

Performance Assessment of Grid Connected 2.5MW Solar Photovoltaic Plant: A Case of the Nigerian Defence Academy

Nsikak Etim Asuquo*^{ID}, Dauda Dahiru*^{ID} Kenneth E. Okedu**^{ID}

* Department of Electrical Engineering, Faculty of Engineering and Engineering Technology, Nigerian Defense Academy, Kaduna, Nigeria

**School of Information Technology and Engineering, Melbourne Institute of Technology, 3000, Melbourne, Victoria, Australia

nsiasuq@gmail.com, dawooddahiru@gmail.com, kokedu@academic.mit.edu.au

‡Corresponding Author: dawooddahiru@gmail.com or kenokedu@mit.edu

Received: 01.02.2026 Accepted: 24.03.2026

Abstract- The influence of the Nigerian Defence Academy's (NDA) 2.5MW Solar Photovoltaic Generation (SPVG) on the 33/11Kv New NDA Feeder is discussed in this study. Nigerian distribution networks have experienced problems such voltage variation, network losses, and insufficient power injection into substations relative to the net power supplied to the load. Reducing line losses and enhancing the network's voltage profile are the goals of distributed generation (DG). One DG that can boost an existing distribution network's overall efficiency by supplying real and reactive electricity is solar photovoltaic generation (SPVG). To increase the generation's performance, this issue must be resolved by examining the effects of dispersed generation. Therefore, this research looks upon. The performance of the developed system was evaluated using static and dynamic response analysis (current and voltage) as performance metrics. Static and dynamic response analysis (voltage and current) were used as performance metrics to assess the proposed system's performance. The impact of the developed 2.5MW SPVG on the network resulted in active and reactive power losses of (0.1887, 0.1317, 0.0942, 0.0886p.u.) and (0.3321, 0.2872, 0.2117, 0.1873pu) when the DG was placed within the five (5) buses, according to the simulation results. The active and reactive power losses were (0.0091, 0.0043, 0.0037, 0.0022pu) and (0.1413, 0.1222, 0.1077, 0.0810pu) when SPVG was positioned ideally on the network. When compared to that without, this led to improvements in voltage profile, active power flow, reactive power flow, active power loss, and reactive power loss of 12%, 21.33%, 24.21%, 26.77%, and 33.22%. This implies that the impact of DG on the NDA network resulted to increase in load demand. Once the DG was introduced, it now increased the amount of power that is available and the same time, the 2.5MW solar hybrid power plant is already injecting into the existing power flow. It also reduces the power losses due to location that it was strategically placed there by curbing the issue of load demand in the NDA. All simulations were implemented in MATLAB and PSAT.

Keywords Grid connected solar photovoltaic (PV) system, distributed generation (DG), power loss minimization, voltage profile improvement.

1. Introduction

The most widely used and efficient energy source in contemporary life is electrical energy. There are three major subsystems inside the electrical power system. These are

systems for distribution, transmission, and generation. These subsystems distribute electricity to users for use through a distribution system. Feeders, distributors, and service mains make up the distribution system. Additionally, it is categorized as a radial, ring main, and interconnected system

Cite this article as: N. E. Asuquo, D. Dahiru, and K. E. Okedu, "Performance Assessment of Grid Connected 2.5MW Solar Photovoltaic Plant: A Case of the Nigerian Defence Academy", International Journal of Environmental, Social and Economic Sustainability, (IJESES), Vol.1, No. 1, pp. 1-18, March, 2026.

based on the connecting scheme [1]. In the past, coal-fired power facilities, hydroelectric power plants, gas power plants, nuclear power plants, large-scale solar power plants, or their mixtures have all produced electricity centrally. Due to the remote location of these traditional power plants, the electrical energy produced must be carried over a considerable distance before being dispersed to the waiting governmental, commercial, industrial, and residential consumers [1]. Due to technical and environmental issues with this vertical approach system, which receives electricity at the load centers via transmission and distribution network systems, a horizontal approach system was introduced, requiring DGs to play a significant role [2]. Based on provided capacity, distributed generations are divided into four types. Micro distributed generation has a capacity range of 1kW to less than 5kW, small distributed generation has a capacity range of 5kW to less than 5MW, medium distributed generation has a capacity range of 5MW to less than 50MW, and large distributed generation has a capacity range of 50MW to fewer than 300MW. The primary purpose of the DGs' structure is to link them to the distribution network near the consumption centers. Photovoltaic arrays, solar thermal, hydro turbines, wind turbines, fuel cells, biomass gasification, battery storage, and geothermal are the most widely employed DG technologies [3]. The performance of the Nigerian grid might be impacted by the incorporation of renewable energy, according to reports in the literature [4],[5], [6]. This article examines the effects of the Nigerian Defence Academy's 2.5MW solar photovoltaic generation on the 33/11kv feeder network, including insufficient power injection into substations relative to the net power provided to the load. This was accomplished by modeling a 2.5 MW NDA solar captive power station in PSAT using a MATLAB/Simulink model for power flow analysis. Additionally, the distribution network's performance was evaluated in terms of network losses and voltage profile enhancement within an acceptable range. The integration of distributed generation (DG) into contemporary power networks has accelerated because to the growing need for sustainable power generation and the rising demand for electrical energy. Photovoltaic (PV) systems have drawn a lot of interest among the various renewable energy technologies because of its advantages for the environment, modular design, and falling installation prices. Transmission losses can be decreased, voltage profiles can be improved, and system dependability can be increased by integrating PV installations into distribution networks [7]. Despite these advantages, high penetration of distributed PV generation may also introduce operational challenges such as voltage fluctuations, reverse power flow, and power quality concerns. These challenges are particularly relevant in developing countries where distribution networks were originally designed for unidirectional power flow. Several studies have investigated the impact of distributed generation on distribution network performance [8], [9]. However, limited research has focused on practical case studies involving Nigerian distribution networks using detailed simulation tools such as PSAT. Therefore, this study evaluates the impact of integrating a 2.5 MW PV system into a distribution feeder and analyzes its

effects on voltage profile and power losses using simulation analysis.

1.1. Problem Statement

The current generation is not enough to meet the load requirement, and the electricity grid is expanded in a radial configuration. As a result, the network needs extra power at the load sites, which distributed generation, also known as units offer. By changing the power delivery through the feeders, the integration of DGs affects the distribution system. Excessive DG capacity, however, might result in reverse power flow, which raises overall circuit losses and may overheat the network's power delivery components, lowering overall efficiency. Numerous distribution feeders have levels of voltage below the permissible range (0.95 pu–1.05 pu), according to studies, which causes large power losses. As a result, a voltage not at its limit causes voltage instability and blackout. The ideal DG size can have a big impact on loss reduction. Therefore, an empirical solution is absolutely necessary to minimize power loss and optimize the voltage profile. Thus, this thesis introduces distributed generation Solar Photovoltaic Generation (SPVG) at the feeder to achieve this purpose. The feeder lines under consideration are Airport, Rigasa, Kinkinau and NDA 33/ 11kV feeder lines.

1.2. Significance of Research

Evaluating and reducing power distribution system losses is essential since they result in significant expenses for electric utilities. A complete system collapse may result from voltage profile deviations at any node that exceed permissible bounds. As a result, this study is important in preventing such circumstances in the power system that was chosen for the case study.

1.3. Objectives

- To model the power flow analysis of the base case study network using PSAT in MATLAB/Simulink
- To determine the impact of SPVG in improving the stability of the power system network on the base case study using static response analysis.
- To evaluate the network performance before and after the installation of SPVG in the base case study network using dynamic response such as voltage and current signal.

2. Power System Network

Generators, loads, transmission lines, transformers, buses, circuit breakers, and other components make up the intricate network that is the electrical power system. An appropriate model is required for the examination of an operational power system. This model essentially depends on the kind of issue at hand. As a result, it could be transfer functions, differential equations, algebraic equations, etc. Because the loads are constantly fluctuating, the power system is never in a steady state [10]. Nonetheless, it is feasible to imagine a quasistatic state in which the loads can be regarded as constant. This could take 15 to 30 minutes. Power flow equations in this state are nonlinear because they contain trigonometric and variable

product terms. Numerical (iterative) approaches are used in the solution procedures to solve nonlinear algebraic problems. The most popular mathematical method is the Newton-Raphson method [11]. It is more appropriate to implement symmetrical, derivative, and integral controllers or the best controllers using Kalman's feedback coefficients when analyzing the system for small load variations, where speed, frequency, and voltage control may be necessary to maintain the usual values, transfer function, and state variable models. Differential equations depicting energy balance over one or two half-cycles of time are needed for transient stability studies including abrupt changes in load or circuit condition caused by faults. Several matrix models are required to examine the steady state performance [12]. Consider the power system depicted in Figure 2.1. Its equivalent circuit is shown in Figure 2.2. For the analysis of fault currents, the equivalent circuit in Figure 2.2 can be simplified to that in Figure 2.3, extending up to the load terminals, while neglecting the transmission line shunt capacitances and the transformers' magnetizing reactance.

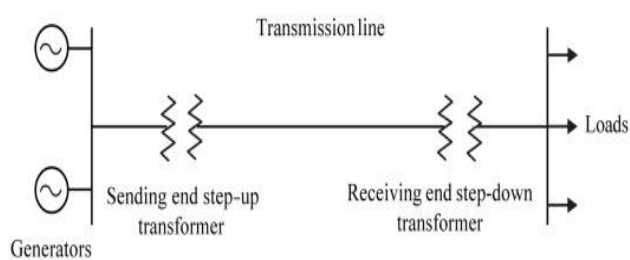


Fig. 1. Power system network [13].

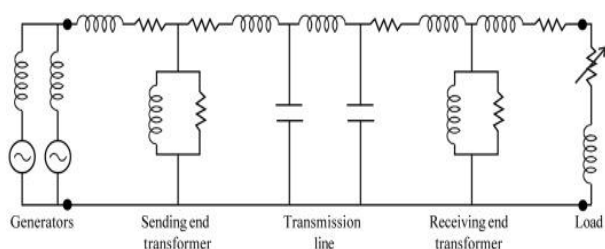


Fig. 2. Circuit sample of the power system network [13].

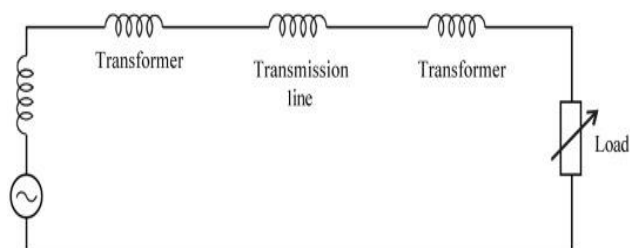


Fig. 3. Reduced equivalent circuit [13].

The machine reactance may vary and take on different values depending on the circumstances, whereas the reactance of static transformers and lines remains constant. Additionally, depending on the makeup of their components, composite loads with 3-phase, 1-phase, d-c, rectifiers, lighting loads, heaters, welding transformers, etc. may have quite diverse models [14]. Controlling a turbo generator to match

varying load demands requires an appropriate system model. For small load variations, a linearized model is suitable for analysis. Such a model can be developed using transfer function concepts, and control can be implemented using either classical or modern control methods. This involves modeling the speed governor, the turbo generator, and the power system itself, as these components form the feedback loop essential for control. The primary goal of power system control is to ensure a continuous power supply with acceptable quality, where quality is defined in terms of voltage and frequency stability [15]. The power system consists of a generating plant, a transmission system, a sub-transmission system, and a distribution system, all interconnected through transformers T1, T2, and T3. To illustrate its operation, consider typical voltage levels: electric power is generated at a thermal plant at around 22 kV (line-to-line). This voltage is then stepped up to approximately 400 kV via transformer T1 for efficient long-distance transmission. Transformer T2 reduces the voltage to 66 kV for delivery through the sub-transmission network to industrial loads that require bulk power at higher voltages. Many large industrial customers have their own transformers to further step down the 66 kV supply to the voltage levels they need. These voltage adjustments are made primarily to minimize transmission line costs for a given power level. Distribution systems, which handle much lower power levels, receive medium-voltage supply to serve end users efficiently [16].

2.1. Power Distribution Network

Medium voltages categorized as both primary and secondary distribution voltages make up the power distribution system. The secondary output (feeder) voltage is rated at 11kV, whereas the primary distribution voltage is 33kV. Distribution substations, transformers, distribution lines or feeders, and sub-feeders are only a few of the components that make up the distribution sector. For balanced loads, both 33kV and 11kV are three-phase, three-wire systems. However, for an unbalanced load, the tertiary distribution section is a 3-phase, 4-wire system [17]. The connection is from the 33kV side before dropping the voltage down to 11kV if the industries (manufacturing, production) are to be fed from the distribution networks. This is due to the fact that the majority of their electric motors and machines operate at this voltage. When these devices and certain loads are used in residential locations, the power quality is typically distorted, power losses are increased, harmonics are produced, voltage swells occur, and flickering occurs. Arcing devices, induction motor starting, information and communications technology (ICT) facilities and equipment, electromagnetic radiation, cables, and embedded generation are some of the technologies that produce these distortions [18]. Typical Nigeria distribution network has the following characteristics:

- Consistent overloading of the distribution installations (distribution lines and transformers)
- Lack of system network upgrade
- Prolonged abandonment of the distribution network
- Deviation/not adhering strictly to engineering ethics, standards and practices.

2.2. Distribution System Losses

energizing the distribution system at the connection of a load with the resistance of all connecting conductor results in many losses [19]. When current flows through cables and other electrical devices (e.g., transformer,) there is bound to be a power loss. Thus, this power loss is known as technical loss, and the losses that do not involve the physical power system but rather are related to electric theft and errors due to billing and metering systems, bypassing the meter, unpaid electricity bills, vandalization of power line were all counted as non-technical losses. A report published by [17], declared that 26-30% of power losses occurred in transmission and distribution systems with a voltage variation of up to 10% of the rated value. However, in their report, they opined those non-technical losses are due to the ageing of equipment of power system, human errors in measurements of a kilowatt-hour (kWh) on energy meters, and the theft of electricity [20]. Highlighted that the losses mentioned above would reduce the overall system's efficiency, thereby increasing the operational cost of service delivery and the high cost of electricity to end users. According to [21], transmission and distribution losses account for a good portion of the power losses in any power system. If the real power losses are greater than the demand, the distribution companies will be adversely affected. Hence, the system engineers need to put in place the necessary mechanism.

2.3. Reducing Distribution System Losses

A distribution network's power loss can be decreased in a number of ways. Among these actions are [22].

- Optimizing feeder capacity through network reconfiguration
- Determining the optimal capacity and sizing of transformers
- Balancing loads across all phases
- Proper coordination of voltage control devices
- Implementing reactive power compensation
- Enhancing the voltage profile through strategic placement of distributed generation (DG) units

2.4. Distributed Generation

Distributed generation, sometimes referred to as embedded generation, on-site generation, dispersed generation, decentralized generation, or distributed energy, is a small plant that produces electricity in close proximity to the final consumer. Distributed Generations (DG) has a capacity of less than 100MW [23]. Cogeneration units, renewable energy systems, or conventional power generation are used in its development. In order to directly supply electricity, several DGs were installed on the customer's property and connected to the customer's side. Others were linked to the distribution system in order to provide electricity to several clients. Building sustainable energy infrastructure can be greatly aided by the deployment of DG in distribution networks [24]. Consumers now prioritize the requirement for a higher-quality power supply. They understand the need of a dependable

power source. Due to a greater R/X value, distribution networks are linked to large power losses. As a result, the client may experience lesser voltage variances in addition to significant voltage dips to almost zero [25]. For instance, in radial networks, bus voltages tend to drop with increasing distances from the distribution transformer and may even go below the utility's minimum voltage [26].

The power flow and voltage conditions at consumers and utility equipment can be greatly affected by the addition of DGs to distribution systems. These effects could be either favorable or negative, depending on the DG and distribution system operational parameters [27]. Loss reduction, improved utility system reliability, voltage support, improved power quality, increased transmission and distribution capacity, delaying the need for new or upgraded infrastructure, ease and speed of installation due to prefabricated standardized components, cost savings by eliminating the need for long-distance high-voltage transmission, and environmental benefits when renewable energy sources are used are all positive effects that are sometimes referred to as "system support benefits." [28]-[29].

2.5. Optimal DG Placement

The main distinction between DG allocation studies and capacitor placement studies is that DG units provide actual power. Using a variety of analytical techniques, numerous research have concentrated on DG allocation and sizing to reduce power losses. Power loss is closely correlated with the quantity of power produced by the DG units, as the relationship between power loss and DG capacity usually exhibits a quadratic trend [30]. Finding the DG size that minimizes power losses over time under various load conditions will yield the ideal DG capacity [31]. For the purpose of this work, this research will focus on the impact of 2.5Mw developed solar photovoltaic generation of the Nigerian Defence Academy, Kaduna on 33/11kv feeder network.

2.6. Impact of Renewable Energy Sources on the Power System Network

Flexibility is a relatively new notion in power systems that has garnered a lot of interest. Additionally, there is a growing need for operational flexibility [26]. Despite its significance, flexibility has not yet been defined consistently and has been approached differently in different research. Planning flexibility and operational flexibility are the two primary categories of flexibility in the literature, with the majority of studies concentrating on the latter. While operational flexibility relates to the equipment of the generation system and its real-time capacity to react to power changes through optimal controllability, planning flexibility mostly concerns with long-term transmission system design and planning [1]. Furthermore, since the interconnections of power systems that serve different countries or areas and operated by different Transmission System Operators (TSOs) have been dramatically increased, the term "exported flexibility" emerged. This term defines the operating flexibility that a TSO can offer to a neighbor network through the tie-points. The

general definition of flexibility in [32], It is considered a more precise definition, describing flexibility as “the ability of a system to deploy its resources to respond to changes in net load.” In conclusion, a flexible power system requires sufficient resources along with optimized operational and planning management [33].

Flexibility has recently been given significant attention under the BRIDGE program, particularly as the distribution grid transforms into a supply-driven system that centers the transmission network on decentralized producers and consumers. According to this "bottom-up" method, flexibility at the voltage level is described as:

- Ensuring a continuous balance between power generation and consumption within the distribution grid to maintain stability increasingly relies on the deployment and utilization of operational flexibility [34].
- on one hand, operational flexibility includes the use of energy storage systems, such as batteries, gas, water, or multi-energy carrier storage [35]
- on the other hand, operational flexibility can also be achieved through flexible, controllable consumption and generation resources via Demand Side Management and Demand Response mechanisms, for example, at the level of a residential urban district [36]-[37]

In this regard, the European Commission’s Smart Grid Task Force, specifically Expert Group 3, [38], Flexibility is defined as follows: "At the individual level, flexibility is the ability to modify patterns of generation output and/or consumption in response to an external signal or activation to provide services within the energy system." A number of indices and metrics have been created to evaluate and measure flexibility, which is recognized as a crucial characteristic of power systems. Inflexibility Signs, Flexibility Chart, GIVAR, Flexibility Assessment Tool (FAST), Insufficient Ramping Resource Expectation (IRRE), Normalized Flexibility Index (NFI), and Loss of Wind Estimation (LOWE) are a few of the instruments and metrics now in use [39]. Ranking method, lack of ramp probability (LORP), and flexibility in location [40].

Large-scale integration of variable renewable energy is technically difficult due to its uncertain nature [41]. Generally speaking, the generation portfolio is designed to offer enough flexibility to effectively manage demand forecast mistakes and unforeseen generating failures, as well as the variability of renewable energy sources (RES). The system must be able to handle the accompanying uncertainty and unpredictability since variable renewables, including wind and solar electricity, contribute to variations in generation capacity [42]. When integrating high levels of intermittent generation, the need for more flexibility has mostly been identified from a centralized perspective. The viewpoint of electrical market participants, who might serve as present or future flexibility suppliers, is also necessary to address this issue. Only when providing flexibility results in financial gain are these participants likely to do so [43]. A power system is considered more flexible than another if it can integrate a greater amount

of renewable energy sources (RES) without restrictions, assuming the same demand and available RES generation. Variations in wind and photovoltaic (PV) output occur across multiple time scales seconds, minutes, hours, days, months, seasons, and years with the primary goal of managing the daily net load cycle. The frequent and inherent fluctuations in wind and PV generation create challenges for conventional generators, requiring rapid, large ramping and frequent start-ups. The need for reserves arises due to inevitable discrepancies between forecasted and actual wind and PV outputs. Therefore, to effectively integrate large volumes of wind and PV power, the system must possess high flexibility to track variable net demand and manage associated uncertainties.[44].

Flexible generation, energy storage, and flexible demand (demand side management) were typically used to meet these needs. Various metrics are used for quantification based on these three fundamental possibilities for offering the necessary flexibility.

In the OECD and IEA joint report [45], Flexibility is the power system's capacity to adjust generation and demand in response to both anticipated and unforeseen unpredictability. It further divides the requirements for flexibility into three fundamental categories: power, energy, and transfer capacity flexibility [46]. Different definitions of power system flexibility reflect and highlight various operational requirements for conventional generating. Three primary metrics are used to measure the flexibility of generation systems: absolute power output range (MW), ramp rate (MW/min), and power output continuity (energy) (MWh) [47].

3. Method

Step-by-step procedure leading to the implementation of the stated objectives are discussed based on the following assumptions. the distribution network was modeled using the Power System Analysis Toolbox (PSAT) within the MATLAB environment. PSAT provides a comprehensive platform for power system simulation and analysis, including load flow studies, stability analysis, and renewable energy integration. In this study, the distribution network parameters including line impedances, bus loads, and transformer ratings were modeled based on available system data. The photovoltaic plant was represented as a distributed generation unit connected at a selected bus within the feeder. Load flow analysis was performed under two operating scenarios: without PV integration and with the 2.5 MW PV system connected to the network. The simulation results analyzed to assess the impact of the PV plant on key system performance including voltage profile, power losses, and power flow distribution within the network.

3.1. Modelling of the Power System Network of NDA 33/11kV in PSAT

The power system line diagram was first obtained from the research of the TCN regional centre. The one-line diagram of 33/11kV NDA Injection substation was modelled using

Power System Analysis Toolbox (PSAT) software in MATLAB/Simulink and then an SPVG was developed.

3.1.1. Data acquisition and analysis

The data used in this work were collected from the public utility service provider known as Transmission Company of Nigeria (TCN) Kaduna regional centre, during visitation to the station. The Company provides Power to Kaduna and other states within the Northwest part of Nigeria. The single line diagram of the power system network of the 2.5 MW NDA solar system on 33Kv Airport feeder was shown in Fig. 4.

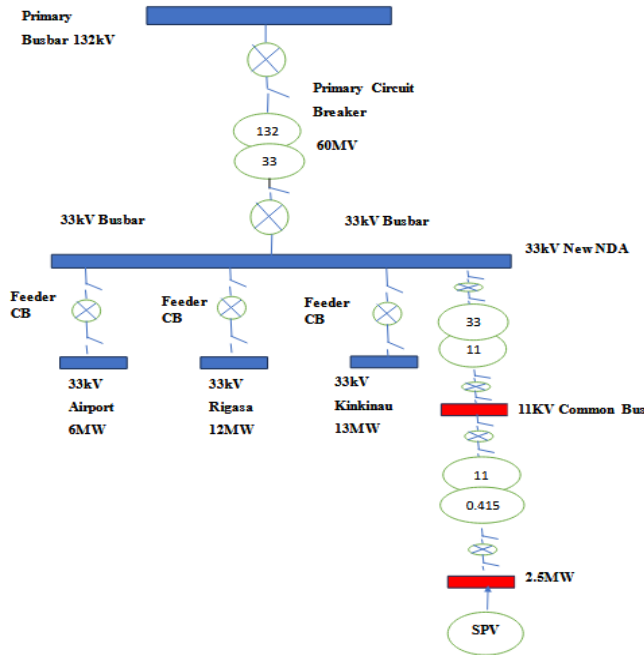


Fig. 4. Single line diagram of the case study.

The Fig.4 shows the single line diagram of 132/33kV substation. This houses 60MVA 132/33kva transformer which step-down the 132kv voltage to 33kV as the secondary voltage system on the Busbar. The 33kV bus-bar of the 60MVA transformer is the distribution centre that feeds the various loads, namely; 33kV Airport feeder (6MW), 33kV Rigasa feeder (12MW), 33Kv Kinkinau feeder (13MW) and 33Kv New NDA feeder. The New NDA 33kv is a dedicated feeder to the NDA permanent site at Afaka, at the 33kv Substation, it was further step-down to 11Kv for reliability purposes. The solar PV plant which is rated 2.5MW, 11kv is connected to the 11kV common busbar, serving as common interphase between the Grid voltage level and the output from the solar generation. The bus information, line information and information of the existing solar system used as the DG of the power system network were shown in Table 1, Table 2 and Table 3.

Table 1. Bus data

| Bus number | Bus location | Voltage (pu = kV/basekV) |
|------------|-----------------|--------------------------|
| 1 | (location of PB | 1 |
| 2 | NDA | 1 |
| 3 | Airport | 1 |
| 4 | Rigasa | 1 |
| 5 | Kinkinau | 1 |

Table 2. Line data

| Line number | From bus | To bus |
|-------------|----------|--------|
| 1 | 1 | 2 |
| 2 | 2 | 3 |
| 3 | 2 | 4 |
| 4 | 2 | 5 |

Table 3. The information of the existing solar system used as the DG

| Parameters (units) | Values |
|------------------------------------|--------|
| Power rating (MW) | 2.5 |
| Number of panels | 5,460 |
| Daily temperature (°C) | 25 |
| Sun irradiance | 800 |
| Percentage efficiency (average) | 86 |
| Number of inverter | 13 |
| Power rating per inverter (Kw) | 185 |
| Current rating of batteries (Amps) | 1300 |
| Number of batteries | 162 |

3.1.2. Modeling of the power system Network in PSAT using MATLAB

The datasets obtained from section 3.1.1 were used to model the power system network in PSAT using MATLAB. The procedure for the modeling of the power system network in PSAT was shown in the flow diagram in Fig. 5

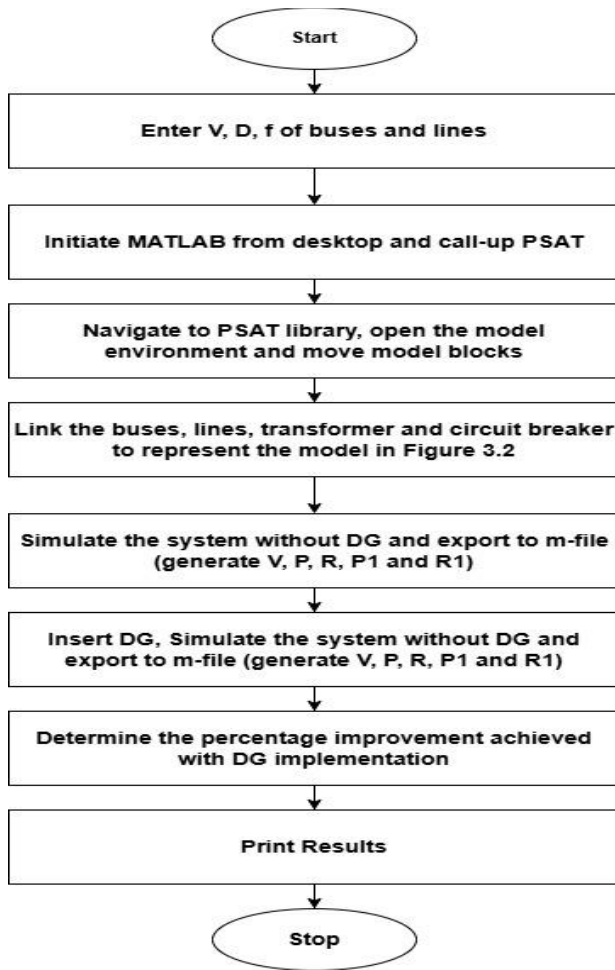


Fig. 5. Flow diagram of the procedure of PSAT modeling of the power system network.

Fig. 6 represents one-line diagram of 33/11kV NDA injection Substation using PSAT software.

The model in Fig. 6 was simulated and the data exported to MATLAB environment for the generation of tables, plots and charts for the power system network static and dynamic parameters for with and without DG. The outcome was presented in the result section of chapter four.

3.2. Determination of the System Impact Without and with the Implementation of the DG on the NDA 33/11 kV Network Feeder

The equation for the determination of the improvement for each voltage profile (%V_{imp}) was shown in Equation 1.

$$\%V_{imp_i} = \frac{V_{DG} - V}{V_{DG}} 100 \quad (1)$$

Then

$$\%V_{imp} = \frac{\sum(V_{imp_i})}{n} \quad (2)$$

Where %V_{imp_i} represents the voltage improvement for each bus, V_{DG} represents the voltage with DG, V represents the voltage without DG and n represents the number of stations.

The percentage real power improvement was shown in Equation 3.

$$\%P_{imp} = \frac{\sum(P_{DG} - P)}{\sum(PG)} 100 \quad (3)$$

Where %P_{imp} represents the real power improvement achieved, P_{DG} represents the real power flow with DG, P represents the real power flow without DG and n represents the number of stations. Other parameters such as reactive power flow, active power loss and reactive power loss followed the format as shown in Equation 3.

The overall percentage improvement of the impact of DG over without DG placement was evaluated based on the equation:

$$\eta = \frac{K_{DG} - K_{WDG}}{K_{DG}} \times 100\% \quad (4)$$

Where η represent percentage improvement of the impact of DG placement over without DG placement (WDG), K_{WDG} is the value obtained on without DG placement on the network and K_{DG} is the value obtained when DG was used.

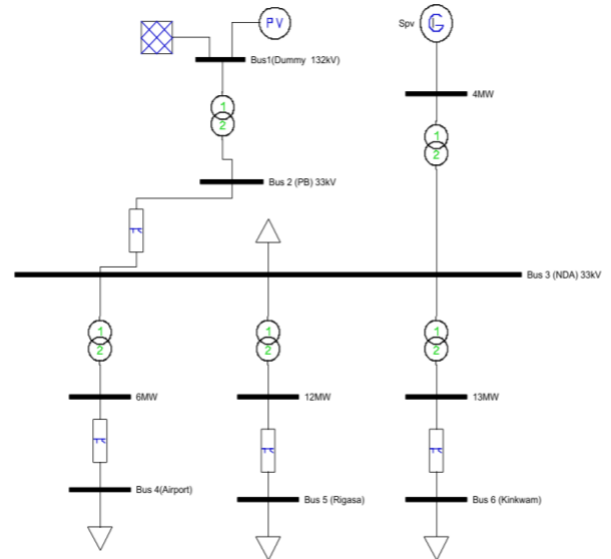


Fig. 6. PSAT model of the power system network with DG.

4. Result and Discussion

The results obtained based on the methodologies presented in Section 3 that addressed the research objectives are discussed.

4.1. Simulation Results of voltage of the system without and with the implementation of the DG

The voltage of the system without and with the implementation of the DG was shown in Table 4.

Table 4. Voltage profile of the system with and without DG

| Bus number | Bus voltage without DG (pu) | Bus voltage with DG (pu) | % Improvement $\%V_{imp_i} = \frac{V_{DG} - V}{V_{DG}} 100$ |
|------------|-----------------------------|--------------------------|--|
| 1 | 0.9500 | 0.9930 | 4.33 |
| 2 | 0.9240 | 0.9941 | 7.05 |
| 3 | 0.8920 | 0.9823 | 8.89 |
| 4 | 0.8950 | 0.9817 | 8.83 |
| 5 | 0.8890 | 0.9789 | 9.18 |

Table 4 summarizes the performance improvement of voltage profile of the impact of DG and that without DG. It was observed from the Table 4 that, bus 1 to 5 has improvement of 4.33, 7.05, 8.89, 8.83 and 9.18% as a results impact of DG placement on the network. However, it can be revealed from the Table 4 that, the impact of DG on the 33/11Kv network resulted to the overall voltage improvement of 9.18% on bus 5 when compared to that without DG placement. This implies the improvement in the voltage profile currently witness in the NDA distribution network is totally attributed to the developed 2.5MW solar captive power plant and such, the improvement witness was on the outcome achieved from the research. The Bar chart of the comparative

analysis of the voltage profile for with and without DG was shown in Fig.7.

The voltage profile of the power system network was shown in Fig.7. It was observed that without the DG implementation, the voltage values were outside the voltage threshold of 0.95 to 1.05pu but the implementation of the DG improved the voltage profile of all the buses to be within the threshold.

The active power flow of the system without and with the implementation of the DG was shown in Table 5.

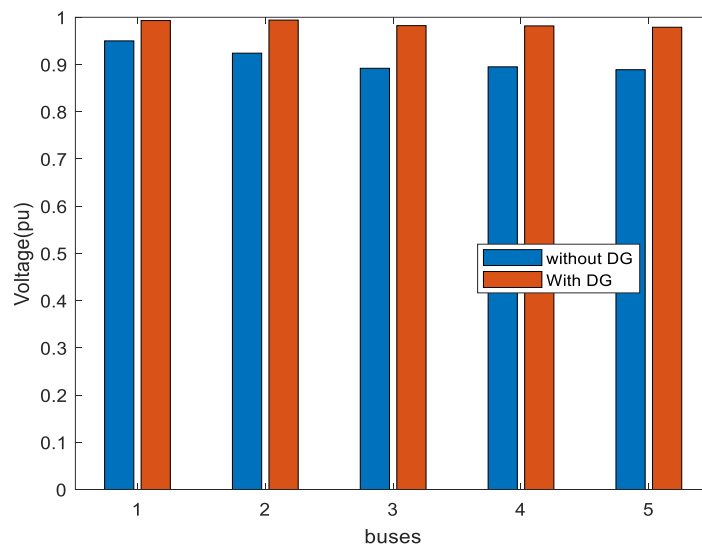


Fig. 7. Bar chart of the voltage profile for with and without DG.

Table 5. Active power flow of the system with and without DG

| Line number | Active power flow without DG (pu) | Active power flow with DG (pu) | % Improvement $\eta = \frac{K_{DG} - K_{WDG}}{K_{DG}} \times 100\%$ |
|-------------|-----------------------------------|--------------------------------|--|
| 1 | 1.1421 | 1.7722 | 35.55 |
| 2 | 0.9977 | 1.8143 | 45.00 |
| 3 | 0.9813 | 1.3317 | 26.31 |
| 4 | 0.9810 | 1.2172 | 19.41 |

Table 5 summarizes the performance improvement of the active power flow of the impact of DG and that without DG. It was observed from the Table 5. that 35.55, 45.00, 26.31 and 19.41%. However, it can be revealed from the Table 5 that, the impact of DG on the 33/11Kv network resulted to the overall improvement of active power flow of 45.00% on line 2 when compared to that without DG placement. This implies that, with the introduction of 2.5MW DG power compensation into the system, more power is available for the NDA military personnel in their day-to-day activities.

The Bar chart of the comparative analysis of the active power flow for with and without DG was shown in Fig. 8.

The active power flow of the power system network is shown in Figure 4.2. It was observed that the introduction of the DG improved the active power by ensuring the reduction in the power flow congestion. Hence, active power flow was improved with DG implementation.

The reactive power flow of the system without and with the implementation of the DG was shown in Table 6.

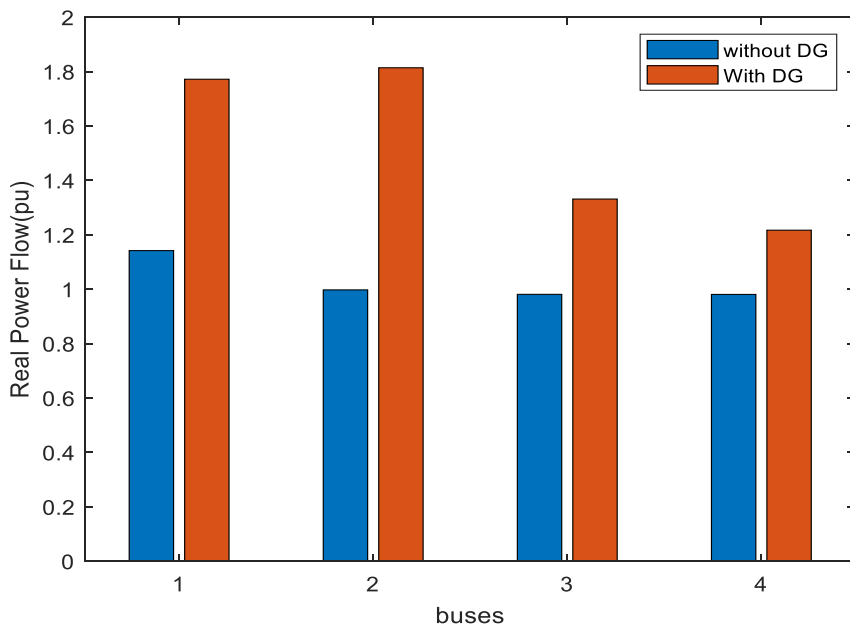


Fig. 8. Bar chart of the Active Power flow for with and without DG.

Table 6. Reactive Power Flow of the System with and without DG

| Line number | Reactive power flow without DG (pu) | Reactive power flow with DG (pu) | % Improvement $\eta = \frac{K_{DG} - K_{WDG}}{K_{DG}} \times 100\%$ |
|-------------|-------------------------------------|----------------------------------|--|
| 1 | 2.1213 | 2.8987 | 26.82 |
| 2 | 1.9887 | 2.9908 | 33.51 |
| 3 | 1.5567 | 1.9928 | 21.88 |
| 4 | 1.2219 | 1.7219 | 29.04 |

Table 6 summarizes the performance improvement of the reactive power flow of the impact of DG and that without DG. It was observed from the Table 5 that 26.82, 33.51, 21.88 and 29.04%. However, it can be revealed from the Table 5 that, the impact of DG on the 33/11Kv network resulted to the overall improvement of active power flow of 33.51% on line 2 when compared to that without DG placement. This implies that, with the introduction of 2.5MW SPVG more power will be delivered to the institution.

The Bar chart of the comparative analysis of the reactive power flow for with and without DG was shown in Fig. 9.

In Figure 4.3, it was observed that the introduction of the DG improved the reactive power flow of the power system network largely due to the introduction of more reactive flow compensation to the power system network. This implied that the introduction of the DG improved the reactive power of the network. The active power loss of the system without and with the implementation of the DG was shown in Table 7.

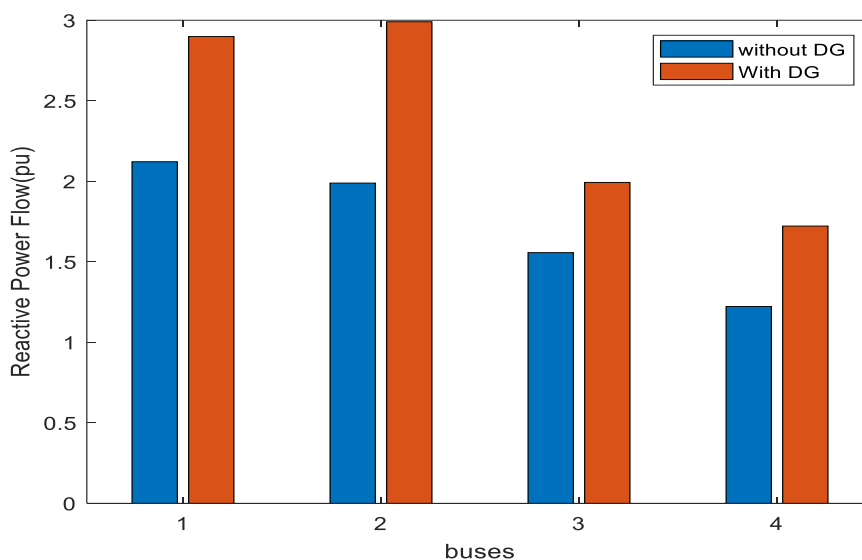


Fig. 9. Bar chart of the reactive power flow for with and without DG.

Table 7. Active power loss of the system with and without DG

| Line number | Active power loss without DG (pu) | Active power loss with DG (pu) | % Improvement $\eta = \frac{K_{DG} - K_{WDG}}{K_{DG}} \times 100\%$ |
|-------------|-----------------------------------|--------------------------------|--|
| 1 | 0.1887 | 0.0091 | 95.18 |
| 2 | 0.1317 | 0.0043 | 96.74 |
| 3 | 0.0942 | 0.0037 | 96.07 |
| 4 | 0.0886 | 0.0022 | 97.52 |

Table 7 summarizes the performance improvement of active power loss on the impact of DG and that without DG. It was observed from the Table 7 that, bus 1 to 4 has improvement of 95.18, 96.74, 96.07 and 97.52% as a results of impact of DG placement on the network. However, it can be revealed from the Table 7 that, the impact of DG on the 33/11Kv network resulted to the overall active power loss reduction of 97.52 % on line 4 when compared to that without DG placement. This implies the reduction of the power loss was a result of power generated from the developed NDA 2.5MW solar captive power plant installed which can be trusted to the end users without any form of loss. Hence, based

on the improvement achieved, a larger percentage of power generated get to the consumers.

The Bar chart of the comparative analysis of the active power loss for with and without DG was shown in Fig. 10

From Figure 4.4, it was observed that the introduction of the DG reduced the real power losses of the power system network by reducing flow congestions in the network. The reactive power loss of the system without and with the implementation of the DG was shown in Table 8.

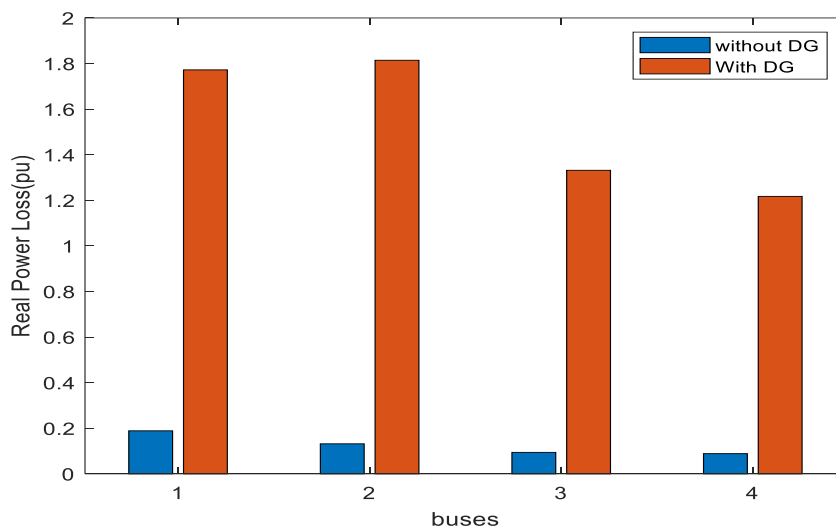


Fig. 10. Bar chart of the active power loss for with and without DG.

Table 8. Reactive Power loss of the System with and without DG

| Line number | Reactive power loss without DG (pu) | Reactive power loss with DG (pu) | % Improvement $\eta = \frac{K_{DG} - K_{WDG}}{K_{DG}} \times 100\%$ |
|-------------|-------------------------------------|----------------------------------|--|
| 1 | 0.3321 | 0.1413 | 57.45 |
| 2 | 0.2872 | 0.1222 | 57.45 |
| 3 | 0.2117 | 0.1017 | 51.96 |
| 4 | 0.1873 | 0.0810 | 56.75 |

Table 8 summarizes the performance improvement of reactive power loss on the impact of DG and that without DG. It was observed from the Table 8 that, bus 1 to 4 has improvement of 57.45, 57.45, 51.96 and 56.75% as a results of impact of DG placement on the network. However, it can be revealed from the Table 8 that, the impact of DG on the 33/11Kv network resulted to the overall reactive power loss reduction of 57.45% on line 1 and 2 when compared to that without DG placement. This implies the introduction of DG reduced the rate of power congestion during flow of electricity that resulted to loss. In reducing the power congestion implies reducing the power loss in the network.

The bar chart of the comparative analysis of the reactive power loss for with and without DG was shown in Fig. 11.

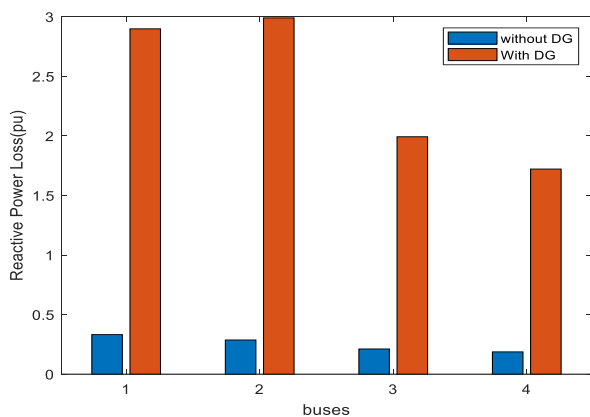


Fig. 11. Bar chart of the Reactive Power Loss for with and without DG.

The comparative analysis of the reactive power losses for with and without DG was shown in Fig.11. It was observed that the introduction of the DG reduced the reactive loss of the power system network. The percentage power quality improvement achieved with the introduction of the DG was shown in Fig. 12

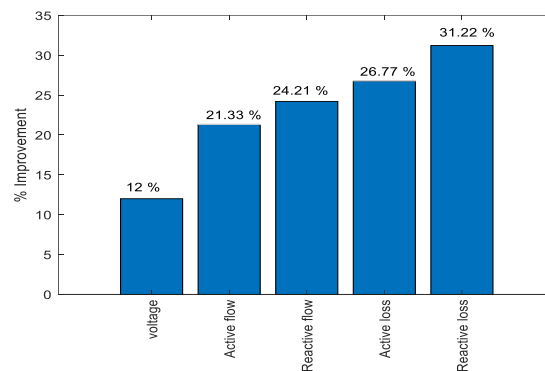


Fig. 12. Impact of DG.

From Fig. 12, it was observed that the introduction of the DG impacted positively to all the static power system parameters with the most impact on the reactive power loss with percentage improvement of 31.22%.

4.3. Simulation Results of Dynamic Improvement

The parameters utilized to study the DG impact on the dynamics of the power system were current and voltage signals. The current signal of bus 1 for with and without DG was shown in Fig. 13.

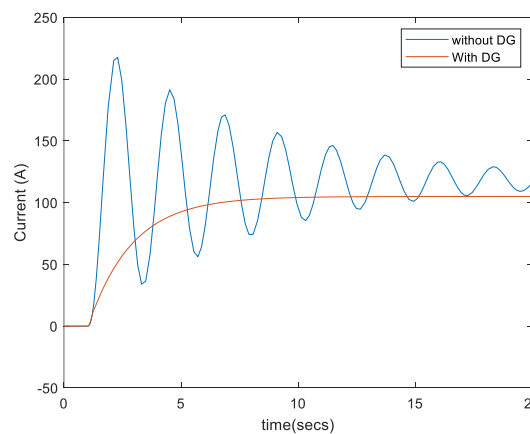


Fig. 13. Current Signal for Bus 1.

The dynamic current signal of bus 1 for without and with the DG was shown in Fig.13. Though the signal tends to stabilize without the DG implementation but it would have required longer period than the monitored 20 seconds. However, the system stabilized faster with the introduction of the solar DG. The current signal of bus 2 for with and without DG was shown in Fig.14.

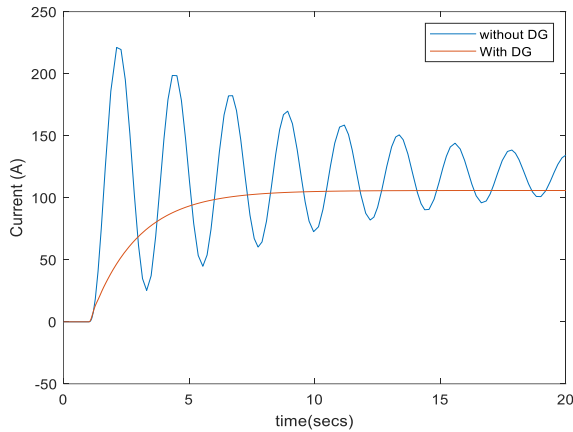


Fig. 14. Current signal for Bus 2.

The current signal for bus 2 for with and without DG was shown in Fig. 14. It was seen that there was a high level of instability at the onset as against the outcome with the DG that was stabilized at 5 seconds. The current signal of bus 3 for with and without DG was shown in Fig. 15

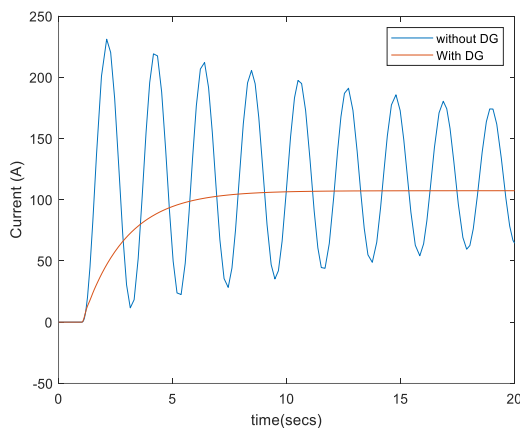


Fig. 15. Current signal for Bus 3.

Fig.15 showed the current signal outcome monitored for 20 seconds for with and without DG. The current signal of the power system showed that the signal was unstable without DG and increased in stability with the introduction of the DG. The current signal of bus 4 for with and without DG was shown in Fig. 16.

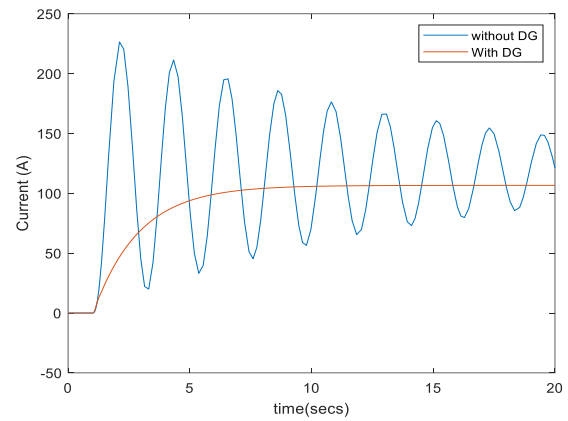


Fig. 16. Current Signal for Bus 4.

Fig. 16 showed the current signal outcome monitored for 20 seconds for with and without DG at bus 4. The current signal of the power system showed that the signal was unstable without DG. However, with the introduction of DG, the system was able to stabilize after 8 seconds. The current signal of bus 5 for with and without DG was shown in fig. 17.

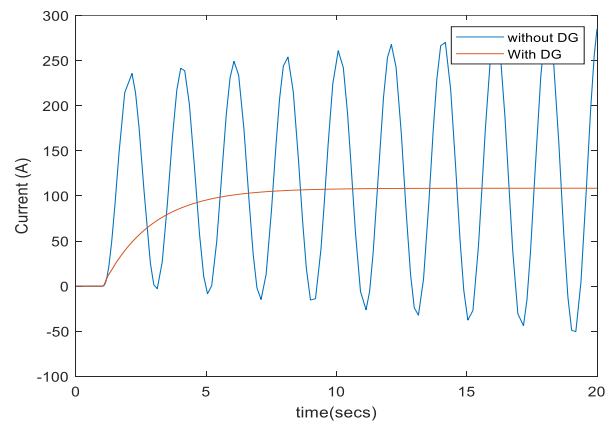


Fig. 17. Current Signal for Bus 5.

From the analysis of Fig. 17, it can be seen that there was an oscillation in amplitude of the current without the DG placement on the network. However, with the introduction of DG it was able to stabilize it faster to zero equilibrium point and the oscillation was negligible when compared to the existing scheme without DG. It implies that the controllability of linear displacement state. This shows that with the introduction of DG, this provides an improved dynamic stability for the power system during operation.

The voltage signal of bus 1 for with and without DG was shown in Fig. 18.

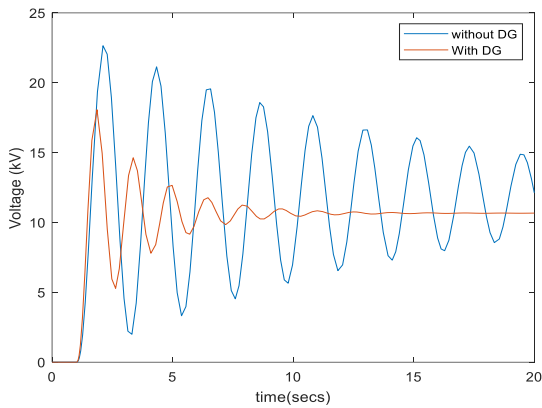


Fig. 18. Voltage Signal for Bus 1.

Fig. 18. show the voltage signal at bus 1 without and with the DG. It was observed from Fig. 18 that, the voltage signal didn't stabilize without the DG implementation but it would have required longer period than the monitored 20 seconds. However, the system stabilized faster with the introduction of the solar DG.

The voltage signal of bus 2 with and without DG was shown in Fig. 19.

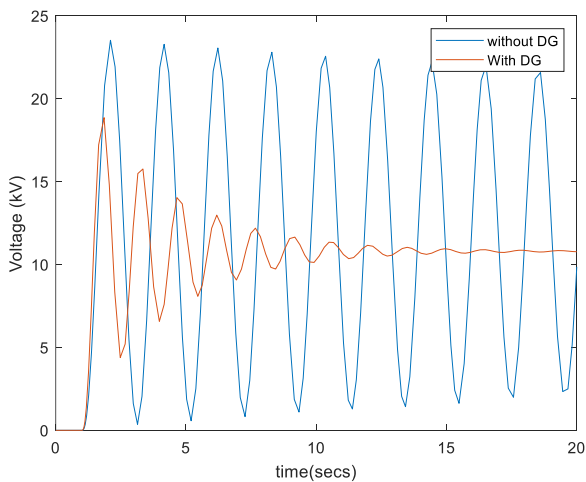


Fig. 19. Voltage Signal for Bus 2.

In Fig. 19, it was observed from the voltage signal at bus 2 without DG placement, there was a uniform oscillation of voltage signal even after 20 second without stabilizing to zero equilibrium point. However, with the introduction of DG, the amplitude of the voltage signal settles faster to the equilibrium position showing improvement in term of stability over without DG. The voltage signal of bus 3 for with and without DG was shown in Fig. 20

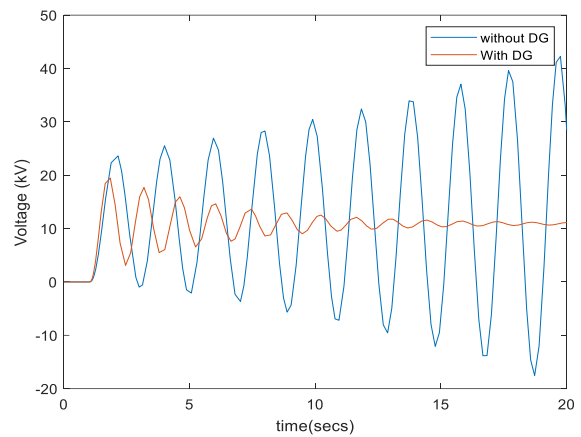


Fig. 20. Voltage Signal for Bus 3.

Fig. 20 shows the voltage signal for bus 3 with and without DG introduction. From the Figure above, it was observed that the voltage signal without DG introduction, there was a rise in amplitude of the voltage oscillation due to transient nature.

Using DG-based introduction, there was a decrease in amplitude of oscillation, which occurred due to transient nature of the system but it took a shorter time to stabilized and converged to the equilibrium. Similarly, the voltage signal of bus 4 for with and without DG was shown in Fig. 21.

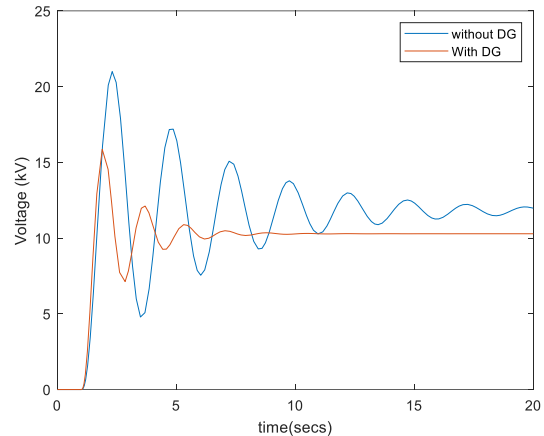


Fig. 21. Voltage Signal for Bus 4.

Fig. 21 shows the voltage signal at bus 4 with and without DG, it can be seen that there was a decrease rise in amplitude of oscillation of the voltage signal when an input signal was applied to the system without the placement of DG. However, when using the DG, the voltage signal was reduced faster to zero equilibrium point within 8 seconds when compared to the existing scheme without DG. It implies that the controllability of voltage signal. This shows that the DG introduction provides an improved dynamic stability.

Also, the voltage signal of bus 5 for with and without DG was shown in Fig. 22.

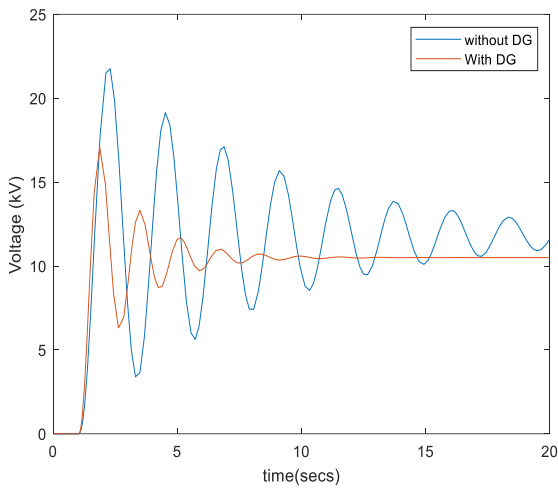


Fig. 22. Voltage Signal for Bus 5

Fig. 22 shows the voltage signals at bus 5 with and without DG placement. From the Figure above, it was observed that the voltage signal without DG introduction there is a rise in amplitude due to transient nature of the system as result of high level of instability at the onset, as against the outcome with DG. Using DG-based introduction, there is a minimum rise in amplitude, which occurred due to transient nature of the system but it took 11 seconds to stabilized and converged to the equilibrium.

4.4. Performance Comparison of the DG Impact with and without Solar Captive on NDA 33/11kv Network.

The performance of the impact of DG on NDA 33/11Kv was assessed on the basis of voltage improvement, active power flow, reactive power flow, active power loss and reactive power loss using

Equation (4). The performance of the DG impact with and without Solar Captive on NDA 33/11kv Network with respect to the performance metrics were presented in Table 9.

Table 9. Performance comparison between the impact of DG and without DG Impact

| Performance Specification | DG | | Percentage Improvement (%) |
|---------------------------|-----------|------------|----------------------------|
| | Impact DG | Without DG | |
| Voltage Improvement | 0.9860 | 0.9100 | 12 |
| Active Power flow | 6.1354 | 4.1021 | 21.33 |
| Reactive Power flow | 9.6042 | 6.8886 | 24.21 |
| Active Power loss | 0.0193 | 0.5032 | 26.77 |
| Reactive Power loss | 0.4462 | 1.0183 | 31.22 |

Table 9 summarizes the performance comparison of the impact of DG and that without DG. However, it can be revealed from the Table 9 that, the impact of DG on the 33/11Kv network has the overall improvement of 31.22% in reactive power loss when compared to that without DG placement.

5. Conclusion

The paper presents an impact of 2.5MW developed solar photovoltaic generation of the Nigerian Defence Academy on 33/11kV Feeder Network in order to improve the voltage profile and minimize power loss, a scientific solution is highly required. Thus, this work introduces distributed generation Solar Photovoltaic Generation (SPVG) at the feeder to achieve this purpose. The feeder lines under consideration are Airport, Rigasa, Kinkinau and NDA 33/ 11kV feeder lines. The data used in this work were collected from the public utility service provider known as Transmission Company of Nigeria (TCN) Kaduna Region, during visitation to the station and the

2.5MW NDA solar captive power plant located at the permanent site of NDA Afaka. Subsequently, modeling of the Power system network in PSAT using MATLAB/Simulink. The Simulation of the developed system was carried out by considering static and dynamic response improvement. The performance evaluation of the results was carried out and compared to the system with and without DG placement in terms of voltage profile improvement, power loss minimization and dynamic improvement (voltage and current signal). The simulation results reveal that the impact of the developed 2.5MW NDA solar captive power plant on NDA 33/11kV feeder network has the overall improvement of voltage profile improvement when considering the buses the DG placement on the network. For power loss minimization and dynamic improvement, the implementation of the DG has an improvement without the placement on the network. This study provides useful insights into the impact of PV integration on distribution network performance; numerous limitations should be addressed. The analysis is mostly focused on simulation using a static load flow model and does

not include dynamic system behavior under transient disturbances. Furthermore, seasonal load swings and variations in solar irradiation were not specifically predicted. By adding time-varying solar generation models, energy storage devices, and the best distributed generation deployment strategies, future study could expand on this work. Additionally, the conclusions' practical usefulness will be enhanced by confirmation using actual operating data from Nigerian distribution utilities.

Author Contributions

N.A carried out the full research work, including problem formulation, system modeling, simulation, data analysis, and manuscript preparation. A.I , K.O, provided academic supervision, technical guidance, and critical review of the work. D.D contributed as a research colleague through discussions, assistance with simulations, and review of the results.

Acknowledgements

Not applicable.

Conflict of Interest:

The authors declare no conflict of interest

References

- [1] T. S. Ustun, J. Hashimoto, and K. Otani, "Impact of smart inverters on feeder hosting capacity of distribution networks," *IEEE Access*, vol. 7, pp. 2–7, 2019, DOI: 10.1109/ACCESS.2019.2952569.
- [2] H. Suyono, M. Shidiq, A. N. Ferdianzah, T. Utomo, I. Musirin, and L. J. Awalin, "Dynamic stability impact of the hybrid wind and microhydro renewable energy sources on the distribution system," in 2018 Electrical Power, Electronics, Communications, Controls and Informatics Seminar (EECCIS), pp. 15–20, 2018, DOI: 10.1109/EECCIS.2018.8692793.
- [3] J. H. C. Yong, J. Wong, Y. S. Lim, and J. H. Tang, "Assessment on various allocations of energy storage systems on radial distribution network for maximum PV systems penetration," in 2018 International Conference on Smart Grid and Clean Energy Technologies (ICSGCE), pp. 89–94, 2018, DOI: 10.1109/ICSGCE.2018.8556803.
- [4] F. O. Akpojedje, A. Mohammed, E. Pereye, and A. Ibhagbemien, "Renewable energy integration: The influence of solar systems in Nigeria's power supply schemes and dependability," *International Journal of Advanced Multidisciplinary Research and Studies*, vol. 5, no. 5, pp. 194–202, Sep. 2025, DOI: 10.62225/2583049x.2025.5.5.4879.
- [5] B. Adebajji, A. Ojo, T. Fasina, S. Adeleye, and J. Abere, "Integration of renewable energy with smart grid application into the Nigeria's power network: Issues, challenges and opportunities," *European Journal of Engineering and Technology Research*, vol. 7, no. 3, pp. 18–24, May 2022, DOI: 10.24018/ejeng.2022.7.3.2792.
- [6] D. O. Obada, M. Muhammad, S. B. Tajiri, M. O. Kekung, S. A. Abolade, S. B. Akinpelu, and A. Akande, "A review of renewable energy resources in Nigeria for climate change mitigation," *Case Studies in Chemical and Environmental Engineering*, vol. 9, p. 100669, Jun. 2024, DOI: 10.1016/J.CSCEE.2024.100669.
- [7] N. Memane, J. Munda, Y. Hamam, and M. Siti, "A review of techniques for the use and management of distributed generation," *Energy Reports*, vol. 15, no. 1, p. 108957, Jun. 2026, DOI: 10.1016/j.egyr.2025.108957.
- [8] A. B. Abdullahi, L. Olatomiwa, J. Tsado, and A. A. Sadiq, "Impact assessment of wheeling renewable distributed generation to residential load," in *International Conference on Electrical, Computer, and Energy Technologies (ICECET)*, pp. 9–10, 2021, DOI: 10.1109/ICECET52533.2021.9698780.
- [9] M. S. Turiman, M. K. N. M. Sarmin, N. Saadun, M. F. Zamri, H. Ali, and Q. Mohammad, "Determination of optimal distributed generation penetration level in distribution networks based on normalized impact factor score," in 2023 IEEE 3rd International Conference in Power Engineering Applications (ICPEA), pp. 274–278, 2023, DOI: 10.1109/ICPEA56918.2023.10093149.
- [10] I. Dumancic, C. Tranchita, and J. Kluge, "Dynamic simulation of distribution power systems with distributed renewable generation," in 2021 IEEE PES/IAS PowerAfrica, 2021, DOI: 10.1109/PowerAfrica52236.2021.9543396.
- [11] R. Sastre, R. Demes, and J. Garcia, "Power voltage transformers for renewable energy substations auxiliary services supply," in 2019 IEEE PES GTD Grand International Conference and Exposition Asia (GTD Asia), pp. 643–648, 2019, DOI: 10.1109/GTDAsia.2019.8715926.
- [12] G. A. Gomez-Ramirez, I. A. Luevano-Reyes, G. Mora-Jimenez, L. Garcia-Santander, M. Z. Laskano, and C. Meza, "Increasing distribution network capacity through storage in Central American countries: A case study," in 2022 IEEE International Conference on Automation / 25th Congress of the Chilean Association of Automatic Control (ICA-ACCA), 2022, DOI: 10.1109/ICA-ACCA56767.2022.10006043.
- [13] C. Jamroen, S. Sirisukprasert, and N. Hatti, "A study on SoC management of energy storage system for voltage regulation application in distribution network," in 11th International Renewable Energy Congress (IREC), 2020, DOI: 10.1109/IREC48820.2020.9310445.
- [14] D. Wang, Y. Yan, and Y. Shen, "The influence of overhead collector feeder on the stability of grid-connected renewable energy multi-converter," in 2019

- 3rd IEEE Conference on Energy Internet and Energy System Integration (EI2), pp. 1402–1407, 2019, DOI: 10.1109/EI247390.2019.9062254.
- [15] D. C. Idoniboyeobu, T. K. Bala, and K. I. Blue-Jack, “Performance evaluation of the 132KV sub-transmission lines in the Nigeria power network: A case study of Port Harcourt sub-region, Rivers State,” *International Journal of Research in Engineering and Science*, vol. 5, no. 12, pp. 28–40, 2017.
- [16] A. K. Sharma, “Voltage enhancement in distribution system using voltage improvement factor,” *IOSR Journal of Electrical and Electronics Engineering*, vol. 7, no. 1, pp. 46–48, 2013, DOI: 10.9790/1676-0714648.
- [17] A. Jafar-Nowdeh, M. Babanezhad, S. Arabi-Nowdeh, A. Naderipour, H. Kamyab, Z. Abdul-Malek, and V. K. Ramachandaramurthy, “Meta-heuristic matrix moth-flame algorithm for optimal reconfiguration of distribution networks and placement of solar and wind renewable sources considering reliability,” *Environmental Technology and Innovation*, vol. 20, 2020, DOI: 10.1016/j.eti.2020.101118.
- [18] C. J. Hatziaadoniu and A. T. Funk, “Development of a control scheme for a series-connected solid-state synchronous voltage source,” *IEEE Transactions on Power Delivery*, vol. 11, no. 2, pp. 1138–1143, 2016, DOI: 10.1109/61.489378.
- [19] A. Qazi, H. Fayaz, N. A. Rahim, G. Hardaker, D. Alghazzawi, K. Shaban, and K. Haruna, “Towards sustainable energy: A systematic review of renewable energy sources, technologies, and public opinions,” *IEEE Access*, vol. 7, pp. 63837–63851, 2019, DOI: 10.1109/ACCESS.2019.2906402.
- [20] A. S. Hassan, Y. Sun, and Z. Wang, “Water, energy and food algorithm with optimal allocation and sizing of renewable distributed generation for power loss minimization in distribution systems,” *Energies*, vol. 15, no. 6, p. 2242, 2022, DOI: 10.3390/en15062242.
- [21] A. A. Saleh, A. A. A. Mohamed, A. M. Hemeida, and A. A. Ibrahim, “Multi-objective whale optimization algorithm for optimal allocation of distributed generation and capacitor bank,” in *Proc. 2019 International Conference on Innovative Trends in Computer Engineering (ITCE)*, pp. 459–465, 2019, DOI: 10.1109/ITCE.2019.8646352.
- [22] D. K. Mishra, M. J. Ghadi, A. Azizivahed, L. Li, and J. Zhang, “A review on resilience studies in active distribution systems,” *Renewable and Sustainable Energy Reviews*, vol. 135, 2021, DOI: 10.1016/j.rser.2020.110201.
- [23] S. K. Kotha, B. Rajpathak, B. Ramesh, and M. K. Khedkar, “Optimal placement of micro-PMUs for real-time monitoring of inter-connected smart distribution networks,” in *2nd Asian Conference on Innovation in Technology (ASIANCON)*, pp. 1–5, 2022.
- [24] H. Sadiq, S. A. H. Raza, U. Hameed, A. K. Janjua, and K. Imran, “Impact analysis of PV penetration on radial distribution feeder of National University of Science and Technology (NUST),” in *4th International Conference on Power Generation Systems and Renewable Energy Technologies (PGSRET)*, pp. 1–5, 2019, DOI: 10.1109/PGSRET.2018.8686012.
- [25] Q. Bai, “Analysis of particle swarm optimization algorithm,” *Computer and Information Science*, vol. 3, no. 1, pp. 180–184, 2010, DOI: 10.5539/cis.v3n1p180.
- [26] Y. Kifle, B. Khan, and P. Singh, “Assessment and enhancement of distribution system reliability by renewable energy sources and energy storage,” *Journal of Green Engineering*, vol. 8, no. 3, pp. 219–262, 2018, DOI: 10.13052/jge1904-4720.832.
- [27] E. Rodriguez-Diaz, F. Chen, J. C. Vasquez, J. M. Guerrero, R. Burgos, and D. Boroyevich, “Voltage-level selection of future two-level LVdc distribution grids: A compromise between grid compatibility, safety, and efficiency,” *IEEE Electrification Magazine*, vol. 4, no. 2, pp. 20–28, 2016, DOI: 10.1109/MELE.2016.2543979.
- [28] M. Z. Malik, M. Kumar, A. M. Soomro, M. H. Baloch, M. Farhan, M. Gul, and G. S. Kaloi, “Strategic planning of renewable distributed generation in radial distribution system using advanced MOPSO method,” *Energy Reports*, vol. 6, pp. 2872–2886, 2020, DOI: 10.1016/j.egyr.2020.10.002.
- [29] M. Khasanov, S. Kamel, E. H. Houssein, C. Rahmann, and F. A. Hashim, “Optimal allocation strategy of photovoltaic- and wind turbine-based distributed generation units in radial distribution networks considering uncertainty,” *Neural Computing and Applications*, vol. 35, no. 3, pp. 2883–2908, 2023, DOI: 10.1007/s00521-022-07715-2.
- [30] D. K. Oliveira, G. S. Djamboladjian, L. N. Silva, R. G. Ferraz, F. F. Vidor, and D. S. Gazzana, “Assessment on technical impacts regarding the massive penetration of nanogrids in electric power distribution systems,” in *2022 IEEE International Conference on Environment and Electrical Engineering and 2022 IEEE Industrial and Commercial Power Systems Europe (EEEIC/I&CPS Europe)*, 2022, DOI: 10.1109/EEEIC/ICPSEurope54979.2022.9854691.
- [31] G. Li, L. Zhang, T. Joseph, J. Liang, and G. Yan, “Comparisons of MVAC and MVDC systems in dynamic operation, fault protection and post-fault restoration,” in *IECON 2019 Proceedings (Industrial Electronics Conference)*, pp. 5657–5662, 2019, DOI: 10.1109/IECON.2019.8927251.
- [32] A. Selim, J. Zhao, F. Ding, F. Miao, and S. Y. Park, “Adaptive deep reinforcement learning algorithm for distribution system cyber attack defense with high penetration of DERs,” *IEEE Transactions on Smart Grid*, vol. 15, no. 4, pp. 4077–4089, 2024, DOI: 10.1109/TSG.2023.3345314.

- [33] F. Zeng, "A sufficient condition producing 16-QAM Golay complementary sequences," *IEEE Communications Letters*, vol. 18, no. 11, pp. 1875–1878, 2014, DOI: 10.1109/LCOMM.2014.2360695.
- [34] Y. Jiang, "Development and application of a novel distribution model reduction approach for utility feeders," in *Proceedings of the IEEE Power Engineering Society Transmission and Distribution Conference*, 2018, DOI: 10.1109/TDC.2018.8440303.
- [35] A. D. P. F. Ferreira, L. D. O. Rego, G. N. Taranto, T. M. L. Assis, and D. M. Falcao, "Technical losses assessment in medium voltage feeders in the presence of distributed generation," in *Proc. 2018 IEEE PES Transmission and Distribution Conference and Exhibition - Latin America (T&D-LA)*, pp. 1–5, 2018, DOI: 10.1109/TDC-LA.2018.8511736.
- [36] T. O. Olowu, S. Dharmasena, H. Jafari, and A. Sarwat, "Investigation of false data injection attacks on smart inverter settings," in *2020 IEEE CyberPELS*, 2020, DOI: 10.1109/CyberPELS49534.2020.9311541.
- [37] M. Barukcic, T. Varga, V. J. Stil, and T. Bencic, "Multiobjective optimal allocation of distributed generation considering load and renewable source power profiles," in *IEEE 3rd International Conference and Workshop in Obuda on Electrical and Power Engineering (CANDO-EPE)*, pp. 113–118, 2020, DOI: 10.1109/CANDO-EPE51100.2020.9337762.
- [38] H. Sadeghian and Z. Wang, "Photovoltaic generation in distribution networks: Optimal vs. random installation," *arXiv:1712.04419*, 2017.
- [39] R. Hunt, B. Flynn, and T. Smith, "The substation of the future: Moving toward a digital solution," *IEEE Power and Energy Magazine*, vol. 17, no. 4, pp. 47–55, 2019, DOI: 10.1109/MPE.2019.2908122.
- [40] S. Deb, A. K. Goswami, P. Harsh, J. P. Sahoo, R. L. Chetri, R. Roy, and A. S. Shekhawat, "Charging coordination of plug-in electric vehicle for congestion management in distribution system integrated with renewable energy sources," *IEEE Transactions on Industry Applications*, vol. 56, no. 5, pp. 5452–5462, 2020, DOI: 10.1109/TIA.2020.3010897.
- [41] S. Arora, S. Kaur, and R. Khanna, "A review on voltage challenges and remedial methods with excessive PV penetration in radial distribution feeder," in *IEEE International Conference on Signal Processing, Computing and Control*, pp. 47–52, 2019, DOI: 10.1109/ISPCC48220.2019.8988454.
- [42] G. C. Kryonidis, K.-N. D. Malamaki, S. I. Gkavanoudis, K. O. Oureilidis, E. O. Kontis, J. M. Mauricio, J. M. Maza-Ortega, and C. S. Demoulias, "Distributed reactive power control scheme for the voltage regulation of unbalanced LV grids," *IEEE Transactions on Sustainable Energy*, vol. 12, no. 2, pp. 1301–1310, 2021, DOI: 10.1109/TSTE.2020.3042855.
- [43] A. Parchure, S. J. Tyler, M. A. Peskin, K. Rahimi, R. P. Broadwater, and M. Dilek, "Investigating PV generation induced voltage volatility for customers sharing a distribution service transformer," *IEEE Transactions on Industry Applications*, vol. 53, no. 1, pp. 71–79, 2017, DOI: 10.1109/TIA.2016.2610949.
- [44] P. Paudyal, F. Ding, S. Ghosh, M. Baggu, M. Symko-Davies, C. Bilby, and B. Hannegan, "The impact of behind-the-meter heterogeneous distributed energy resources on distribution grids," in *Conference Record of the IEEE Photovoltaic Specialists Conference*, pp. 857–862, 2020, DOI: 10.1109/PVSC45281.2020.9300626.
- [45] M. Abdelmalak, M. Gautam, S. Morash, A. F. Snyder, E. Hotchkiss, and M. Benidris, "Network reconfiguration for enhanced operational resilience using reinforcement learning," in *SEST 2022 - 5th International Conference on Smart Energy Systems and Technologies*, pp. 2–7, 2022, DOI: 10.1109/SEST53650.2022.9898469.