

SUSTAINABILITY ASSESSMENT OF A STANDALONE SOLAR MICROGRID FOR OPTIMAL OPERATION

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ABSTRACT

The nonlinear characteristics of output current and power in a photovoltaic source present challenges in establishing operating curves under various conditions. Existing models inadequately assess performance across all model parameters and series-parallel combinations. This study evaluates the performance of the solar power source at Kwara State University, Malete, Nigeria for optimal operation. Using the Simscape library in MATLAB Simulink, the microgrid's basic components—photovoltaic source, inverter, and load—were modelled to examine operational characteristics under different conditions. Simulation results revealed the effects of solar irradiation and temperature on the photovoltaic source. The study also assessed the impact of maximum power point tracking control as the chosen control mechanism. Findings showed that the power source's performance falls short of simulated generation levels, suggesting areas for system improvement. The model not only serves as a performance analysis tool and microgrid capacity evaluation method but also lays the groundwork for overall system enhancement.

Keywords: Inverter; Microgrid; Phase lock loop; Photovoltaic; Solar Panel.

INTRODUCTION

Electricity plays a pivotal role in Nigeria's socio-economic development across various sectors. Crucially, it is indispensable for industrial growth, powering machinery and fostering economic diversification and job creation. Educational institutions depend on electricity for classrooms, lighting, and technology, enhancing the quality of education and technological literacy. In healthcare, reliable power is vital for medical equipment and overall functionality. Electricity improves domestic living conditions, supports modern agriculture practices, drives infrastructure development, and fuels the growth of the Information and Communication Technology (ICT) sector. Access to electricity significantly enhances the overall quality of life, particularly in rural areas, by providing modern amenities and bridging development gaps (Adoghe *et al.*, 2023; Dioha & Kumar, 2020).

Despite its critical importance, Nigeria faces challenges such as inadequate power generation and distribution inefficiencies, necessitating solutions to fully realize the

potential benefits of electricity for national development. According to the ongoing daily operational report from the Nigeria Electricity Supply Industry, the current electricity supplies are only reaching approximately 56% of their generation capacity (TCN-NCC, 2024). Furthermore, the national grid collapses frequently, primarily attributed to the overwhelming demand for the limited power available and challenges in operating within the expected frequency range (Adoghe *et al.*, 2023; Bamisile *et al.*, 2020).

A microgrid is a compact power grid designed to function autonomously or in coordination with larger power grids. It represents a localized and small-scale power station equipped with its own generation and storage resources, operating within well-defined boundaries. The microgrid emerges as a superior alternative to the national grid, distinguished by unique characteristics like purity and inexhaustibility (Fouad *et al.*, 2017). Despite these advantages, there is a scarcity of methodologies essential for

enhancing their effectiveness (Hu *et al.*, 2023; Karimi-Davijani & Ojo, 2011; Salihu *et al.*, 2020; Yang *et al.*, 2016).

Among the diverse sources of renewable energy in microgrids, photovoltaic (PV) solar energy has emerged as a primary resource. It is defined by its ability to harness unlimited, pure solar energy, contributing to the creation of an environmentally friendly and sustainable energy landscape (Hirsch *et al.*, 2018; Pandiarajan & Muthu, 2011). Solar power can be utilized within a solar microgrid to provide energy to specific loads while also having the capability to connect to the main grid.

Nigeria's geographical location, coupled with its solar energy potential ranging from 3.5 to 7.0 kWh/m², presents a highly advantageous environment for PV microgrids (Madugu *et al.*, 2019a). These microgrids play a pivotal role in addressing the power shortages prevalent in the country (Osinowo *et al.*, 2015). Therefore, the solar microgrid stands as a significant alternative power supply for the country, representing a promising way of addressing its energy needs (Salihu *et al.*, 2020).

Microgrids encounter various technical challenges, including issues like feeder disconnection from the utility system, complexities during the startup of the microgrid's Island mode, achieving a balance between generation and load in Island mode operation, and the design of a suitable feeder for the microgrid (Madugu *et al.*, 2020). Additionally, these challenges necessitate unique control requirements and techniques to maintain load equilibrium while maximizing economic benefits for the utility (Madugu *et al.*, 2019b; Muhammad & Darma, 2014).

Researchers propose strategies to address microgrid challenges, such as using a controlled approach to gradually introduce loads in Island mode for stability and advanced inverters with grid-forming capabilities for seamless transitions. They

also recommend balancing generation and load, incorporating energy storage to buffer fluctuations, and using demand response programs to adjust load dynamically (Bullich-Massagué *et al.*, 2019; Fu *et al.*, 2014; Han *et al.*, 2017; Xu *et al.*, 2018).

However, it is noteworthy that the various approaches developed by different researchers have not comprehensively resolved the multitude of challenges encountered by microgrids (Karimi-Davijani & Ojo, 2011; Lidula & Rajapakse, 2011; Zamora & Srivastava, 2010).

This work aims to develop a model for a solar PV microgrid of Kwara State University (KWASU) Malete. Malete and Ilorin environment belongs to a region that receives an average peak irradiance between 812 W/m² and 958 W/m² (Tutiempo, 2024), making it highly conducive for harnessing power from sunlight to cater to the school community. Efficient utilization and optimal performance of the system could position the generation of solar power within the school as a viable alternative to the inconsistent grid supply.

METHODOLOGY

In essence, a PV microgrid consists of key components outlined in Fig. 1. These components include the photovoltaic panels constituting the PV source, the DC/AC inverter, filters, bus, and the load. The inverter control section is positioned between the PV source and the inverter. Each of these components plays a crucial role in the functioning of the microgrid.

Model of a Photovoltaic (PV) Source

The transformation of solar irradiance into an electrical signal is facilitated by the PV cell. The PV panel, or module, is composed of one or more of these PV cells, and the PV source comprises one or several PV panels. The analysis of the electrical characteristics of PV cells reveals that the generated current is influenced by factors such as solar irradiance, temperature, environmental conditions, and

the maximum power point (Baimel *et al.*, 2019; Bellia *et al.*, 2014; Madugu *et al.*, 2020; Madugu *et al.*, 2019a).

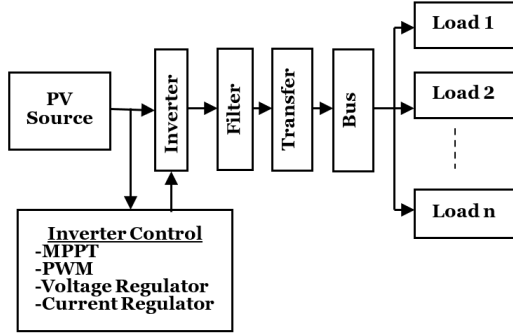


Fig. 1: Block Diagram of Photovoltaic Microgrid

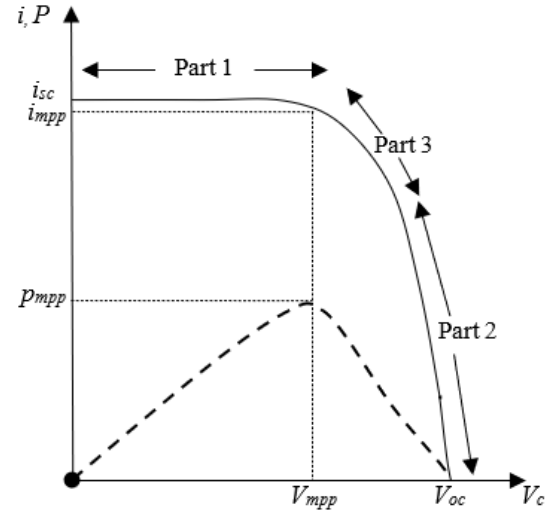
The output current i and power p are nonlinear. Hence the curve in Fig. 2a is divided into three parts namely part 1, part 2, and part 3. In part 1, the PV cell behaves like a current source, in part 2 it behaves like a voltage source while there are intermediate operating points in part 3, which can be determined by maximum power point (MPP). Where i_{sc} represents the short circuit current ($V_c = 0$), V_{oc} represents the open-circuit voltage ($i_c = 0$) and p_{mpp} is the maximum power.

The PV cell can be modelled as a photocurrent (I_{ph}) source which is in direct relation to the irradiance level (g) and is linearly dependent on the temperature (θ). The non-linear characteristics enclosed in the PV are modelled by a diode, which is parallel to the current source.

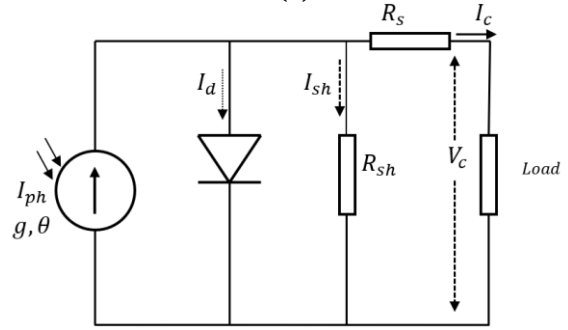
Applying Kirchhoff's current law to the equivalent circuit of Fig. 2b results in equation 1, the PV cell output current equation.

$$I_c = I_{ph} - I_d - I_{sh} \quad (1)$$

where I_c is the output current of the PV cell; I_d is the current flowing through the diode and I_{sh} represents the current flowing through the shunt resistor (R_{sh}).



(a)



(b)

Fig.2: (a) Current – Voltage Characteristics of a PV cell. (b) Equivalent Circuit of a PV Cell

The PV cell output varies at a different level of irradiance and temperature, therefore the current through the photocurrent I_{ph} is given as equation 2 (Bevrani *et al.*, 2017).

$$I_{ph} = I_{sc} \left(\frac{g}{g^*} \right) (1 + K_I (\theta - \theta^*)) \quad (2)$$

where I_{sc} is the short circuit current; g^* is the solar irradiance at reference Standard Test Condition (STC) (1000 W/m^2); K_I is the temperature coefficient of current while θ^* is the STC cell temperature reference ($\theta^* = 298.15\text{K}$).

Current I_d is given by the Shockley diode equation 3

$$I_d = I_o \left(e^{\frac{V_c + I_c R_s}{nV_T}} - 1 \right) \quad (3)$$

where saturation current I_o is expressed as

$$I_0 = \frac{I_{sc} \left(\frac{\theta}{\theta^*} \right)^{\frac{3}{n}} e^{\left(\frac{-qE_G}{nk} \left(\frac{1}{\theta} - \frac{1}{\theta^*} \right) \right)}}{\left(e^{\left(\frac{qV_{oc}}{nk\theta^*} \right)} - 1 \right)} \quad (4)$$

where E_G is the Bandgap energy; n is ideally factor of a diode (1 or 2); k is the Boltzmann constant and q is the charge of an electron.

The equation of the current I_{sh} through the resistor R_{sh} is given by equation 5.

$$I_{sh} = \frac{V_c + I_c R_s}{R_{sh}} \quad (5)$$

Therefore, the overall equation for current I_c is given as;

$$I_c = I_{ph} - I_0 \left(\exp \left(\frac{V_c + I_c R_s}{nV_T} \right) - 1 \right) - \left(\frac{V_c + I_c R_s}{R_{sh}} \right) \quad (6)$$

$$V_T = \frac{k\theta}{q} \text{ (Thermal voltage)}$$

For a PV source consisting of modules, the PV source current is described by equation (7).

$$i_{pv} = i_{ph} - i_0 \left(e^{\left(\frac{v_{pv} + i_{pv} N_s N_{pv} R_s}{n N_s N_{pv} V_T} \right)} - 1 \right) - \frac{v_{pv} + i_{pv} N_s N_{pv} R_s}{n N_s N_{pv}} \quad (7)$$

where; i_{pv} is PV source output current, N_s is the cells in series in one panel, N_{pv} is the PV panel in series in one source and V_{pv} is the voltage across the PV source.

i_{pv} results in a nonlinear equation of four variables ($g, \theta, i_{pv}, v_{pv}$) and three unknown constants (n, R_s, R_p).

The equations described above were implemented in MATLAB Simulink. The CSUN 305-72M PV module in MATLAB Simulink exhibits characteristics similar to the PV panels at the KWASU solar farm, with the parameters detailed in Table 1. Consequently, the PV array of the Microgrid was constructed through a series-parallel configuration of these modules.

Fig. 3 illustrates the Simulink model of the solar farm. The model primarily incorporates

two input parameters: a variable irradiance level and a relatively constant temperature. The terminal (I_r) is linked to an input that signifies fluctuations in solar radiation. Meanwhile, the terminal (T) is connected to an input that represents changes in cell temperature, measured in degrees.

Table 1: Specifications of the Solar Panel (CSUN 305-72M PV)

Parameter	Value
Maximum Power	305.283 W
Open Circuit Voltage (V_{oc})	45 V
Voltage at Maximum Power Point (V_{mpp})	36.3 V
Short-Circuit Current (I_{sc})	8.87A
Current at Maximum Power Point (I_{mp})	8.41A
Diode Saturation Current (I_0)	$1.1087e^{-9}A$
Diode Ideality Factor	1.0667
Shunt Resistance (R_{sh})	973.9768 Ω
Series Resistance (R_s)	0.35727 Ω
Temperature Coefficient of I_{sc} (%/Deg.)	0.05

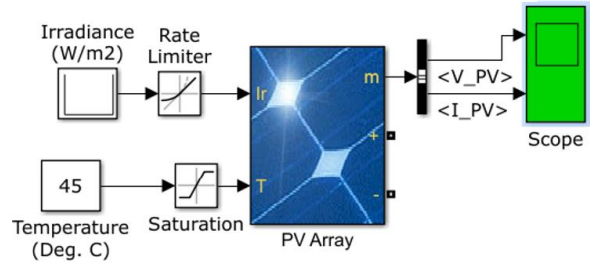


Fig. 3: KWASU Solar Farm Array

The inverter was configured as a three-phase DC-AC converter employing Insulated Gate Bipolar Junction Transistors (IGBTs). Utilizing six IGBT transistors, the three-phase inverter transforms DC voltage into AC voltage with a phase difference of 120° degrees. In the Simulink model, the pulse generator supplies pulses to the thyristor. Typically, the arms of the inverters are delayed by an angle of 120° degrees, resulting in the generation of a three-phase AC supply. Each switch in the inverter operates with a duty cycle

of 50%, and the switching occurs at intervals of $T/6$, where T is the period.

The interface between the PV system and the utility grid is established through the use of a boost converter and a voltage source inverter. The boost converter plays a role in maintaining balance within the system, while the voltage source inverter is responsible for converting DC power into AC power, which is the form of power consumed by the load.

Four main inverter control strategies were applied: Maximum Power Point Tracking (MPPT), Phase Lock Loop, Voltage Regulator, and Current Regulator. MPPT is an algorithm employed for extracting the maximum available power from a PV array. It dynamically adjusts the power interface to deliver optimal power across various temperature and irradiation conditions. There are several types of MPPT control, including Perturb and Observe (P&O), Incremental Conductance method, and Fractional the design and performance of the microgrid model.

The system is configured in an island mode, allowing it to independently supply the local grid. In this mode, any variance between the demand and the power generated by the microgrid is supplemented by the national grid. This arrangement ensures a reliable and continuous power supply to meet the local demand, with the national grid acting as a backup source when needed (Madugu *et al.*, 2019b; Osinowo *et al.*, 2015).

The PV system consists of 305.23W polycrystalline solar module of type China Sunenergy (CSUN 305-72P) with 800 modules connected in series-parallel arrangement to generate an average power of 245 kW. To analyse the performance of the PV system with connection to the local grid on the school campus on the MATLAB software, a model of the KWASU microgrid was rated in the Simulink with a connection of 70 strings in parallel and 15 strings in series giving an average power of 240 kW.

The primary voltage of the transformer is 415V and the output to the grid system is 11kV since the local grid consists of an 11kV and 33kV distribution feeders. The local grid system that has been modelled consists of the substation transformer with 5MVA, 33/11KV and 87.48/

Open-circuit voltage. In this work, the Perturb and Observe MPPT control strategy was implemented (Bellia *et al.*, 2014).

The Phase Lock Loop (PLL) functions as a feedback control system, comprising three main components: the Phase Detector, Loop Filter, and Voltage-Controlled Oscillator. It is employed for frequency and phase detection, working in conjunction with conventional microgrid active power (or frequency) and reactive power (voltage) variations. The PLL helps maintain synchronization and stability within the microgrid system.

Fig. 4 depicts the integrated representation of the KWASU Microgrid. The Simulink model was adapted to match the specifications of the KWASU solar farm and its associated loading. As previously noted, Ilorin region receives an average radiation that peaks around 812 W/m² and 958 W/m² (Tutiempo, 2024), influencing

262.43 A; admin transformer of 500kVA, 11/0.415 kV and 26.25/695.6 A; staff quarters transformer of 300 kVA, 11/0.415 kV and 15.75/417.4A.

Also included are the AA block transformer of 500 kVA, 11/0.415 kV, 26.25/695.6A; Works transformer of 500 kVA, 11/0.415 kV, 26.25/695.6A; General hostel transformer of 300kVA, a voltage of 11/0.415 kV, and a current of 15.75/417.4A.

RESULTS AND DISCUSSION

Simulation results from the microgrid model are presented across various sections and operating conditions. These include results from the reference PV array, outcomes from the MPPT control, voltage characteristics of the microgrid, current characteristics of the microgrid, and an overall assessment of the system's performance.

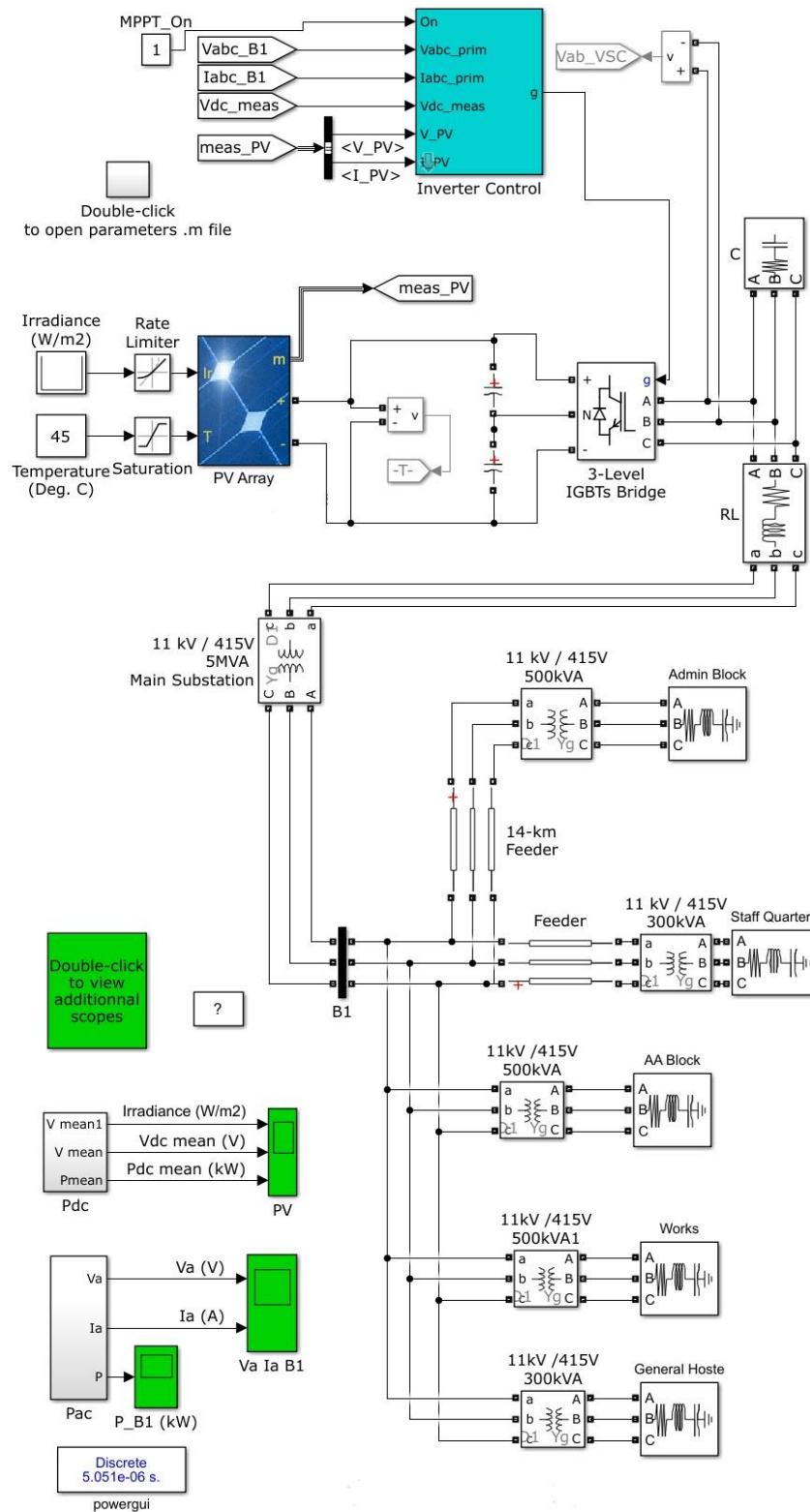


Fig. 4: Simulink Model of Kwasu Solar Microgrid

The simulated results of the reference PV array are analysed considering the following: I-V and P-V characteristics under varying irradiation levels with constant temperature, with the irradiation level ranging from 1000 to 500 to 100, respectively; I-V and P-V characteristics under varying temperature and constant irradiance, with the temperature ranging from 75°C to 45°C to 25°C respectively.

Fig. 5a and Fig. 5b show the current-voltage and power-voltage characteristics of the PV array respectively, under a varying irradiation level and a constant temperature. It can be deduced that as the irradiation level increases, there is an increase in the power output, voltage, and current output of the PV array.

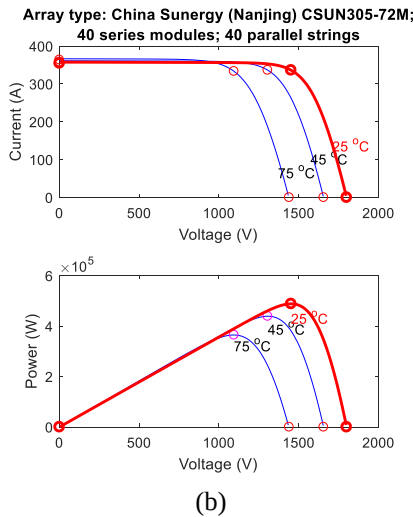
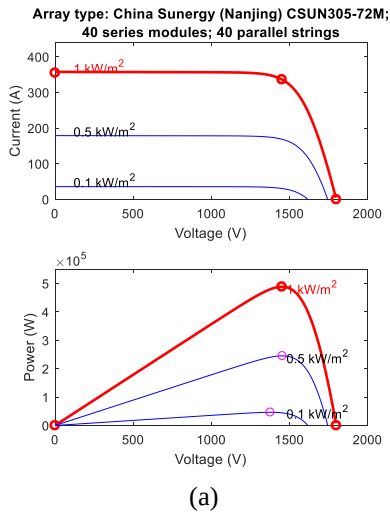


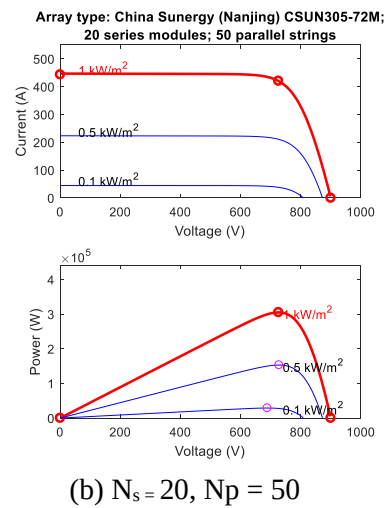
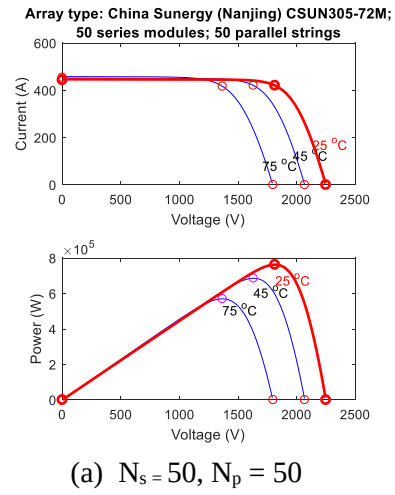
Fig. 5: (a) I-V and P-V characteristics under varying irradiation levels with constant temperature (b) I-V and P-V characteristics of the reference PV source under varying temperature and constant irradiation level.

In Fig. 6, the current-voltage and power-voltage characteristics of the PV source are depicted

under varying numbers of connected series and parallel modules. The simulated results reveal that increasing the series connection of the PV modules in the reference PV source leads to higher voltage output and lower current output.

Conversely, a higher parallel connection of PV modules results in lower voltage output and higher current output from the PV source. This observation emphasizes the impact of series and parallel configurations on the voltage and current characteristics of the PV source.

Fig. 7 depicts the outcomes of the three-phase inverter utilizing different inverter control techniques (MPPT, PWM, Voltage regulator, Current regulator) based on the Simulink models presented in Fig. 4. The results indicate an output voltage of 489.89V from the inverter.



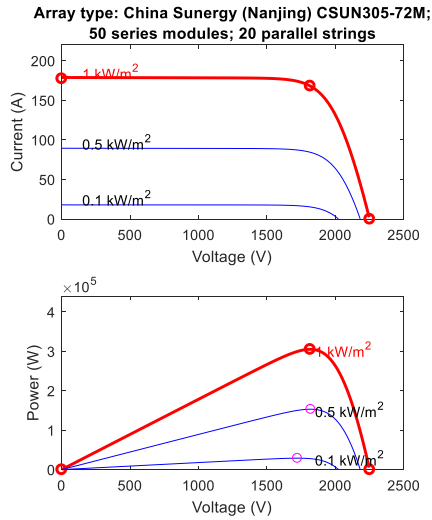
(c) $N_s = 50$, $N_p = 20$

Fig. 6: I-V and P-V characteristics of the reference PV source under a varying number of connected series modules and connected parallel modules.

Fig. 8 presents the result obtained from the PV array showing the irradiance level, power, and voltage output. The figure also depicts a variation of the irradiance at $t(0-1.5s)$, with the average voltage of the Microgrid gradually rising to 200V and gradually maintaining averagely a value of about 450V from time ($t=0.2-1.5s$) and at the time ($t: 0 - 0.35s$) the average power from the microgrid to be 269kW at a solar irradiance of $1kW/m^2$, and gradually dropping to as low as 50kW as the irradiance level decreases and gradually rising to 269kW as the irradiance level increases.

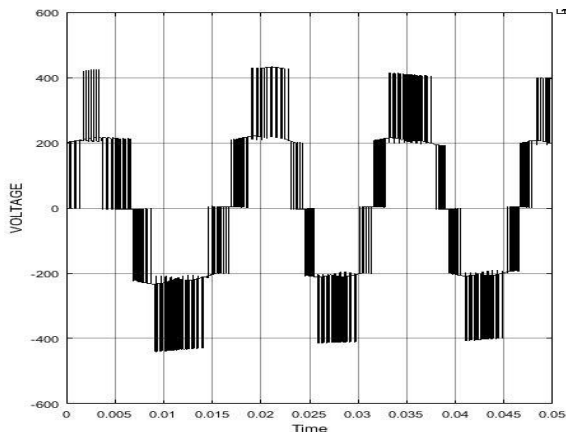


Fig. 7: Output Voltage from the Inverter

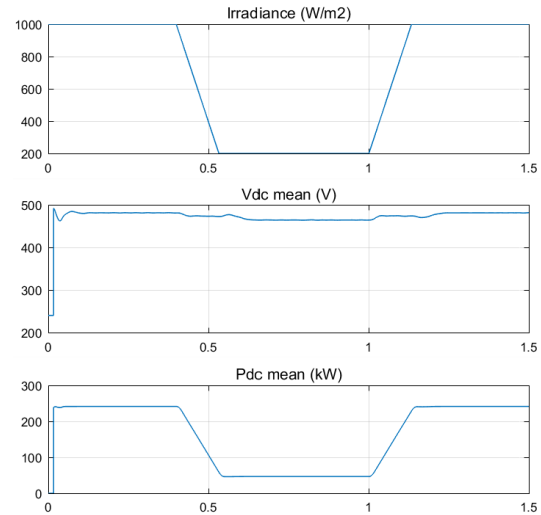


Fig. 8: Irradiance level, Output Voltage and Power of the Photovoltaic Microgrid

The current and voltage profiles of the microgrid are shown in Fig. 9. The average AC voltage supplied to the grid is approximately 3500V, while the average current is around 41.6A, resulting in an average power output of 146 kW.

The graph in Fig. 10 presents the overall assessment of the microgrid while supplying the loads. It is seen that at first the power been fed from the microgrid to the load was as high as 246kW but within a short period gradually drops towards zero, and with observations from the simulations, it was observed that the voltage output from the inverter decreased rapidly with time.

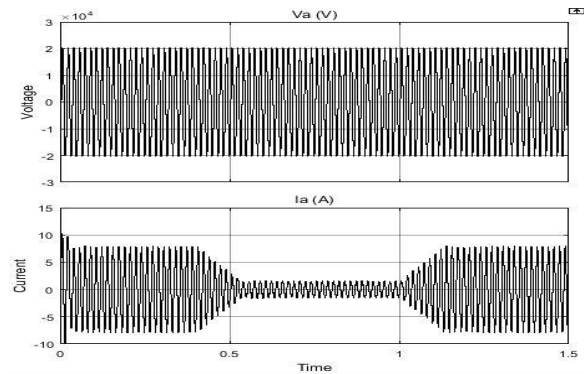


Fig. 9: Voltage and Current Characteristics of the Microgrid

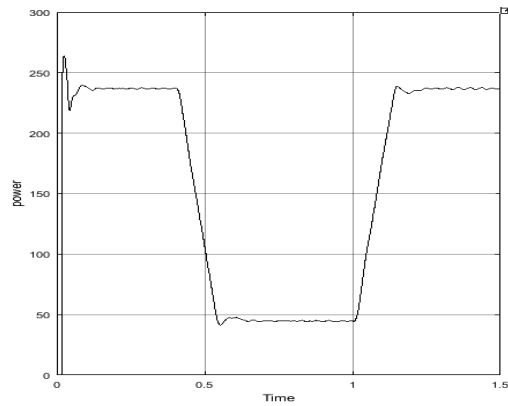


Fig. 10: Performance Assessment of the Microgrid

The microgrid benefits from an average solar irradiance of approximately 812 W/m^2 , making it highly conducive for efficient power generation from sunlight within the University. When optimally utilized, the generation of solar power in the school can serve as a significant alternative source.

However, the findings of this study reveal that the power and voltage output recorded at the substation are considerably low compared to the potential capacity of the system. The arrangement of the microgrid's arrays yields an average power of 240 kW, which is less than 45% of the power supplied by the local grid. This indicates a gap between the microgrid's performance and its potential capacity, highlighting the need for further optimization and improvement in the system.

From Fig. 10, as depicted in the graphs, it is evident that the power output from the microgrid rapidly decreases towards zero. This decline is attributed to the throttling of the inverter, and various factors such as the number of solar PV modules, the condition of the transformer, transformer settings, and prevailing weather conditions can contribute to this behaviour.

To address this issue, it is crucial to establish appropriate settings for the local transformer that align with the power generated by the PV array. This adjustment will help prevent the throttling of the inverter, ensuring a more consistent and substantial amount of AC power is supplied to the grid. It underscores the importance of fine-tuning system parameters to optimize the performance of the microgrid.

The findings indicate a requirement for better arrangement and more PV modules. The quantity

of PV modules notably impacts array power generation. To effectively increase solar power generation near the school, enhancing PV array capacity through proper arrangement and scaling up module numbers seems crucial. This adjustment could enhance overall microgrid system performance and output.

CONCLUSION

The PV microgrid has become a significant and essential presence in Nigeria, addressing the evident challenges in power supply primarily derived from fossil fuels. KWASU is actively contributing to technological advancement in the country by hosting a PV microgrid on its campus, which plays a crucial role in supplying power to the school.

This study used MATLAB software to model and assess the microgrid, aiming to identify improvements. The analysis reveals that the microgrid's current capacity is less than its potential power generation when optimized. The study underscores the need to restructure PV microgrid components and adjust transformer settings for better efficiency. These findings offer valuable guidance for optimizing the microgrid's performance, contributing to a more sustainable and reliable power supply for KWASU.

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