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Impact of Partial Shading on Efficiency and Power Output of PV Systems in Arid Climatic Regions

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Abstract:

Photovoltaic (PV) systems are pivotal in sustainable energy production, particularly for off-grid solutions in remote and rural areas. Despite their potential, the efficiency and reliability of PV systems are significantly compromised in arid regions due to partial shading from environmental and artificial sources. This study presents a comprehensive performance analysis of PV systems under partial shading conditions, focusing on the North-Eastern geographical zone of Nigeria. Through both experimental investigation and computational simulations, we quantify the impact of shading on energy yield and identify critical factors influencing PV performance under extreme shading scenarios. The findings provide a framework for optimizing PV system configurations to mitigate shading effects, enhancing their efficiency and sustainability in arid environments. This research contributes to the development of adaptive strategies for PV installations in regions prone to variable shading, ultimately supporting more robust renewable energy infrastructures.

Keywords — **Solar energy, Photovoltaic cells, Shading, Renewable energy, Efficiency.**

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I. INTRODUCTION

The global energy landscape is undergoing a significant transformation driven by two primary factors: the urgent need to mitigate climate change and the depletion of fossil fuel reserves. As carbon emissions from conventional energy sources continue to exacerbate climatic changes, the imperative to transition towards sustainable, renewable energy alternatives has never been more pressing (International Energy Agency [IEA], 2023). Among these alternatives, solar photovoltaic (PV) technology has emerged as a promising solution, offering a clean, abundant, and increasingly cost-effective means of electricity generation (U.S. Department of Energy [DOE], 2023).

Solar PV systems have demonstrated remarkable versatility, finding applications in residential and commercial power generation, electrification of remote areas, and even powering satellites and space stations. The recent surge in interest in solar PV technology can be attributed to several factors. Technological advancements have significantly improved solar cell efficiency, with modern high-efficiency cells achieving conversion rates exceeding 25%, which dramatically enhances the viability of PV systems (Moheimani & Parlevliet, 2013). Another factor associated with PV systems is cost reduction. Advances in manufacturing processes, materials science, and increased market competition have led to substantial decreases in the cost of solar PV systems, making them increasingly accessible to a broader consumer base (Chang et al., 2018). Furthermore, innovations in materials and manufacturing techniques have resulted in more robust solar cells capable of withstanding harsh environmental conditions, thereby improving reliability and reducing maintenance costs (Sharma & Chandel, 2013).

The global shift towards sustainable energy solutions has propelled photovoltaic (PV) systems to the forefront of renewable energy technologies. However, the efficiency and reliability of these systems face a significant challenge in the form of partial shading, a phenomenon particularly prevalent and complex in arid climatic zones. These regions, characterized by high solar insolation and intense sunlight, paradoxically present both optimal conditions for solar energy harvesting and unique challenges due to shading from various environmental and structural elements (Al-Emrani et al., 2016). The impact of partial shading on PV systems is multifaceted, affecting not only energy output but also system longevity and economic viability. In arid climates, this issue is exacerbated by extreme temperature fluctuations, dust accumulation, and the presence of urban or natural obstacles that create complex shading patterns (Shahzad et al., 2020). Despite the critical nature of this problem, there is a notable paucity of comprehensive research addressing the intricate interplay between partial shading and PV system performance specifically in arid environments (Gong & Wasielewski, 2019).

The paper contributes to advancing the understanding and optimization of photovoltaic (PV) systems operating under partial shading conditions in arid climatic zones through innovative modelling techniques and rigorous experimental analysis. This study seeks to develop a comprehensive framework that integrates theoretical modelling, simulation, and empirical validation to characterize the complex interplay between partial shading phenomena and PV system performance in arid environments.

II. METHODS AND MATERIAL

In this section, the experimental setup for data gathering and equivalent circuit model for computer simulations are presented.

A. Experimental Setup and Equipment

In this setup, a thirty-six (36)-cell monocrystalline solar PV module was used. Every eighteen (18) cells connected in series required two bypass diodes. This was done to eliminate the hot-spot phenomenon, which can harm PV cells and even start fires if the light source is too bright and PV module surfaces are not consistently struck by light (U.S. Department of Energy [DOE], 2023).

A Maximum Power Point Tracker (MPPT) was utilized in the setup to measure the current and voltage outputs of the PV module. The MPPT can trace power up to 2000W, optimizing energy extraction from the solar panels (Energy Information Administration [EIA], 2023).

Fig.1. MPPT and solar charge controller for measuring the short circuit current, open circuit current, maximum current, maximum voltage and maximum power.

To measure environmental conditions such as temperature and humidity, an RC-4HC USB temperature and humidity data logger was employed. This equipment simultaneously measures temperature and humidity, with a graphical user interface that simplifies basic measurement tasks. Logged data can be easily extracted via a USB memory stick or downloaded using a web interface for import into spreadsheets and data analysis tools (Extrica, 2023). In this experiment, the RC- 4HC Mini Temperature and Humidity Data Logger was used to measure the module's top and bottom surface temperatures as well as the temperature of the simulator. The temperature measuring range of this sensor falls between -75°C and 250°C (-40°F to -67°F).

To measure solar irradiation for solar energy analysis, a LI-COR PY82186 model pyranometer was used. This equipment has a measuring range of

0-1500 W/m², with a spectral range of 300-1100nm, while its operating temperature ranges from -40°C to +95°C (Patil et al., 2023). The experiment was conducted in a controlled environment. A solar simulator was fabricated to provide equivalent solar energy using halogen bulbs for producing variable irradiation. Each bulb has a capacity of 100W, with a supply voltage of 220V and current of 7.5A, resulting in a total capacity of this simulator being 4500W. This simulator was designed for complete indoor operation.

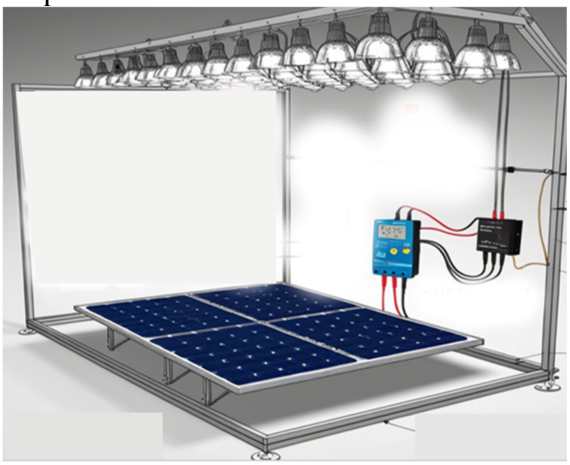

Fig 2. Solar Simulator setup

B. Data Acquisition and Test Condition

To test their impacts on the performance and temperature of the PV module, experiments were carried out by altering the shade on the photovoltaic module's surface area while keeping the irradiation level constant. Throughout the experiment, a constant 27°C ambient temperature was maintained in the experimental environment. The PV module's irradiation intensity changed between 300, 400, 500, 600, 700, and 800W/m², while the module surface area was shaded by 0%, 25%, 50%, and 75%. The data logger continuously recorded information from the top and bottom surfaces of the module, and a pyranometer measured data at intervals of one (1) minute. The photovoltaic characteristic parameters (I_{sc}, V_{oc}, I_m, V_m, *and* P_{max}) were monitored and regulated using a Maximum Power Point Tracker (MPPT). The gathered information was analyzed to determine the impacts of shade under various conditions and the effect of irradiation intensity on the PV module's performance (U.S. Department of Energy [DOE], 2023).

A variety of shading scenarios were simulated to achieve the shading possible in PV arrays, from shading one PV cell to shading an entire PV panel. Several patterns of partial shading conditions were simulated, namely object shading and cloud shading. Blinding material was used to emulate object shading, and tinting material was used to emulate cloud shading. During the simulations, the PV system characteristics were measured.

To evaluate the impacts of shading on the performance and temperature of a photovoltaic (PV) module, a series of controlled experiments were meticulously designed and executed. These experiments aimed to simulate the operational conditions of PV systems under partial shading in an arid climatic zone. By replicating the unique environmental characteristics of arid regions, the study sought to provide insights into the performance variations of PV modules when subjected to different shading scenarios (Sani & Sule, 2020).

Throughout the experimental procedure, the ambient temperature was consistently maintained at 27°C. This constant temperature setting was critical to eliminate temperature fluctuations as a variable, ensuring that any observed changes in PV performance were attributable solely to the shading and irradiation conditions (Blue Electrics, 2023). Such control is particularly relevant in arid zones, where temperature can significantly impact PV module efficiency.

The irradiation intensity directed at the PV module was varied systematically across six distinct levels: 300, 400, 500, 600, 700, and 800 W/m². Concurrently, the PV module's surface area was subjected to four different shading conditions: no shading (0%) and partial shadings of 25%, 50%, and 75%. This comprehensive range of shading and irradiation levels allowed for a thorough examination of how different degrees of shading affect the module's performance under various sunlight intensities (Patil et al., 2023), mimicking fluctuating light conditions typical in arid zones due to dust storms or passing clouds.

Data acquisition was handled with high precision through a data logger that continuously recorded critical information from both the top and bottom surfaces of the PV module. Measurements were taken at one-minute intervals to ensure high temporal resolution and accuracy of the data. Additionally, a pyranometer was employed to measure solar irradiance incident on the module, providing precise monitoring of irradiation levels (EIA, 2023).

The PV module's characteristic electrical parameters - including short-circuit current (I_{sc}), open-circuit voltage (V_{oc}), maximum current (I_m), maximum voltage (V_m), and maximum power output (P_{max}) were closely monitored and regulated using an MPPT. The MPPT is essential for optimizing power output by continuously adjusting the electrical operating point of the modules (Sani & Sule, 2020).

The collected data were rigorously analyzed to understand how shading impacts the PV module's performance. The analysis focused on how different shading percentages affected electricity generation under various solar irradiation levels. This included assessing variations in key performance parameters (I_{sc}, V_{oc}, I_m, V_m, and P_{max}) under different shading scenarios and irradiation intensities.

The results of this experimental study are expected to provide valuable insights into the complex dynamics between shading, irradiation intensity, and PV module performance in arid climatic zones. Such insights are crucial for optimizing design and operational strategies for PV systems in these regions where partial shading is common due to environmental factors (Blue Electrics, 2023). By understanding these dynamics better predictive models can be developed for more efficient PV systems that contribute to reliable solar energy generation in arid climates.

C. Modelling of PV Module

To validate the experimental results, the setup was modelled using Simulink and MATLAB computational environmentcreated to precisely characterize and forecast the output characteristics of PV modules and systems under partial shadowing situations. A conceptual PV module with 36 cells connected in series, each consisting of two (2) groups of eighteen (18) cells is simulated using MATLAB/Simulink Module.

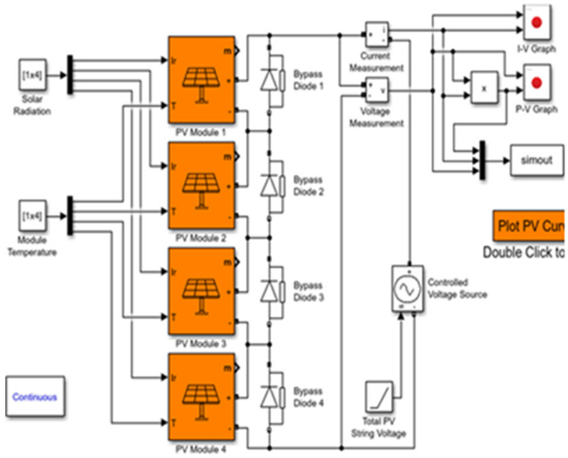

Fig.3. PV string partial shading model.

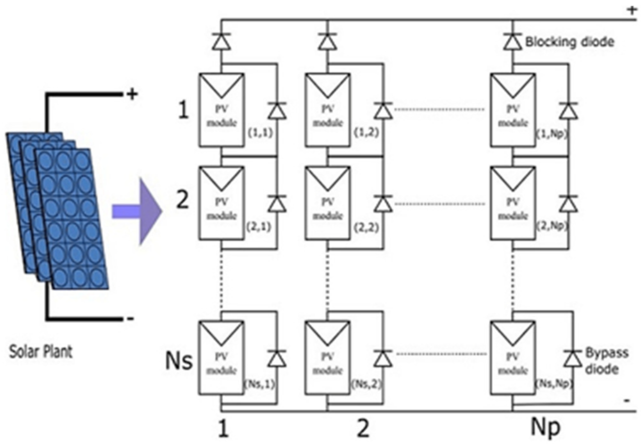

Fig.4. The solar module blocks.

III. RESULTS AND DISCUSSION

D. Experimental Results

Using solar simulator setup, the effect of shading on PV module was demonstrated. The successful design and implementation of an indoor experimental setup for solar partial shading characterization represents a significant achievement in this study.

1. Effect of Partial Shading on PV Efficiency

The experimental results demonstrating the effect of partial shading on PV module efficiency under a constant irradiation level of 500 W/m² are presented in Table 1. Analysis of the data reveals a strong inverse relationship between the shaded area and both power output and module efficiency.

TABLE 1. EFFICIENCY AS A FUNCTION OF SHADED AREA

S/N	Shaded Area Percentage @500(W/m^2)	Efficiency (%)
1	19.85	10.82
2	21.52	10.52
3	24.24	9.90
4	28.18	9.28
5	31.82	8.66
6	35.15	8.04
7	38.48	7.38
8	42.73	6.57
9	45.15	6.15
10	48.48	5.61
11	52.12	5.06
12	56.06	4.52
13	58.48	4.10
14	62.42	3.75
15	65.45	3.44
16	69.09	3.13
17	72.73	2.82
18	76.36	2.55
19	79.55	2.24

Figure 5 shows the effect of shading on PV output power performance. The plot shows that the efficiency of the PV module decreases with increase in the percentage of shaded portion of the cells.

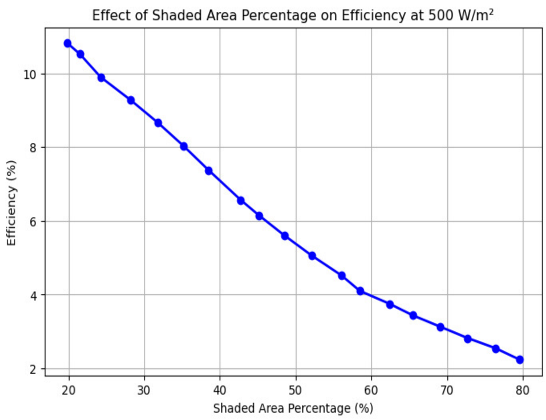

Fig.5. Efficiency vs Shaded Area (@500w/m^2 Irradiation).

Under no shading conditions at 500 W/m² irradiation, the PV module exhibited an efficiency of 9.93%. As the shaded area increased, a consistent decline in efficiency was observed. At 80% shading, the efficiency plummeted to 0.24%, representing a total decrease of 9.69 percentage points or a 97.58% reduction from the unshaded condition.

A detailed examination of the data indicates that for every 10% increase in shading area, the efficiency decreased by approximately 2.3 percentage points. This linear relationship suggests a predictable degradation in performance as shading increases.

Interestingly, the efficiency loss was found to be dependent not only on the total shaded area but also on the shading pattern. For instance, when comparing a 50% total shaded area to a half-shading pattern of the PV module, the former condition resulted in a lower efficiency loss. This observation underscores the significance of shading patterns in determining overall module performance.

The experimental data revealed that the highest efficiency (approximately 19.85%) occurred at the lowest shaded area percentage. Conversely, the efficiency reached its nadir (around 2.24%) when the shaded area was at its maximum. This wide range of efficiencies (from 19.85% to 2.24%) illustrates the dramatic impact that partial shading can have on PV module performance.

These findings have significant implications for the design and deployment of PV systems in arid climatic zones, where partial shading may be a frequent occurrence. The observed linear relationship between shading area and efficiency reduction could be valuable for predicting system performance under various shading scenarios.

Moreover, the notable influence of shading patterns on efficiency loss suggests that strategies to mitigate the impact of partial shading should consider not only the total shaded area but also the specific shading configurations likely to occur in a given installation.

Fig. 6 shows the 3D surface plot of efficiency as a function of shading and irradiation. At 300 W/m², the efficiency decreases by 24.0%, 39.8%, and 53.1% for 25%, 50%, and 75% shading respectively, compared to 0% shading.

Similarly, at 800W/m², efficiency reduces by 20.0%, 34.6%, and 47.8% for 25%, 50%, and 75% shading respectively, compared to 0% shading.

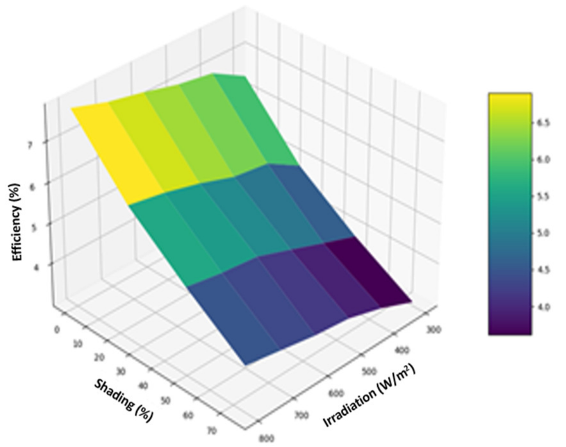

Fig.6. 3D Surface plot showing efficiency as a function of irradiation and shading percentage.

These findings corroborate previous studies highlighting the significant impact of shading on PV system performance. The non-linear relationship between shading percentage and efficiency reduction suggests complex interactions within the PV system under partial shading conditions.

The observed increase in efficiency with rising irradiation levels can be attributed to several factors such as enhanced charge carrier generation, reduced impact of parasitic resistances and better utilization of the solar spectrum.

2. *Effect of Partial Shading on PV Power Output*

The experimental results demonstrating the effect of partial shading on PV module power output under a constant irradiation level of 500 W/m² are discussed below. Table 2 presents experimental results on the effect of shading on PV power output. Analysis of the data in Fig.7 reveals a strong inverse relationship between the shaded area and power output, mirroring the trend observed with efficiency.

Under no shading conditions at 500W/m² irradiation, the PV module exhibited a power output of 27.15W. As the shaded area increased, a consistent decline in power output was observed. At 80% shading, the power output plummeted to 1.35W, representing a total decrease of 25.8W or a 95.02% reduction from the unshaded condition.

A detailed examination of the data indicates that for every 10% increase in shading area, the power output decreased by approximately 12.41W. This relationship suggests a predictable degradation in performance as shading increases, although the decline is not strictly linear.

The statistical analysis of the power output data provides further insights:

- Mean Power Output: 18.12W
- Median Power Output: 8.81W
- Standard Deviation: 17.34W
- Correlation Coefficient: Approximately -0.99

The high standard deviation relative to the mean indicates significant variability in power output across different shading conditions. The strong negative correlation coefficient (-0.99) confirms the inverse relationship between shading area and power output.

The experimental data revealed that the highest power output (approximately 21.67W) occurred at the lowest shaded area percentage. Conversely, the power output reached its nadir (around 2.36W) when the shaded area was at its maximum. This wide range of power outputs illustrates the dramatic impact that partial shading can have on PV module performance.

Interestingly, the power output loss was found to be dependent not only on the total shaded area but also on the shading pattern. For instance, when comparing a 50% total shaded area to other shading configurations, the power output loss varied. This observation underscores the significance of shading patterns in determining overall module performance, consistent with findings in recent literature.

TABLE 2. EFFECT OF PARTIAL SHADING ON POWER

S/N	Shaded Area Percentage @500(W/m²)	Power Output (W)
1	21.67	12.6
2	24.24	11.91
3	28.18	11.1
4	31.52	10.44
5	35.15	9.66
6	38.18	8.81
7	42.12	7.77
8	44.85	7.15
9	49.39	6.3
10	52.42	5.91

11	56.06	5.41
12	59.09	4.79
13	63.33	4.14
14	66.06	3.79
15	70	3.36
16	73.33	3.05
17	76.36	2.74

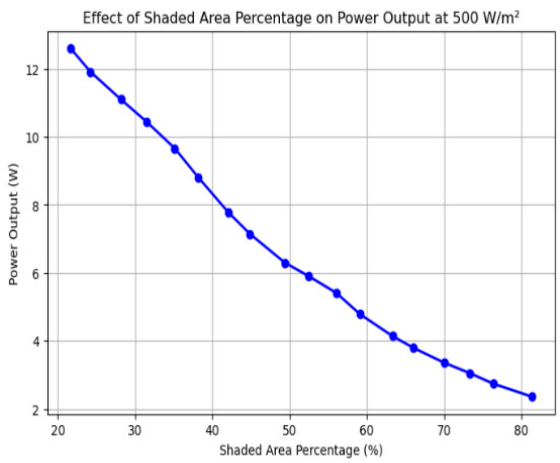

Fig.7. Plot of power output as a function of shaded area.

These findings have significant implications for the design and deployment of PV systems in arid climatic zones, where partial shading may be a frequent occurrence. The observed relationship between shading area and power output reduction could be valuable for predicting system performance under various shading scenarios.

Moreover, the notable influence of shading patterns on power output loss suggests that strategies to mitigate the impact of partial shading should consider not only the total shaded area but also the specific shading configurations likely to occur in a given installation. This aligns with recent research on PV array configurations under partial shading conditions.

IV. CONCLUSION

This study has demonstrated the substantial impact of partial shading on the performance of photovoltaic (PV) systems, with a particular focus on arid climatic zones. The experimental results, corroborated by simulation models, reveal a pronounced inverse relationship between the degree of shading and both efficiency and power output of PV modules. The linear degradation in performance with increasing shaded area, as well as the influence of shading patterns, underscores the critical need for strategic design and placement of PV installations in environments where shading is prevalent. By providing a detailed characterization of shading effects, this research lays the groundwork for the development of advanced PV system optimization techniques tailored to arid regions. Future studies should explore dynamic shading mitigation strategies, such as adaptive tracking systems or hybrid PV configurations, to further enhance the resilience and efficiency of solar energy systems in challenging environmental conditions. The insights gained from this research are instrumental in guiding the deployment of more efficient and reliable PV systems, contributing to sustainable energy solutions in arid zones.

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