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Analysis of a Power System Distributed Energy Resources (DES) Management System

Anthony Ejum; Dennis Okonkwo; Ikenna Onyegbadue; & Fred Izilein

Department of Electrical and Computer Engineering, College of Engineering, Igbinedion University, Okada, Nigeria.

Corresponding Author: ejum.anthony@iuokada.edu.ng

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Abstract

The integration of distributed energy resources into power networks is critical in meeting the growing demand for clean and reliable electricity. This study analyses the operation of a distributed energy resources management system with emphasis on voltage regulation using VQ droop control. An IEEE 13-bus distribution network was modelled in OpenDSS, with MATLAB used to implement the droop algorithm for reactive power control. Simulation results reveal that increased penetration of solar photovoltaic resources causes significant voltage rise and fluctuations, alongside an increase in network losses. Without control, a 100 kVA integration produced a 1.4% rise in maximum per unit voltage and a 321% variation in real power, highlighting the destabilising effect of unmanaged DERs. With VQ droop control applied, these deviations were restricted to 0.095% for voltage and 0.89% for real power, showing clear improvements in network stability. The study confirms the effectiveness of droop control in maintaining voltage within limits (1.05, 0.95 p.u), balancing active and reactive power flow, and reducing operational risks. The findings establish VQ droop control as a practical and scalable solution for enhancing the reliability of distribution networks with high levels of renewable penetration.

Keywords: Distributed energy resources, DERMS, Solar photovoltaic, Voltage regulation, Droop control, Smart grids.

Introduction

There is an ongoing transition from fossil fuel-based energy systems to environmentally sustainable energy sources to reduce greenhouse gas emissions and limit rising global temperatures. Projections indicate that fossil fuels will still account for up to 80% of global electricity generation by 2030, which poses significant environmental risks if not addressed (Ukagu et al., 2025; Zhukovskiy et al., 2021). Renewable energy technologies, such as solar, wind, hydro, and biomass, are viewed as key alternatives due to their minimal environmental impact in terms of carbon dioxide emissions (Mostafaeipour et al., 2022; Omorodion et al., 2025). These sources are often deployed through distributed energy systems, which are decentralised configurations where electricity is generated and consumed within proximity (Burger et al., 2019; I. A. Onyegbadue et al., 2024).

Distributed energy resources consist of small-scale technologies like solar panels, wind turbines, microturbines, energy storage devices, and backup generators that work either independently or in coordination to supply energy to meet demand (Krishan & Suhag, 2019; I. Onyegbadue et al., 2022). They support grid reliability and allow local generation close to consumption points, which reduces transmission losses and improves supply efficiency (Medina et al., 2022; Nyiekaa & Onyegbadue, 2021). These resources are becoming more important due to their ability to supplement centralised grids, especially where grid coverage is limited or unstable. As energy systems move towards smarter infrastructure, distributed energy resources play a major role in modernising networks to support real time power quality control and distributed generation management (Aleem et al., 2020). Smart grids offer advanced control and monitoring of power flows, facilitating the seamless integration of distributed resources (Jabr & Dzafic, 2022). This evolution brings about new complexities, particularly in power system operation and control. As more distributed units are connected, conventional one directional power flows are replaced with multidirectional flows, causing operational and planning challenges for utility companies (Lopes et al., 2020). Conventional grid designs are radial, assuming centralised power generation and unidirectional flows. With the connection of renewable based distributed units and microgrids, these networks become active and more difficult to manage (Bordbari & Nasiri, 2024; Yekini et al., 2024).

The rapid increase in the number of generation sources across distribution networks has created an urgent need for effective management platforms. These platforms must be able to coordinate, control, and optimise the operations of several distributed units in real time to ensure energy stability. In practice, these management systems group and present distributed resources as virtual power plants, simplifying their integration into utility operations (Sikorski et al., 2020). A distributed energy resources management system is an application environment designed to enable control, coordination, and optimisation of distributed units through monitoring and data acquisition (Rangu et al., 2020). This system helps in reducing technical challenges while

supporting the efficient functioning of the grid. Its application is necessary for improving power supply reliability, reducing losses, and managing variable generation sources.

As the level of renewable penetration increases in distribution systems, it becomes clear that the nature of energy generation introduces new operational complications (Impram et al., 2020). Renewable resources, especially solar and wind, are inherently variable and less predictable, which makes it difficult to maintain system balance (Sweeney et al., 2020). The inclusion of these sources complicates energy flow, causing voltage fluctuations, frequency deviations, and system congestion in networks that were not originally designed for such diversity (Ibrahim & Hossain, 2021). Traditional distribution operators are not equipped to handle the uncertainty and variability that come with multiple distributed sources, especially when many of them operate without central coordination (Gabrel et al., 2014).

These emerging problems make it necessary to study how distributed energy resources management systems can reduce complexity and improve control in such integrated environments. This research focuses on evaluating how a management system can address the technical challenges introduced by DERs while improving the reliability and efficiency of the power system. The goal is to simulate the system and observe its operation under various load and generation scenarios. The specific objectives include assessing how management systems contribute to voltage and frequency stability, how they support higher integration of renewable energy into the grid, and how they reduce the operational complexity of modern distribution networks.

With the growing reliance on renewable sources for energy generation, there is an increasing need for systems that can manage their integration effectively (Oyekale et al., 2020). The use of distributed energy resources management systems has the potential to support this need by improving how energy is delivered, controlled, and stored. Understanding these systems is important because they help in making the power grid more reliable and efficient (Rathor & Saxena, 2020). They reduce power losses, support real-time control, and make it easier to handle supply and demand changes. Their role in helping to incorporate renewable energy sources such as solar and wind is also essential, since these sources are not constant in their production. When well-managed, distributed resources can reduce stress on the grid, increase energy availability, and improve overall power quality (Kabeyi & Olanrewaju, 2022). They also give the grid the flexibility to respond better during times of peak demand. Analysing these systems provides insight into how energy delivery can be improved, especially in areas where centralised systems may not be enough to meet the energy needs.

The integration of renewable energy sources complicates the operation and planning of power systems due to their variable and intermittent output. Traditionally, distribution grids were designed to deliver power to loads, but with the addition of distributed energy resources (DERs), power flow has become more complex. As DERs increase, technical issues such as voltage fluctuations, frequency imbalances, and congestion arise, challenging the conventional one-way flow of electricity. These challenges are especially evident in areas with high levels of renewable energy resources, which impose new difficulties that traditional grid

operators are not prepared for. To address these challenges, complementary technologies and solutions must be developed and implemented, especially considering the uncertainty of renewable energy production periods, to ensure the system operates efficiently and remains stable while meeting demand.

LITERATURE REVIEW/THEORETICAL UNDERPINNING

Distributed Energy Resources (DERs) are small-scale energy systems that generate or store electricity close to the point of use. These systems include technologies such as solar photovoltaics, wind turbines, energy storage systems, and combined heat and power units. The decentralised nature of DERs enables them to support the traditional grid by supplying localised power, reducing transmission losses, and enhancing system reliability (Strezoski, 2023). Integrating these technologies into the main grid offers environmental and economic benefits while also posing challenges in system planning and operation due to their intermittent and unpredictable nature (Venkateswarlu & Kishore, 2021).

Distributed Energy Resource Management Systems (DERMS) have emerged as an essential solution for managing the complexities of DER integration. DERMS enhance system visibility, enable remote control and coordination, and allow the aggregation of distributed assets to provide grid services. These systems ensure the optimal use of available resources and improve the overall reliability and flexibility of the power grid (Strezoski, 2023).

In a recent review, (Nadeem et al., 2023) conducted a comprehensive review aimed at classifying distributed energy systems (DES), including their technologies, applications, and policy frameworks. The study reviewed over 180 million installed off-grid solar systems, highlighting global efforts in DES adoption. Using descriptive qualitative analysis, the authors evaluated current trends in distributed generation and revealed that policy incentives play a crucial role in DES expansion, especially in developing countries. Their findings show that standardisation and regulation are key drivers in achieving effective DES deployment.

(Gao et al., 2019) focused on the techno-economic integration of distributed photovoltaic (PV) systems into the distribution grid. The study compared traditional infrastructure upgrades, autonomous volt-var controls, and DERMS using a bottom-up approach that combined cost modelling, sequential hosting capacity analysis, and quasi-static time-series simulations. Analysis was performed on two real distribution feeders. Results showed that DERMS expanded hosting capacity more than traditional upgrades, although it resulted in higher PV curtailment. Volt-var control emerged as the lowest cost method but had limited capacity at higher penetration levels.

(Aziz et al., 2019) developed an optimisation model for managing a hybrid power system comprising solar photovoltaic, diesel generators, and battery storage. The model was implemented in MATLAB to determine optimal power flow by considering photovoltaic availability, battery state-of-charge, and load demand. The findings showed that assigning higher priority to battery wear reduction, rather than fuel costs, yielded improved cost efficiency and battery longevity. Their results compared trade-offs under different

optimisation scenarios and demonstrated how energy management strategies can be adjusted to balance competing operational objectives.

(Ahmadipour et al., 2023) introduced an advanced load shedding approach for isolated power systems using a Grasshopper Optimisation Algorithm (GOA). Their study, conducted on an IEEE 33-bus test system with four distributed generation (DG) units, used voltage stability margin (VSM) constraints to maintain grid stability during islanded operation. Simulation outcomes showed that the GOA method outperformed other algorithms such as particle swarm optimisation and grey wolf optimisation in minimising voltage instability and power loss. The model determined the optimal load to be curtailed under various grid conditions, improving stability without excessive generation loss.

(Bhargavi et al., 2021) proposed a power management control strategy tailored for a medium-voltage microgrid containing both synchronous and inverter-based DERs. Using PSCAD/EMTDC for time-domain simulations, the study implemented a virtual droop-based scheme to balance real and reactive power flows. The simulations demonstrated improved dynamic response and steady-state performance of the microgrid, especially under sudden load changes. Their results supported the efficiency of combining droop control and inverter-based strategies to achieve optimal power sharing and system stability.

METHODOLOGY

The methodology is centred on modelling and simulating a distribution network integrated with distributed energy resources. The IEEE 13-bus feeder was adopted in OpenDSS to represent a typical low voltage distribution network. Solar photovoltaic units were selected as the distributed energy resource and placed on high-load buses. MATLAB was employed alongside OpenDSS through a COM interface to implement the V-Q droop control algorithm for voltage regulation. The approach enabled evaluation of network performance under varying levels of DER penetration, both with and without droop control, to assess the effectiveness of distributed energy resource management systems.

System Architecture

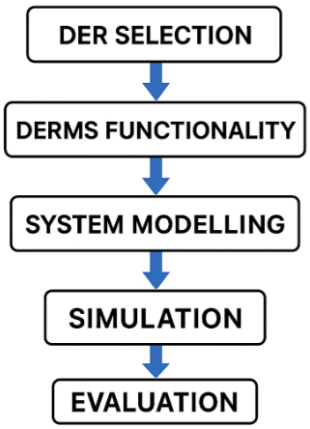


Figure 1: Block Diagram of the System

Data Source

The system modeling requires data from the distribution network, distributed resources, and the management system algorithm. The distribution network data includes information such as feeder topology, line impedance, bus locations, transformer ratings, and load profiles, which are sourced from the built-in libraries of the simulation software. The data for distributed resources focuses on solar photovoltaic systems, detailing capacities, locations, and characteristics like power-irradiance curves and irradiance profiles for realistic generation scenarios. The Distributed Energy Resource Management System (DERMS) data is based on voltage regulation using a droop control algorithm, which adjusts reactive power based on local voltage measurements. A positive voltage deviation reduces reactive power, while a negative deviation increases it, keeping the voltage within acceptable limits. The droop coefficient determines the balance between control speed and accuracy. The simulation will assess how well voltage quality is maintained, how distributed resources interact with the grid, and the effectiveness of the droop-based DERMS in ensuring grid stability. The data used in this study were sourced from standard open-source libraries within OpenDSS simulation software, which includes default values for the IEEE 13-bus feeder network. Solar photovoltaic data, including array capacity, inverter characteristics, and performance curves, were utilised for modelling distributed energy resources. Weather data for solar generation, such as irradiance (4.21 kW/m²) and temperature (25.3°C), were taken from the NASA meteorological database for Port Harcourt, Nigeria. Droop control data, including the droop coefficient and settings, were configured in MATLAB and linked to OpenDSS through a COM interface. These datasets were used to simulate the behaviour of the distribution network with and without the integration of distributed energy resources.

DER Type

The distributed resource selected for this study is solar photovoltaic, chosen due to its relevance as one of the most widely deployed renewable resources. Its ability to provide clean energy directly at the distribution level makes it suitable for grid studies where demand centres are close to supply points. In this work, the solar photovoltaic systems were placed on the distribution feeder based on load demand so that buses with heavier loads received greater support from distributed resources. From the IEEE 13-bus feeder data, bus 675 carries the highest load of 485 kW, while bus 671 also has a significant demand. Both were selected for resource placement since buses with load values above 250 kW were prioritised. The solar resources were integrated into the network model through the OpenDSS platform, where their output characteristics, such as irradiance profiles and inverter parameters, were configured. This approach ensures that the simulation reflects realistic scenarios of distributed integration in a low-voltage network.

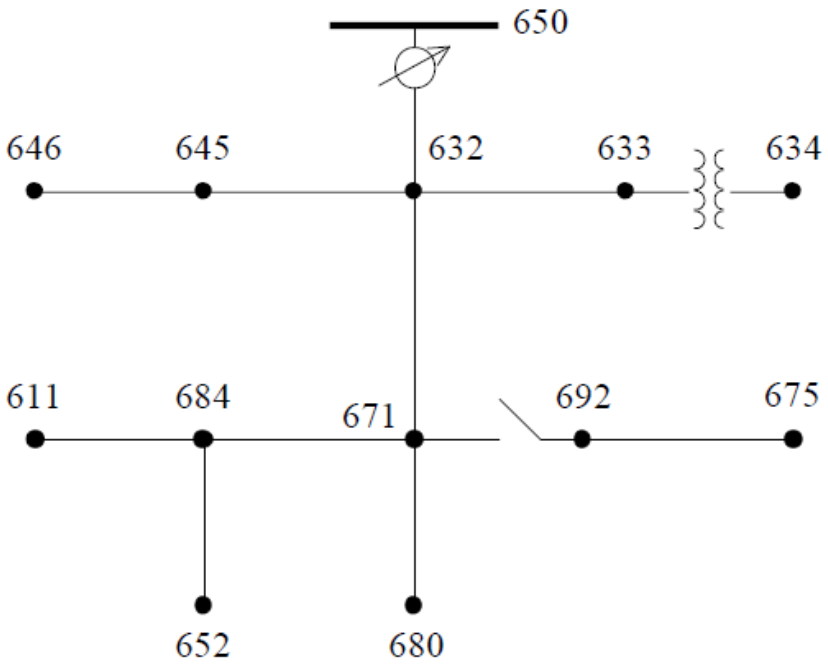


Figure 2: IEEE 13 node feeder network.

Network Modelling

The network model used in this study is the IEEE 13-bus feeder, widely recognised as a standard for simulating low voltage distribution systems. It operates at 4.16 kV and incorporates features typical of a distribution grid, including overhead and underground lines, unbalanced loading, shunt capacitors, and distribution transformers. Its characteristics closely resemble those found in Nigerian distribution systems, making it a reliable reference for this research. The feeder is short but relatively highly loaded, with a single voltage regulator at the substation, providing a realistic platform for studying distributed resource integration and voltage behaviour. All network components such as transformers, voltage regulators, lines, loads, capacitors, and switches were modelled using default codes in OpenDSS, ensuring accurate representation of system behaviour. After introducing solar photovoltaic systems on the selected buses, the network was simulated at varying levels of distributed resource penetration. This allowed the performance of the network to be studied both with and without distributed integration, highlighting the effect on voltage levels and system stability.

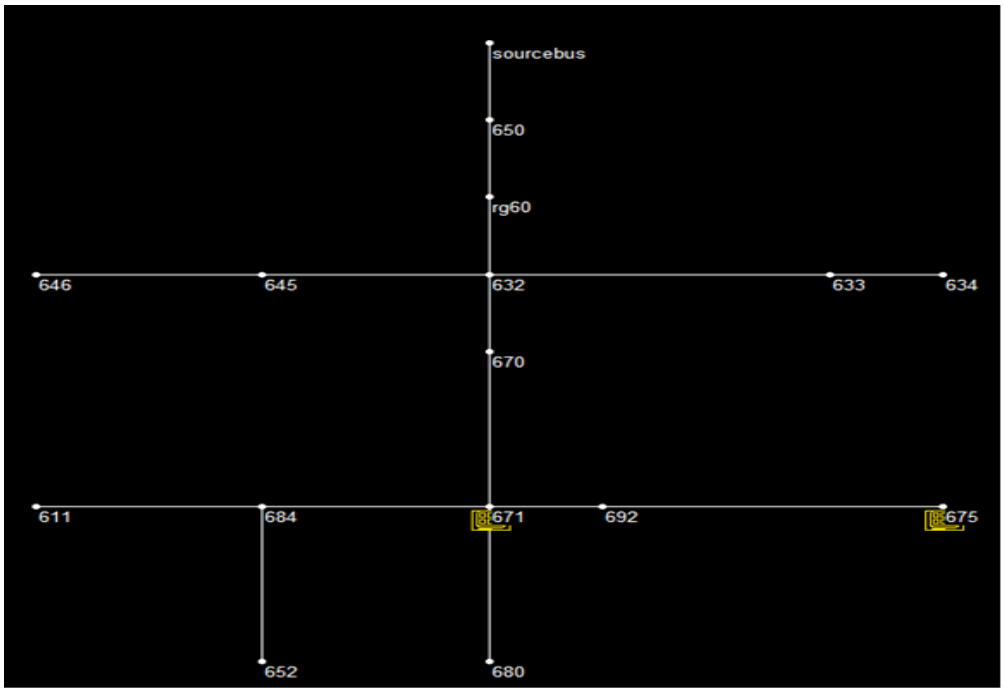


Figure 3: IEEE 13 node feeder network integrated with DER.

Simulation Tools and Functional Focus

OpenDSS served as the primary platform for modelling and simulating the IEEE 13-bus feeder network. It provided the framework for representing the distribution system, defining its components, and running scenarios with and without distributed resources.

MATLAB was applied for implementing the voltage reactive power droop control. Through the COM interface, MATLAB communicated with OpenDSS, processed data, and adjusted control actions based on the droop algorithm to achieve voltage regulation (Kim & Harley, 2018).

Voltage regulation was selected as the central function of the management system, focusing on maintaining network stability under varying levels of distributed energy penetration.

Mathematical Formulations

Based on some terms stated in the previous section, there a number of mathematical formulations that will be required in this paper. Below shows a summary of all the mathematical formulations in this paper;

Power flow equations: Model network power flow under different load and DER operating conditions. Since we are dealing with a power distribution network, load flow equations will be required to account for the active and reactive power flows in the network. Again, since the voltage regulation deals with reactive power outputs from the DERs, these load flow equations must be stated. They are as follows;

Let V_i be the voltage at i^{th} bus, then;

$$V_i = |V_i|\angle\delta_i \quad (1)$$

Let Y_{ii} and Y_{ij} be;

$$Y_{ii} = |Y_{ii}|\angle\theta_{ii} \quad Y_{ij} = |Y_{ij}|\angle\theta_{ij} \quad (2)$$

The net current injected into the network at bus i is represented as Eqn. 3.3;

$$I_i = Y_{i1}V_1 + Y_{i2}V_2 + \cdots + Y_{iN}V_N = \sum_{n=1}^{N} Y_{in}V_n \quad (3)$$

Where N is the total number of buses in the network. Let P_i and $Q_i$be the net real and reactive power entering the network at the bus i, then it can be shown in Eqn. that;

$$P_i + jQ_i = V_iI_i^* \quad (4)$$
$$P_i - jQ_i = V_i^*I_i$$

Where,

$$P_i - jQ_i = V_i^* \sum_{n=1}^{N} Y_{in}V_n \quad (5)$$

On substitution,

$$P_i - jQ_i = |V_i|\angle-\delta_i \sum_{n=1}^{N}|Y_{in}||V_n|\angle\theta_{in} + \delta_n$$
$$\cong P_i - jQ_i = \sum_{n=1}^{N}|Y_{in}||V_i||V_n|\angle\theta_{in} + \delta_n - \delta_i \quad (6)$$

Equating real and imaginary parts,

$$P_i = \sum_{n=1}^{N}|Y_{in}||V_i||V_n|\cos(\theta_{in} + \delta_n - \delta_i) \quad (7)$$
$$Q_i = -\sum_{n=1}^{N}|Y_{in}||V_i||V_n|\sin(\theta_{in} + \delta_n - \delta_i) \quad (8)$$

Droop control equation: Describes the reactive power adjustment based on voltage error and droop coefficient. The OpenDSS software utilizes droop equation to model the decentralized voltage regulation functionality of Distributed Energy Resources Management Systems (DERMS). This equation define how DER units like inverters adjust their reactive power output in response to voltage changes, contributing to maintaining voltage stability within a network. Eqn. 9 describes concept;

$$\Delta Q = -K_d \times (V_m - V_s) \quad (9)$$

Where ΔQ = Reactive power adjustment (kvar)

K_d = Droop coefficient (p.u/kvar)

V_m = Measured voltage at the DERMS connection point (p.u)

V_s = Voltage set point (p.u)

This equation essentially states that the reactive power injected by the DERMS unit (ΔQ) will decrease in proportion to the positive difference between the measured voltage (V_m) and the voltage set point (V_s). The droop coefficient (K_d) determines the sensitivity of the DERMS response to voltage deviations. A higher K_d value results in a larger reactive power adjustment for a given voltage error. Creating the droop control algorithm however would be carried out in MATLAB due to its programming capabilities. The MATLAB is able to simulate the behaviour of the droop controller under various conditions. This algorithm is then linked to the OpenDss software to retrieve voltage measurements, calculate reactive power setpoints using the droop algorithm in MATLAB and finally send the calculated reactive power values back to OpenDSS to adjust generator or inverter output. Thus, MATLAB acts as the brain for the droop control strategy, performing the necessary calculations and decision-making while

OpenDSS provides the power system environment where the droop control is applied and tested.

Solar PV power output equations: Represent the dynamic power generation based on weather conditions. For the solar PV model, it calculates output power based on irradiance, module temperature, and electrical characteristics like open-circuit voltage, short-circuit current, and series/shunt resistances. The solar PV power equation uses mathematical expressions with these parameters to approximate I-V characteristic and power output. These are as follows;

$$P_{pv} = G_i \times A_p \times \eta_{pv} \quad (10)$$

Where:

P_{pv} = Power output of the solar panel (in Watts)

G_i = Solar irradiance (incident solar power per unit area)

A_p = Area of the solar panel

η_{pv} = Efficiency of the solar panel

Control Implementation

The droop control algorithm was developed in MATLAB and linked with OpenDSS through the COM interface to enable coordinated simulation and control of the distribution network. The MATLAB environment communicates directly with the OpenDSS engine, allowing the exchange of data such as bus voltages and reactive power outputs during simulation. The droop algorithm adjusts the reactive power set points of the inverters based on the voltage deviation from the reference value.

The control is implemented using the V-Q droop relationship, where reactive power increases or decreases in proportion to the difference between the measured voltage and the set reference voltage. This ensures that each distributed energy resource contributes independently to voltage regulation, improving network stability. The droop coefficient determines the level of sensitivity, with higher values providing faster response but less precision in maintaining the voltage reference.

The combined use of MATLAB and OpenDSS enables the control algorithm to read real-time values from the simulated distribution system, process the droop control logic, and return updated values for reactive power injection. This method reflects a decentralised approach to voltage regulation in networks with significant penetration of distributed energy resources.

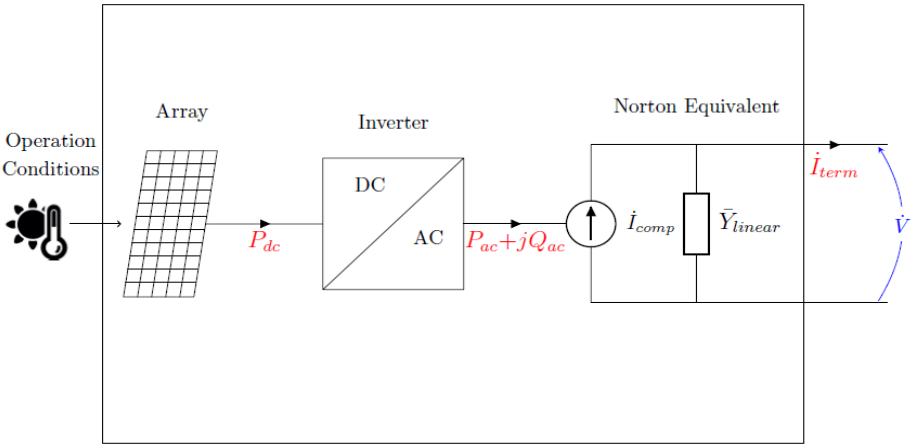


Figure 4: OpenDSS PVSystem element model (Ribeiro et al., 2019)

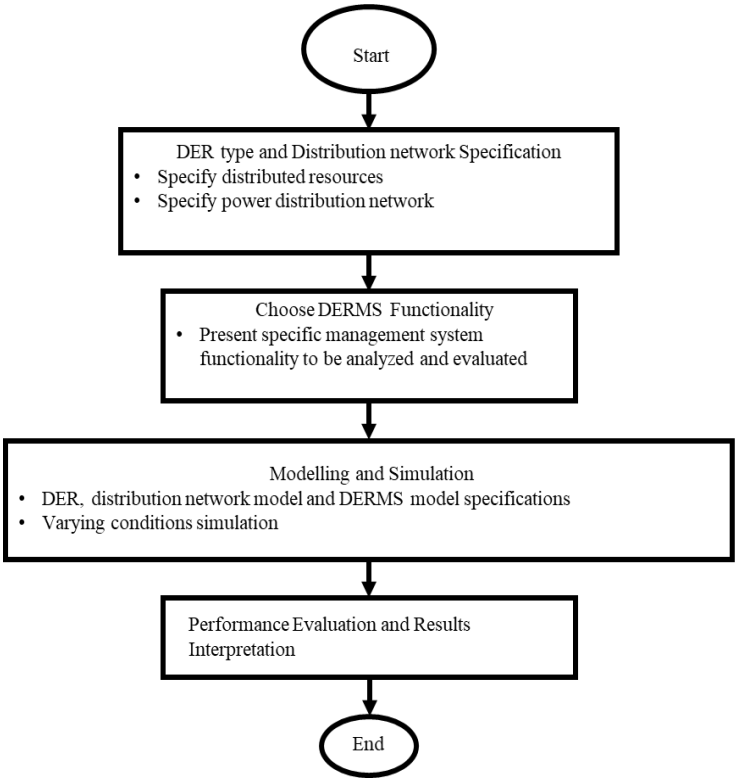


Figure 5: Flowchart of the study

RESULTS/FINDINGS

The results examine the IEEE 13-bus distribution network under baseline, DER-integrated, and controlled conditions. Simulations show the effect of solar photovoltaic penetration on voltage, power flow, and losses, while the V-Q droop control demonstrates its role in maintaining stability and improving overall system performance.

Network Performance

The table below shows the summary of the normal operating characteristics of the network without the inclusion of DER.

Table 1: Bus Normal operating characteristics

Parameter	Value
MW	2.684
Mvar	1.056
Max. p.u voltage	1.0499
Min. p.u voltage	0.988
MW losses	0.0602

Figure 6 depicts the voltage profile of the network.

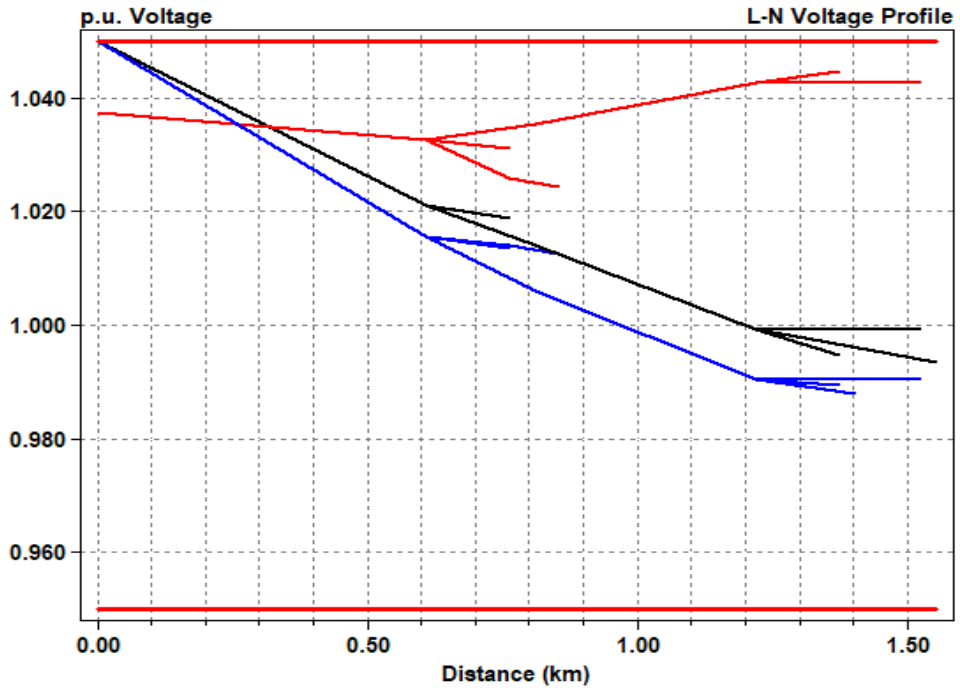


Figure 6: Network voltage profile at normal operating conditions

From the simulation set up, an energy meter was placed at the substation transformer bus and a bus connected to a PV system, Figure 6 and 7 shows the phase power and voltage levels read from the meters at normal operation conditions before the integration of DER.

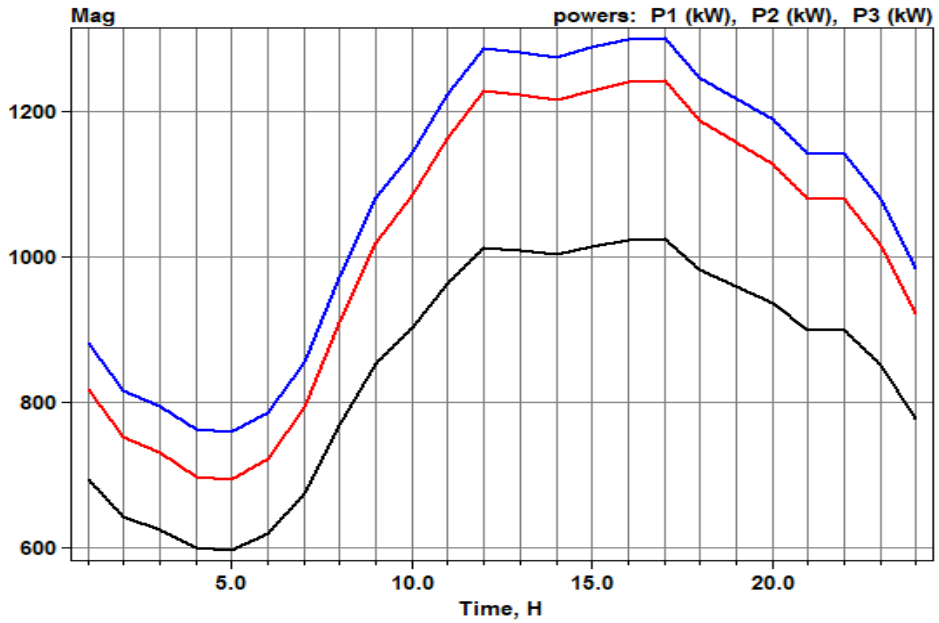


Figure 7: Power levels of the network per phase without DER

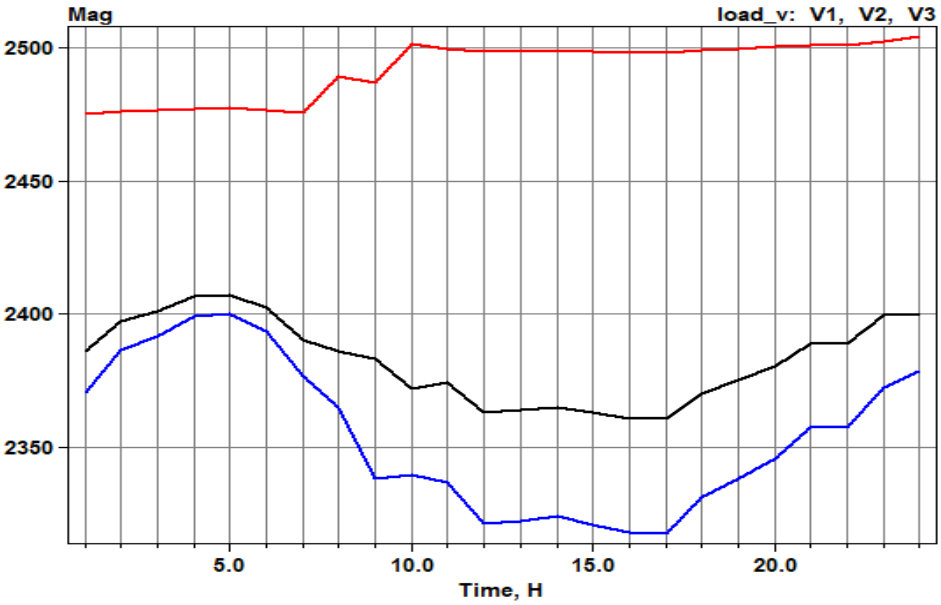


Figure 8: Voltage levels of the network per phase without DER

The following table however shows the operation of the network at different levels of DER penetration while the figures following shows the voltage profiles of the network at these levels of DER penetration.

Table 2: 13Bus operating characteristics with DER integration

DER rating	MW	MVar	Max. p.u voltage	Min.p.u voltage	MW losses
100	-5.95	1.96	1.064	0.985	0.352
200	-13.66	6.925	1.089	0.960	1.905
300	-20.00	15.79	1.101	0.951	4.702

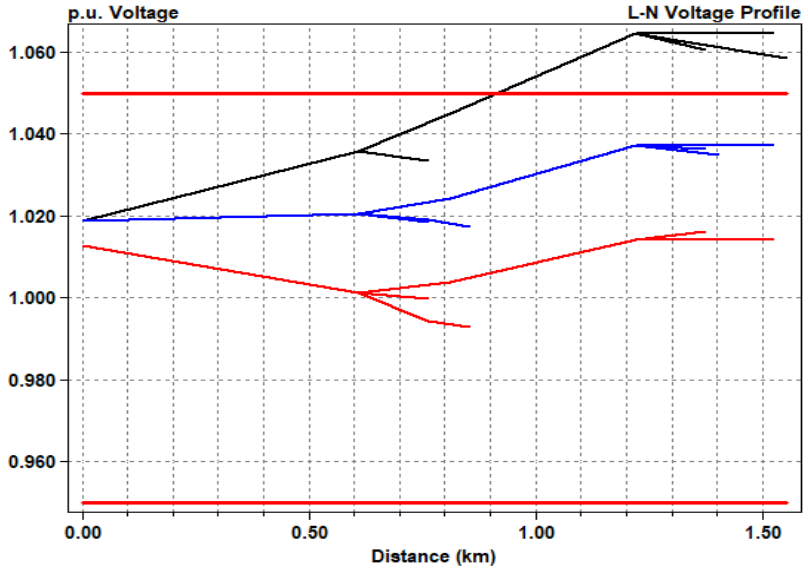


Figure 9(a): Voltage profile at 100kVA

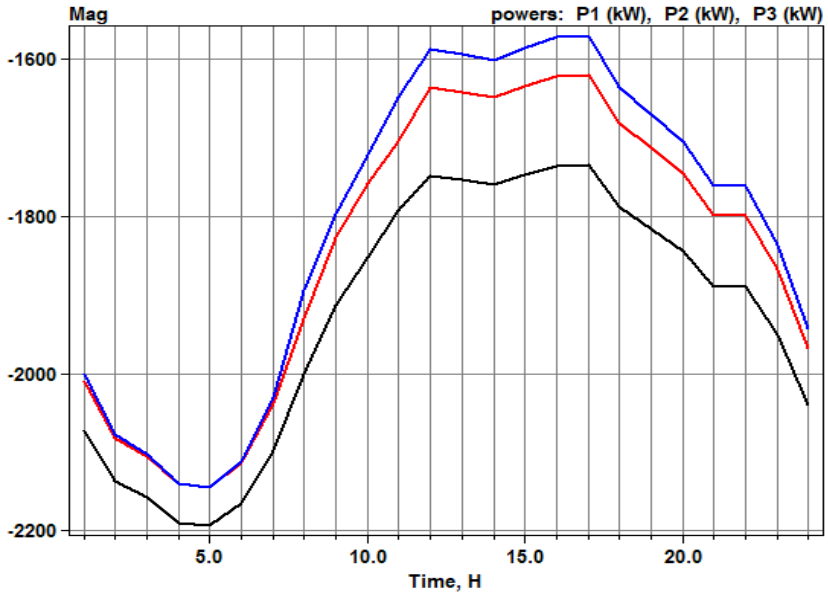


Figure 9(b): Power levels at 100kVA

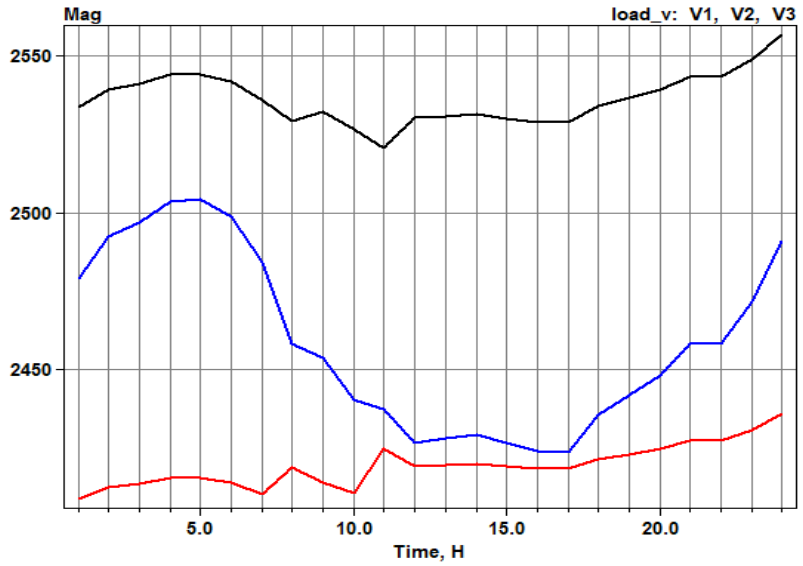


Figure 9(c): Phase voltage levels at 100kVA

The figures describe the voltages and power for each phase of the network with the black representing phase 1, red representing phase 2 and the blue representing phase 3. From Figure 8(a), it was shown that the nodal voltages in phase 1 of buses 670,671,680,684,675,692 and 652 all experience and increase in p.u voltage beyond the set point or maximum operating voltage of the network due to the addition of a 100kVA solar PV system. This can easily be explained, these buses those are closest to the point of coupling or buses integrated with DER and as such get the impact of this input first.

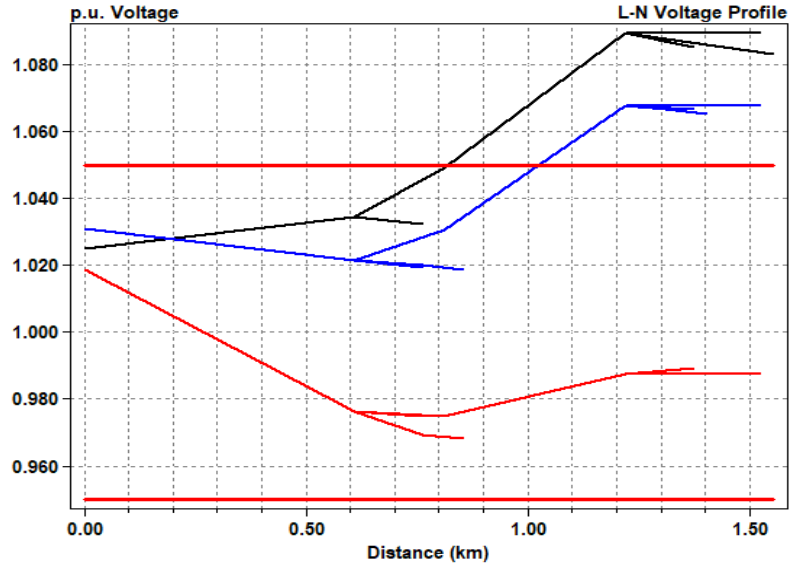


Figure10(a): Voltage profile at 200kVA

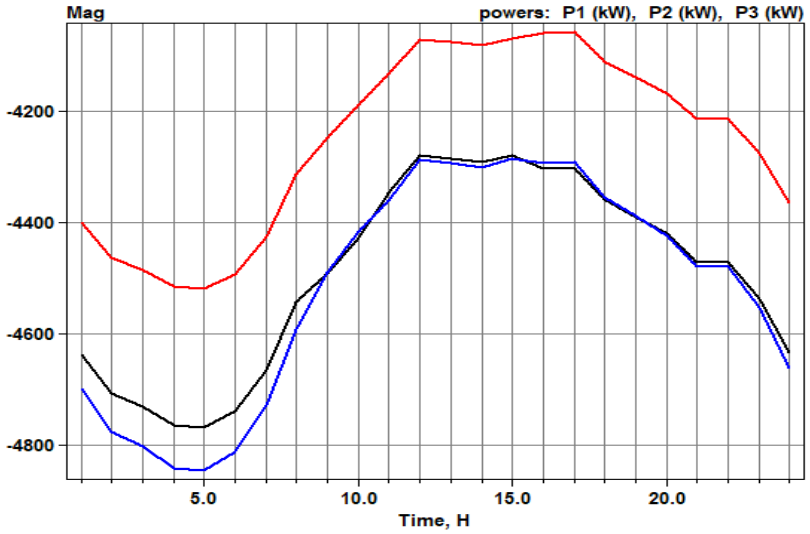


Figure 10(b): Power levels at 200kVA

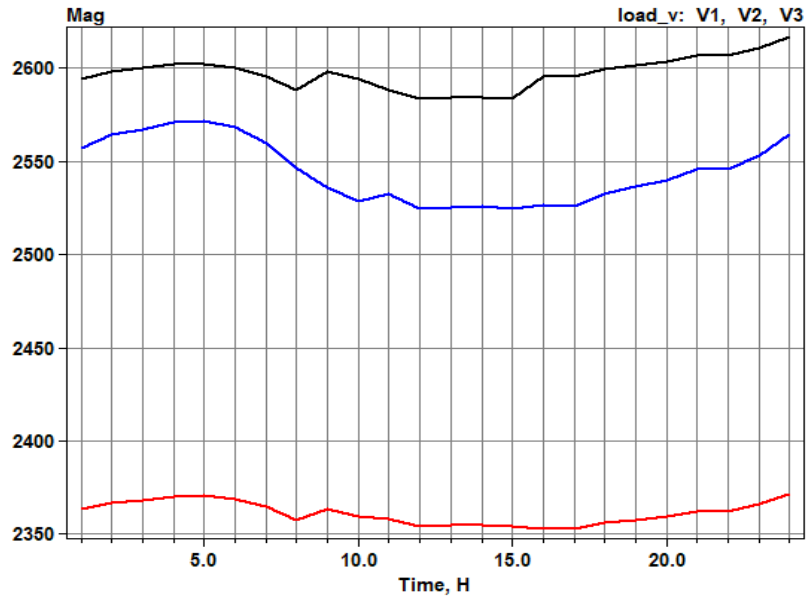


Figure 10(c): Phase voltage at 200kVA

Again, with an increase in DER levels Figure 8(a) shows a continuous increase in nodal voltages of phase 1 and an increase in nodal voltages of phase 3 beyond the voltage limit of the network. The figure also shows a continouzs decrease in the nodal voltage of phase 2 with the increase in the PV input.

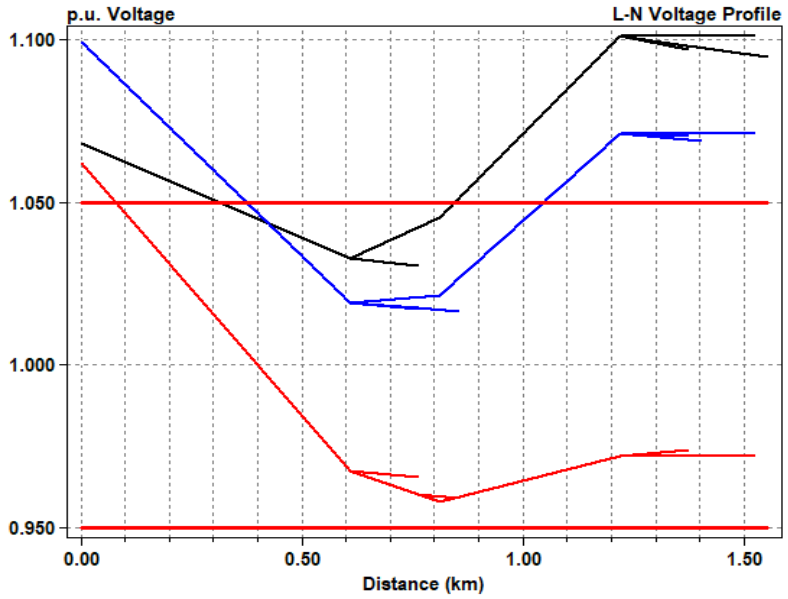


Figure 11(a): Voltage profile at 300kVA

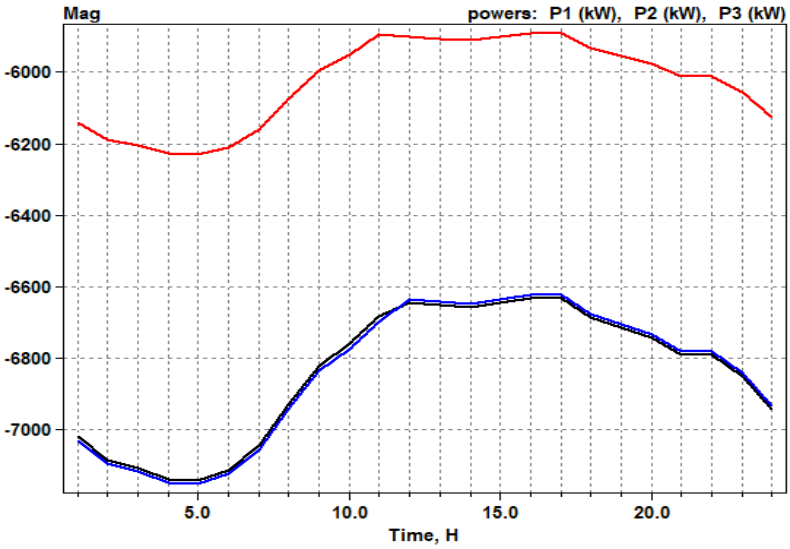


Figure 11(b): Power levels at 300kVA

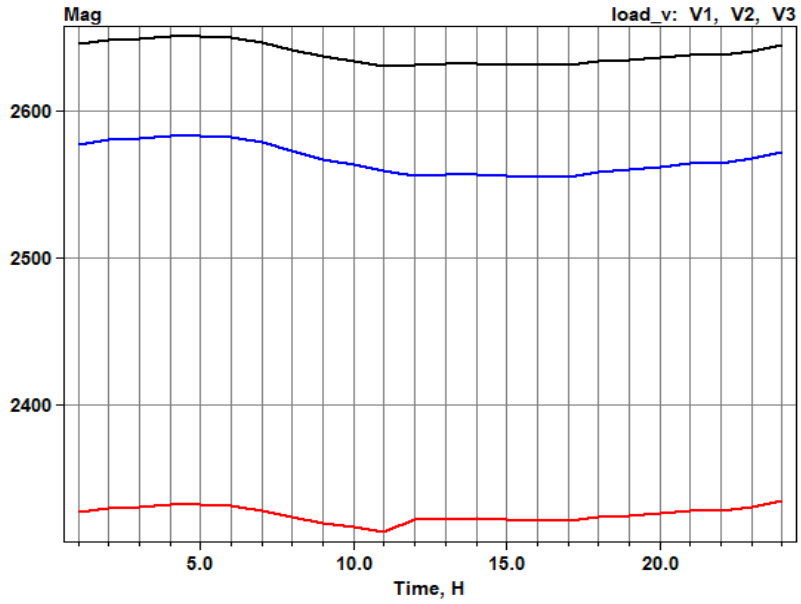


Figure 11(c): Phase voltage levels at 300kVA

At 300kVA solar PV input, the outputs show that the source bus is then affected by the increase in DER penetration, showing that power flows to the generator or main input source of the network. This increase shows an increase in the source voltage of the network, way above the maximum set voltage for all three phases of the distribution network. Phase 2 can be seen to experience a continuous decrease as well, while phase 1 experiences the most of the increased penetration. Figure 10 below describes the behaviour of the max and min p.u voltage with this increase.

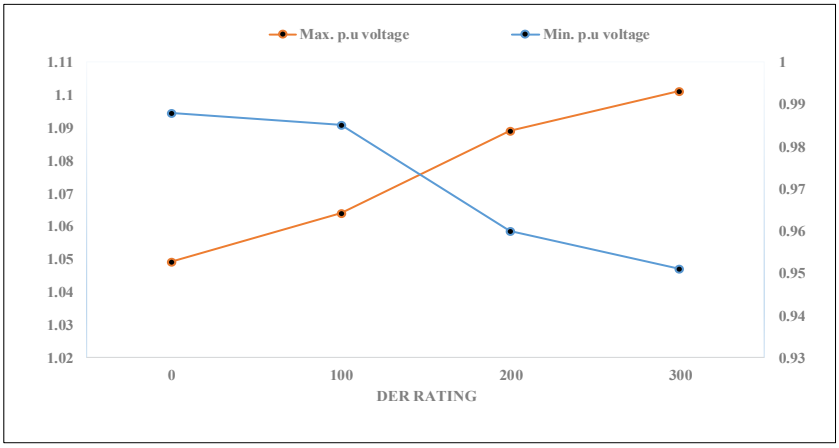


Figure 112: Effect of increased DER levels on network max. and min. p.u voltage.

Based on Figure 12, it is evident that as the amount of distributed resources increases, the maximum per unit voltage of the network rises steadily, and the minimum per unit voltage decreases. This is also a common characteristic in systems with solar photovoltaic systems that inject reactive power, especially when the sun is out, resulting in voltage elevation propagating into the network. The higher the rating of the solar units, the more reactive they are, and as such, the voltage will increase to a sharper level, and there is are danger that overvoltage will be recorded in the case of low demand in the system. The drop in minimum voltages is coupled to increased current flows and drops in lines. This tendency decreases network reliability and can break the apparatus. The simulations also indicate that active power decreases as penetration increases and tumbles into negative values when generation overcomes demand, which implies extra power is exported to the grid. Table 2 indicates that network losses will grow with penetration, whereas active and reactive powers will move in opposite directions, as shown in Figure 13.

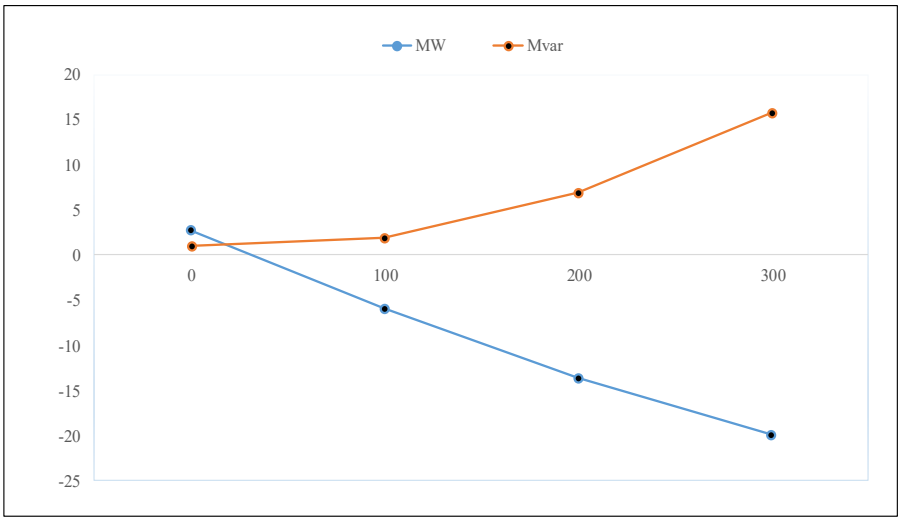


Figure 13: Effect of DER resources on power components of the network

From the figure, it can be seen that the active power drops steadily to levels much lower than the reactive power, and this poses a negative effect on the network, where excessive reactive power can cause voltage levels to rise above acceptable limits and can also limit the amount of active power distributed through the network. As such, advanced control algorithms, in this case the droop, can be used to coordinate the reactive power output of multiple DERs, ensuring optimal power factor correction while maintaining grid stability.

Control Method

The effect of a control method cannot be overemphasised for any voltage level network integrated with DER due to the intermittency of operation based on several natural constraints, mainly weather. Table 3 below shows the droop algorithm's effect on the operation of the

network. The droop control is responsible for adjusting the output of the inverter to ensure reactive power and voltage balance of the network.

Table 3: 13Bus operating characteristics with control

DER rating	MW	Mvar	Min.pu voltage	Min. P.U voltage	MW losses
100	2.66	0.952	1.049	0.991	0.058
200	2.63	0.844	1.0495	0.994	0.056
300	2.61	0.743	1.052	0.951	0.054

From the table above, it can be seen that the inclusion of droop control into the network at different levels of DER penetration is able to keep the power of the network at a stable range. It can also be seen that even as the DER rating increases, the control method conveniently keeps the network operating condition at nominal values. The figures below show the voltage profiles of the network after the droop control. Again, the figure describes the efficiency of the droop control on managing the implementation of distributed energy resources on a low-voltage distribution network.

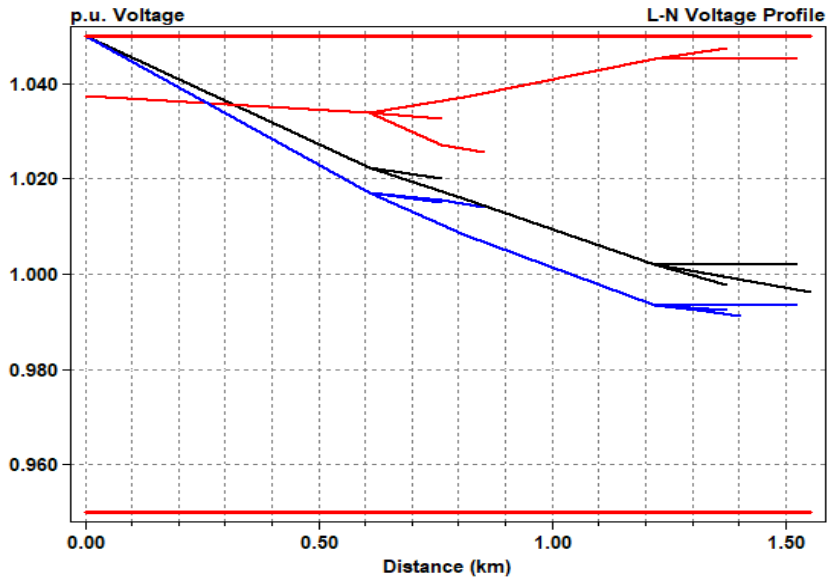


Figure 14(a) Voltage profile at 100kVA with control

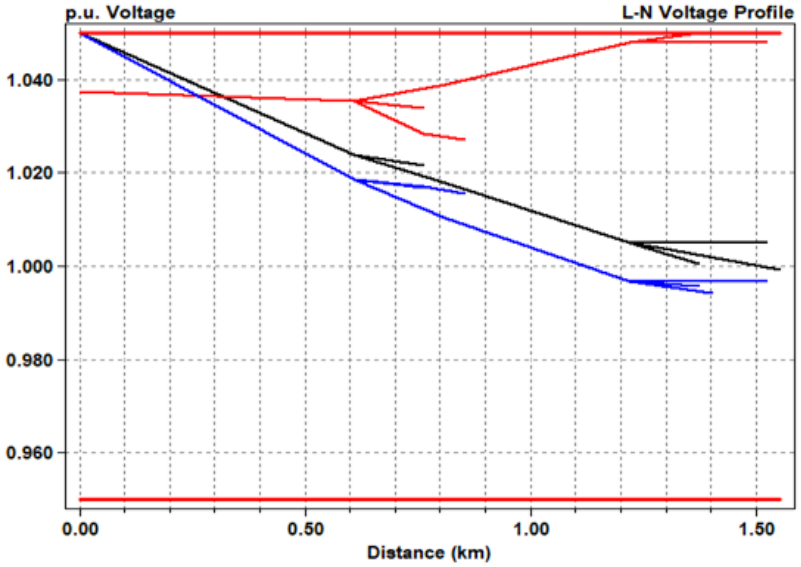


Figure 14(b) Voltage profile at 200kVA with control

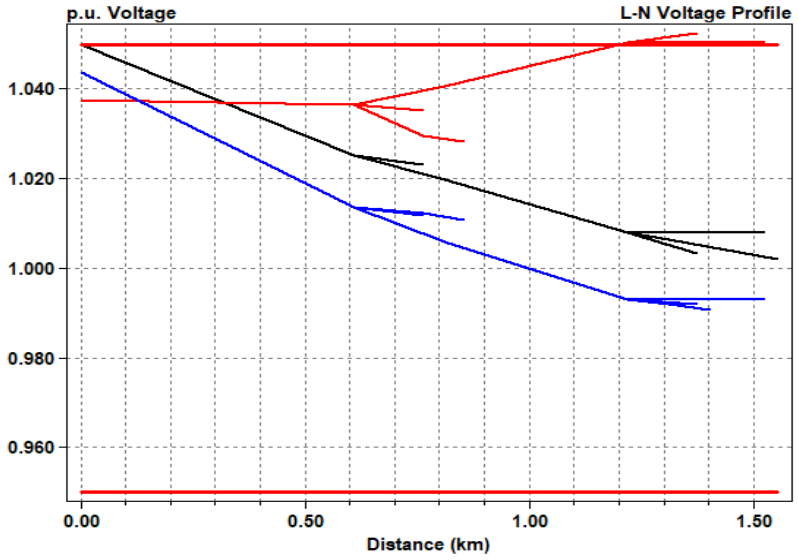


Figure 14(c) Voltage profile at 300kVA with control

The droop control in OpenDSS effectively reduces the impact of distributed resources on voltage stability. Through the V-Q droop mechanism, reactive power output is adjusted in relation to terminal voltage using a droop coefficient. As shown in Figure 15, this ensured that maximum and minimum per-unit voltages remained within the set points of 1.05 and 0.95, even under significant solar penetration.

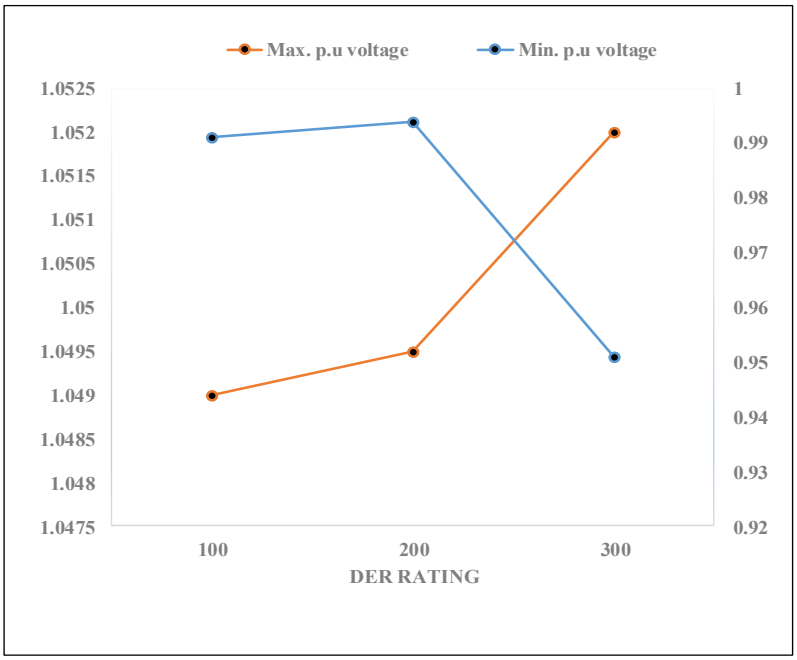


Figure 15: Effect of control on network max. and min. p.u voltage.

The V-Q droop control proves robust and adaptable for integrating large-scale renewables, enhancing grid resilience by allowing DERs to share voltage regulation. It stabilises system voltage by adjusting reactive power as real power rises, preventing excess injection and reducing fluctuations. This effect is illustrated in Figure 16.

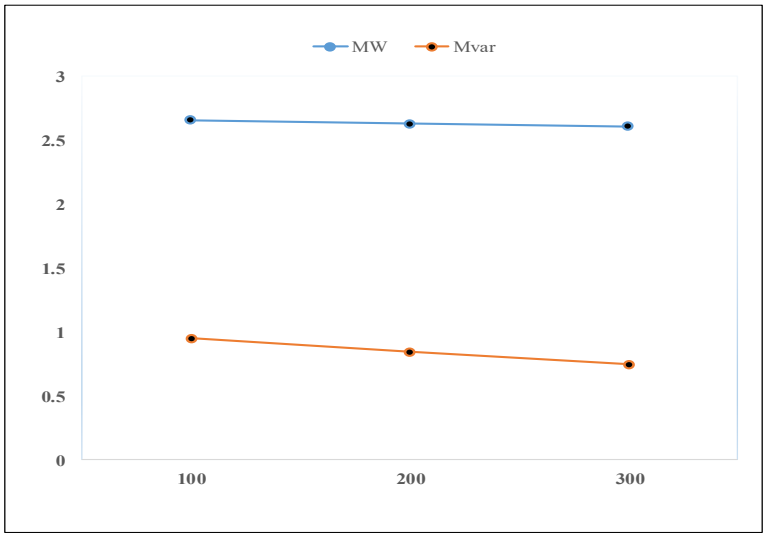


Figure 16: Effect of controlled DER resources on power components of the network

The simulation confirms that V-Q droop control effectively mitigates the impact of solar DER on the IEEE 13-bus network. Real power decreased gradually from 2.66 to 2.61, while reactive power reduced from 0.952 to 0.743 as DER output increased. This shows the control managed both active and reactive contributions, ensuring grid balance and preventing instability.

DISCUSSION

The results of the simulations examining the IEEE 13-bus distribution network under baseline, DER-integrated, and controlled conditions provide valuable insights into the challenges of integrating distributed energy resources (DERs), especially in regions with weak grid infrastructure. The study highlights the effects of solar photovoltaic (PV) penetration on voltage profiles, power flow, and system losses. While the V-Q droop control algorithm demonstrated its effectiveness in stabilizing voltage and improving system performance, it is crucial to consider how other control strategies and real-world DERMS (Distributed Energy Resource Management System) deployments may influence outcomes in different contexts, especially in developing countries where grid infrastructure may be less robust.

The practical implications for utilities in these regions are significant. Weak and outdated grids, combined with inconsistent power generation from renewable sources like solar, can exacerbate issues such as overvoltage, undervoltage, and power imbalances. In many developing contexts, these challenges could hinder the successful integration of DERs, especially when systems lack the necessary flexibility and control mechanisms. Therefore, adopting advanced control strategies such as V-Q droop control becomes crucial to mitigate these issues and improve grid reliability. Other strategies such as Model Predictive Control (MPC), Adaptive Control, and dynamic Volt/VAR control could also offer insights into managing these fluctuations, particularly in environments with unstable weather patterns and limited grid resources.

In the study, as DER penetration levels increased, voltage profiles began to show overvoltage in certain phases, particularly in areas closest to the DER integration points. This is a common issue when integrating high levels of solar PV, which injects reactive power into the grid, raising the voltage. The study illustrates how the V-Q droop control method helps mitigate these risks by adjusting the reactive power output to maintain voltage stability, even under significant solar PV penetration. Further research into other DERMS approaches, such as droop control combined with energy storage or hybrid control strategies, could enhance performance and provide more tailored solutions for specific grid challenges in these regions. Real-world DERMS deployments, like those in countries with emerging solar energy markets, offer practical lessons in how utilities manage the integration of renewable energy. Combining DERMS with energy storage solutions could address issues such as overgeneration and power export when demand is low, which is often seen with high solar penetration.

The results also indicate that power loss in the network increases with higher DER penetration, with active power decreasing as reactive power increases. The reduction of active power and the growing dominance of reactive power can further exacerbate the issue of voltage

instability. The V-Q droop control, by adjusting the output of multiple DERs based on terminal voltage, helps alleviate these challenges by preventing excessive reactive power injection and ensuring that voltage remains within acceptable limits. Other control methods, such as those used in larger DERMS deployments, may use real-time load forecasting or more sophisticated algorithms to adjust the DER outputs dynamically, depending on demand and weather conditions.

CONCLUSION

A distributed energy resources control performance study was conducted by applying V-Q droop control on the IEEE 13-bus network combined with solar photovoltaic units. The simulations revealed the ability of the droop control to stabilise the maximum and minimum per unit voltages and control the real and reactive power flows. This affirmed its capacity to limit the destabilising impacts of divided resources and allow grid dependability. The results also revealed the strategy as a decentralised and scalable feature that can handle the complexity of renewable penetration. Ensuring that voltage is held within an acceptable range and managing any power flows quickly and efficiently meant that the system was better able to tolerate the fluctuations of solar generation. Results show that V-Q droop control is a viable and realistic method when deploying distributed energy resources into existing networks in order to increase stability and improve overall network efficiency.

RECOMMENDATIONS AND FUTURE RESEARCH

In spite of the promising results obtained with the V-Q droop control in stabilising networks with distributed resources, there is still room to develop this approach even further. In future research, its performance should be compared with that of alternative techniques like reactive power sharing and voltage-dependent control, so as to know when it is best suited. Further studies on how multiple-objective optimisation methods can be used to balance goals such as loss minimisation, cost-effectiveness, and stability may enhance control performance. There is also the possibility of adopting advanced technologies in communication that could improve coordination among the scattered units and, consequently, make it more adaptive in the situation. Testing of more complex networks on a larger scale would provide some clues into scalability.

REFERENCES

Ahmadipour, M., Murtadha Othman, M., Salam, Z., Alrifaey, M., Mohammed Ridha, H., & Veerasamy, V. (2023). Optimal load shedding scheme using grasshopper optimization algorithm for islanded power system with distributed energy resources. *Ain Shams Engineering Journal*, *14*(1). https://doi.org/10.1016/j.asej.2022.101835

Aleem, S. A., Suhail Hussain, S. M., & Ustun, T. S. (2020). A review of strategies to increase PV penetration level in smart grids. In *Energies* (Vol. 13, Issue 3). https://doi.org/10.3390/en13030636

Aziz, A. S., Tajuddin, M. F. N., Adzman, M. R., Ramli, M. A. M., & Mekhilef, S. (2019). Energy management and optimization of a PV/diesel/battery hybrid energy system using a combined dispatch strategy. *Sustainability (Switzerland)*, *11*(3). https://doi.org/10.3390/su11030683

Bhargavi, K. M., Jayalakshmi, N. S., Gaonkar, D. N., Shrivastava, A., & Jadoun, V. K. (2021). A comprehensive review on control techniques for power management of isolated DC microgrid system operation. In *IEEE Access* (Vol. 9). https://doi.org/10.1109/ACCESS.2021.3060504

Bordbari, M. J., & Nasiri, F. (2024). Networked Microgrids: A Review on Configuration, Operation, and Control Strategies. In *Energies* (Vol. 17, Issue 3). https://doi.org/10.3390/en17030715

Burger, S. P., Jenkins, J. D., Huntington, S. C., & Perez-Arriaga, I. J. (2019). Why distributed?: A critical review of the tradeoffs between centralized and decentralized resources. *IEEE Power and Energy Magazine*, *17*(2). https://doi.org/10.1109/MPE.2018.2885203

Gabrel, V., Murat, C., & Thiele, A. (2014). Recent advances in robust optimization: An overview. In *European Journal of Operational Research* (Vol. 235, Issue 3). https://doi.org/10.1016/j.ejor.2013.09.036

Gao, S., Jia, H., & Marnay, C. (2019). Techno-Economic Evaluation of Mixed AC and DC Power Distribution Network for Integrating Large-Scale Photovoltaic Power Generation. *IEEE Access*, *7*. https://doi.org/10.1109/ACCESS.2019.2931985

Ibrahim, I. A., & Hossain, M. J. (2021). Low Voltage Distribution Networks Modeling and Unbalanced (Optimal) Power Flow: A Comprehensive Review. In *IEEE Access* (Vol. 9). https://doi.org/10.1109/ACCESS.2021.3120803

Impram, S., Varbak Nese, S., & Oral, B. (2020). Challenges of renewable energy penetration on power system flexibility: A survey. In *Energy Strategy Reviews* (Vol. 31). https://doi.org/10.1016/j.esr.2020.100539

Jabr, R. A., & Dzafic, I. (2022). Distribution Management Systems for Smart Grid: Architecture, Work Flows, and Interoperability. *Journal of Modern Power Systems and Clean Energy*, *10*(2). https://doi.org/10.35833/MPCE.2021.000542

Kabeyi, M. J. B., & Olanrewaju, O. A. (2022). Sustainable Energy Transition for Renewable and Low Carbon Grid Electricity Generation and Supply. In *Frontiers in Energy Research* (Vol. 9). https://doi.org/10.3389/fenrg.2021.743114

Krishan, O., & Suhag, S. (2019). An updated review of energy storage systems: Classification and applications in distributed generation power systems incorporating renewable energy resources. *International Journal of Energy Research*, *43*(12). https://doi.org/10.1002/er.4285

Lopes, J. A. P., Madureira, A. G., Matos, M., Bessa, R. J., Monteiro, V., Afonso, J. L., Santos, S. F., Catalão, J. P. S., Antunes, C. H., & Magalhães, P. (2020). The future of power systems: Challenges, trends, and upcoming paradigms. In *Wiley Interdisciplinary Reviews: Energy and Environment* (Vol. 9, Issue 3). https://doi.org/10.1002/wene.368

Medina, C., Ana, C. R. M., & González, G. (2022). Transmission Grids to Foster High Penetration of Large-Scale Variable Renewable Energy Sources -A Review of Challenges, Problems, and Solutions. *International Journal of Renewable Energy Research*, *12*(1). https://doi.org/10.20508/ijrer.v12i1.12738.g8400

Mostafaeipour, A., Bidokhti, A., Fakhrzad, M. B., Sadegheih, A., & Zare Mehrjerdi, Y. (2022). A new model for the use of renewable electricity to reduce carbon dioxide emissions. *Energy*, *238*. https://doi.org/10.1016/j.energy.2021.121602

Nadeem, T. Bin, Siddiqui, M., Khalid, M., & Asif, M. (2023). Distributed energy systems: A review of classification, technologies, applications, and policies: In *Energy Strategy Reviews* (Vol. 48). https://doi.org/10.1016/j.esr.2023.101096

Nyiekaa, E. A., & Onyegbadue, I. (2021). Optimal Power Flow Methods-A Survey. *International Journal of Advances in Engineering and Management (IJAEM)*, *3*(2), 20–32. https://doi.org/10.35629/5252-03022032

Omorodion, I., Onyegbadue, I., & Izilein, F. (2025). Optimising Power Flow in Transmission Networks: A Comparative Study of Genetic Algorithm and Particle Swarm Optimisation Approaches. *Journal of Systematic, Evaluation and Diversity Engineering*, *9*(5), 72-97. https://doi.org/10.70382/ajsede.v9i5.017

Onyegbadue, I. A., Ukagu, S. N., & Okonkwo, D. O. (2024). Voltage Stability Assessment of Nigeria 330 kV Power Grid: A Critical Bus Perspective. *UNIZIK Journal of Engineering and Applied Sciences*, *3*(5), 1382-1401.

Onyegbadue, I., Ogbuka, C., & Madueme, T. (2022). Robust least square approach for optimal development of quadratic fuel quantity function for steam power stations. *Indonesian Journal of Electrical Engineering and Computer Science*, *25*(2), 732-740. https://doi.org/10.11591/ijeecs.v25.i2.pp732-740

Oyekale, J., Petrollese, M., Tola, V., & Cau, G. (2020). Impacts of renewable energy resources on effectiveness of grid-integrated systems: Succinct review of current challenges and potential solution strategies. In *Energies* (Vol. 13, Issue 18). https://doi.org/10.3390/en13184856

Rangu, S. K., Lolla, P. R., Dhenuvakonda, K. R., & Singh, A. R. (2020). Recent trends in power management strategies for optimal operation of distributed energy resources in microgrids: A comprehensive review. In *International Journal of Energy Research* (Vol. 44, Issue 13). https://doi.org/10.1002/er.5649

Rathor, S. K., & Saxena, D. (2020). Energy management system for smart grid: An overview and key issues. In *International Journal of Energy Research* (Vol. 44, Issue 6). https://doi.org/10.1002/er.4883

Ribeiro, L. C., Vieira, F. L., Bonatto, B. D., De Souza, A. C. Z., & Ribeiro, P. F. (2019). Modeling and simulation of active electrical distribution systems using the OpenDSS. In *Decision Making Applications in Modern Power Systems*. https://doi.org/10.1016/B978-0-12-816445-7.00005-0

Sikorski, T., Jasiński, M., Ropuszyńska-Surma, E., Węlglarz, M., Kaczorowska, D., Kostyla, P., Leonowicz, Z., Lis, R., Rezmer, J., Rojewski, W., Sobierajski, M., Szymańda, J., Bejmert, D., Janik, P., & Solak, B. (2020). A case study on distributed energy resources and energy-storage systems in a virtual power plant concept: Technical aspects. *Energies*, *13*(12). https://doi.org/10.3390/en13123086

Strezoski, L. (2023). Distributed energy resource management systems—DERMS: State of the art and how to move forward. In *Wiley Interdisciplinary Reviews: Energy and Environment* (Vol. 12, Issue 1). https://doi.org/10.1002/wene.460

Sweeney, C., Bessa, R. J., Browell, J., & Pinson, P. (2020). The future of forecasting for renewable energy. In *Wiley Interdisciplinary Reviews: Energy and Environment* (Vol. 9, Issue 2). https://doi.org/10.1002/wene.365

Ukagu, S. N., Atu, M. O., & Onyegbadue, I. A. (2025). Energy Storage: The Key to Reliable Renewable Energy Grids. *ARID ZONE JOURNAL OF ENGINEERING, TECHNOLOGY AND ENVIRONMENT*, *21*(2), 389–400. https://doi.org/10.63958/azojete/2025/21/02/007

Venkateswarlu, S., & Kishore, T. S. (2021). Enhancement of Static Voltage Stability Margin Using STATCOM in Grid-Connected Solar Farms. *Lecture Notes in Electrical Engineering*, *710*. https://doi.org/10.1007/978-981-15-8815-0_33

Yekini, S. M., Guiawa, M., Onyegbadue, I. A., & Olowoniyi, F. (2024). Assessment of Sustainable Energy for Agricultural Energy Provision in Rural Sub-Saharan Africa. *African Journal of Agricultural Science and Food Research*, *15*(1), 61–76. https://doi.org/10.62154/sz7j2452

Zhukovskiy, Y. L., Batueva, D. E., Buldysko, A. D., Gil, B., & Starshaia, V. V. (2021). Fossil energy in the framework of sustainable development: Analysis of prospects and development of forecast scenarios. *Energies*, *14*(17). https://doi.org/10.3390/en14175268