. In addition, the results indicated the possibility of reverse power flow due to excess power injection exceeding local load demand. Such conditions can negatively affect protection coordination, transformer operation, and voltage regulation within the feeder. These findings confirm that although distributed PV integration is beneficial, uncontrolled penetration may compromise reliable feeder operation.

The hosting capacity assessment demonstrated that the Apo 33 kV feeder can safely accommodate moderate PV penetration without violating voltage stability constraints. Beyond the identified hosting threshold, however, additional control measures become necessary to prevent voltage violations and reverse power flow problems. Consequently, PV hosting capacity must be carefully regulated through proper planning, operational monitoring, and implementation of advanced inverter control strategies. Overall, the study established that distributed solar PV can significantly improve feeder efficiency, voltage support, and operational reliability when properly controlled and integrated within allowable penetration limits. The findings therefore provide useful technical guidance for utility operators, renewable energy developers, and distribution planners seeking to achieve stable and efficient distributed PV integration in weak-grid environments such as Nigeria.

## REFERENCES

Abubakar, H. A., Mustafa, M. W., & Mokhlis, H. (2025). Impact assessment of different PV generation levels on low-voltage distribution networks. *Computers and Electrical Engineering, 122*, 109913. https://doi.org/10.1016/j.compeleceng.2025.109913

Abubakar, H. A., Mustafa, M. W., & Mokhlis, H. (2025). Impact assessment of different PV generation levels on low-voltage distribution networks. *Computers and Electrical Engineering, 122*, 109913. https://doi.org/10.1016/j.compeleceng.2025.109913

Adebayo, A. A., Ibrahim, M. T., & Yusuf, S. O. (2024). Assessment of distributed photovoltaic integration on Nigerian distribution feeders. *Nigerian Journal of Technology, 43*(1), 112–124.

Adebayo, A. A., Ibrahim, M. T., & Yusuf, S. O. (2024). Assessment of distributed photovoltaic integration on Nigerian distribution feeders. *Nigerian Journal of Technology, 43*(1), 112–124.

Adedokun, O. A., Akinyemi, L. A., & Adewale, T. R. (2023). Renewable energy deployment and distributed solar photovoltaic adoption in Nigeria. *Energy Reports, 9*, 1456–1468.

Adeyemi, K. O., & Lawal, M. A. (2023). Voltage rise mitigation in PV-integrated radial distribution networks using smart inverter control. *International Journal of Electrical Power and Energy Systems, 148*, 108923.

Akinwale, Y. O., Salisu, A. A., & Ojo, T. O. (2023). Impact of distributed generation penetration on voltage stability of radial

Corresponding author: Ubril Adesanya Oladimeji
oladimejiluvall@gmail.com
Baze University, Abuja, Nigeria and Department of Electronics and Telecommunications Engineering, Ahmadu Bello University, Zaria.

distribution feeders. *Sustainable Energy Technologies and Assessments, 58*, 103421.

Aremu, F. M., & Ogunbiyi, O. (2022). Application of three-phase power flow analysis to the Nigerian distribution networks. *Journal of Engineering Research and Reports, 23*(4), 1–15.

Aremu, F. M., Ogunbiyi, O., & Salami, A. A. (2023). Conductor size and spacing effects on power losses in Nigerian distribution networks. *Nigerian Journal of Technology, 42*(2), 189–202.

Balamurugan, S., Ramesh, L., & Sathish Kumar, S. (2023). A multi-objective approach for voltage stability enhancement and loss reduction under PQV and P buses through reconfiguration and distributed generation allocation. *IEEE Transactions on Power Systems, 38*(4), 3421–3435.

Balogun, O. A., Sun, Y., & Gbadega, P. A. (2024). Coordination of smart inverter-enabled distributed energy resources for optimal PV-BESS integration and voltage stability in modern power distribution networks: A systematic review and bibliometric analysis. *e-Prime - Advances in Electrical Engineering, Electronics and Energy, 100800*. https://doi.org/10.1016/j.prime.2024.100800

Bello, M. O., Danjuma, U. M., & Abdullahi, A. (2024). Analysis of voltage profile improvement in solar photovoltaic integrated distribution systems. *Journal of Engineering Research and Reports, 26*(3), 45–58.

Chathurangi, D., Jayatunga, U., & Perera, S. (2022). Recent investigations on the evaluation of solar PV hosting capacity in LV distribution networks constrained by voltage rise. *Renewable Energy, 199*, 11–20.

Ejum, E. A. (2025). Assessment of hosting capacity and voltage regulation in photovoltaic-rich distribution systems. *Electric Power Systems Research, 231*, 110124.

Electric Power Research Institute (EPRI). (2010). *Distributed PV Feeder Analysis: Hosting capacity evaluation*. EPRI Technical Report.

Esobinenwu, C. S. (2025). Distributed photovoltaic generation and reverse power flow analysis in weak distribution networks. *Renewable Energy Focus, 52*, 67–79.

Fasina, A. T. (2024). Voltage stability enhancement in radial distribution systems with distributed solar generation. *Heliyon, 10*(2), e24031.

Gönen, T., Ten, C. W., & Mehrizi-Sani, A. (2024). *Electric power distribution engineering* (4th ed.). CRC Press.

IEEE/CIGRE Joint Task Force. (2004). Definition and classification of power system stability. *IEEE Transactions on Power Systems, 19*(2), 1387–1401.

International Renewable Energy Agency (IRENA). (2024). *Renewable capacity statistics 2024*. IRENA Official Website

Jaramillo Leon, B. D. (2025). *Optimization of photovoltaic power plant allocation and smart inverter settings to maximize the distribution network's hosting capacity* [Doctoral dissertation, Universidade Estadual Paulista]. Repositório Institucional da UNESP. https://hdl.handle.net/11449/261096

Kumar, R., & Singh, P. (2023). Solar photovoltaic penetration and operational challenges in modern distribution networks. *Energy Conversion and Management, 287*, 117019.

Kundur, P., Paserba, J., Ajjarapu, V., Andersson, G., Bose, A., Canizares, C., ... & Taylor, C. (2004). Definition and classification of power system stability. *IEEE Transactions on Power Systems, 19*(2), 1387–1401.

Lee, J., Kim, S., & Park, J. (2018). Hosting capacity analysis of many distributed photovoltaic systems in future

*Corresponding author: Ubril Adesanya Oladimeji*
oladimejiluvall@gmail.com
*Baze University, Abuja, Nigeria and Department of Electronics and Telecommunications Engineering, Ahmadu Bello University, Zaria.*

distribution networks. *IEEE Transactions on Power Systems, 33*(6), 6120–6132.

Makinde, K. A., Akinyele, D. O., & Amole, A. O. (2021). Voltage rise problem in distribution networks with distributed generation: A review of technologies, impact, and mitigation approaches. *Indonesian Journal of Electrical Engineering and Informatics, 9*(3), 575–600.

National Renewable Energy Laboratory (NREL). (2023). *Distributed photovoltaic hosting capacity and advanced inverter functionalities*. NREL Official Website

Nigerian Electricity Regulatory Commission (NERC). (2024). *Nigerian electricity supply industry operational report*. NERC Official Website

Nigerian Electricity Regulatory Commission (NERC). (2024). *Nigerian electricity supply industry operational report*. NERC Official Website.

Nwafor, E. E., & Okafor, C. C. (2023). Need for network reconfiguration in Nigerian distribution systems: A review. *IEEE Xplore Conference Proceedings*.

Ogunjuyigbe, A. S. O., Ayodele, T. R., & Akinola, O. A. (2022). Technical challenges of distributed renewable energy integration in Nigeria's power distribution system. *Energy for Sustainable Development, 68*, 85–96.

Olatunji, O. O., & Salami, A. A. (2024). Evaluation of feeder loss reduction using distributed solar photovoltaic systems. *International Journal of Renewable Energy Development, 13*(1), 101–113.

Rahmat, M. K., & Sari, D. (2017). Voltage stability assessment of distribution systems including D-STATCOM using NEPLAN. *IEEE Xplore Conference Proceedings*. https://ieeexplore.ieee.org/document/7836984

Saleem, M., Khan, I., & Ahmad, S. (2024). Reverse power flow and voltage rise assessment in photovoltaic integrated radial feeders. *IEEE Access, 12*, 55421–55435.

Sanni, A. B. (2024). Hosting capacity determination of active distribution networks with renewable energy penetration. *Energy Systems, 15*(2), 411–428.

SurgePV. (2026). Hosting capacity: Definition and guide. *SurgePV Glossary*. https://www.surgepv.com/glossary/hosting-capacity

Wu, Y., Chen, Y., Li, Z., & Golshannavaz, S. (2025). Robust co-planning of distributed photovoltaics and energy storage for enhancing the hosting capacity of active distribution networks. *Renewable Energy, 253*, 123645. https://doi.org/10.1016/j.renene.2025.123645

Zain, M. H., Jayatunga, U., & Perera, S. (2025). Grid resilience: A hybrid approach to sustainable grid stability and renewable integration. *IEEE Xplore Conference Proceedings*. https://ieeexplore.ieee.org/document/11450857

Zhang, Y., et al. (2024). Assessing voltage stability in distribution networks: A methodology considering correlation among stochastic variables. *Applied Sciences, 14*(15), 6455. https://doi.org/10.3390/app14156455.

*Corresponding author: Ubril Adesanya Oladimeji*
*oladimejiluvall@gmail.com*
*Baze University, Abuja, Nigeria and Department of Electronics and Telecommunications Engineering, Ahmadu Bello University, Zaria.*