Mitigating mismatch power losses in photovoltaic systems under partial shading: a comparative study of series-parallel and alternative configurations

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ABSTRACT

Utilizing the photovoltaic effect, photovoltaic (PV) systems are a popular technique for capturing solar energy and turning sunlight into electricity. However, environmental factors, especially shade, significantly impact photovoltaic system efficiency. Shadows cast on PV panels by surrounding structures, trees, accumulated dirt, clouds, and debris can seriously impair their performance. The purpose of this study was to investigate how shade affects photovoltaic systems utilized in residential settings. Series-parallel (SP) topology for PV system have been investigated. Additionally, in this work, a PV system of 5 kW of the residence home has been proposed and multi cases of shading examined. Through the results obtained when partial shading was applied, it was found that the highest efficiency of the system was when partial shading irradiance (Ir = 500 W/m^2) was applied to one column (5 modules) as 82.84%, while the worst and least equipped case was when the shading was applied to the corners and random shading at (8 modules), where the efficiency decreased to approximately 39.24% and 40.64% respectively.

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1. INTRODUCTION

When compared to other renewable energy sources, photovoltaic (PV) sources are widely used worldwide [1]–[5]. PV cells are used in solar photovoltaic systems to convert solar radiation into energy, hence fostering the global growth of the PV sector [6]. The total installed PV capacity worldwide at the end of 2018 was 480 GW, and projections indicate that capacity will reach 2,840 GW by 2030 [7]. The amount of solar radiation that a PV module's cells receive affects the module's performance [8], [9]. Passing clouds and tall objects surrounding the PV area can cause shade, which is one of the trigger causes for PV performance decline [10]. In homes with shaded areas, solar energy systems can be quite successful thanks to a variety of tactics and technological advancements.

To achieve the required voltage and current level, a series/parallel combination of PV modules forms a solar photovoltaic array [3], [11]–[14]. The generated output power has a direct and inverse relationship with these two parameters (irradiation and temperature, respectively). As a result, "temperature" and "irradiation" variables are important when it comes to PV systems' ability to generate electricity. Partial shading conditions (PSC) or non-homogenous irradiation refers to varying irradiation levels within a PV structure [15]–[18]. The performance of solar photovoltaic systems is greatly reduced by shading, which also lowers system stability and energy production. In areas with shadow, awareness, monitoring, and system adjustments are essential for effectiveness. Photovoltaic systems, photovoltaic modules, reconfiguration, PV orientation, and the impact of soiling and partial shading on solar energy output are the main topics of the study. It discusses the negative effects that partial shade and dust accumulation have on the performance of PV modules, highlighting the necessity of creative ways to optimize energy [5], [19]–[22]. If operated in accordance with ecological governance principles, solar home systems can successfully end energy poverty and contribute to environmental preservation; however, a reform of governance is required for long-term sustainability [23]. Because photovoltaic systems rely on direct sunshine to create electricity, they are particularly vulnerable to shade compared to other energy producing systems. Significant power losses and inefficiencies in the system can result from even a single module in a PV array being partially shaded. It is essential to comprehend how shading affects PV system performance in order to maximize energy yield, optimize design, and guarantee the financial sustainability of solar energy projects. This introduction examines the ways in which shade impacts the efficiency of photovoltaic systems and provides tips for reducing these effects to improve system performance as a whole.

The current study examines how solar PV array output power varies with irradiation level (at a constant temperature). A solar PV array's output power under uniform illumination conditions has a peak point that corresponds to its maximum power. A non-homogeneous irradiation scenario results in a lower peak power generation. Mismatch loss (ML) is the term used to describe the variation in generated output power under uniform and non-homogeneous irradiation levels [24]. Non-homogeneous irradiation reduces PV facilities' output power generation and efficiency.

2. SIGNIFICANT OF THIS STUDY

Photovoltaic systems' efficiency can be severely harmed by shading. The power output of a photovoltaic array can be significantly decreased by partially shading even one solar panel. This is due to the fact that cells that are shaded generate less current, and in a series connection, the lowest generating cell sets the current limit. These cells lose power instead of producing it when they are shaded, which could cause overheating and damage. Because the shaded and unshaded cells in a PV array operate at different locations on their current-voltage (I-V) characteristics, shading results in mismatch losses. The PV array's (I-V) curve is impacted by shading, which makes it more challenging for the maximum power point tracking (MPPT) algorithm to determine the actual maximum power point. As a result, energy conversion is less effective. When one panel is shaded in a series configuration, the current flowing through the entire string is impacted. Shading in a parallel arrangement may result in an unequal power distribution and possible overloading of the shaded panels. Since the series-parallel (SP) arrangement is frequently used in real-world solar systems, the article's main goal is to demonstrate its benefits and suitability for reducing the impacts of partial shadowing. Although additional designs such as total cross-tied (TCT), bridge link (BL), and honeycomb (HC) are significant, they are not included in this study. The comparative study of other configurations is left as a possible direction for future research as this work attempts to offer a thorough investigation of the SP configuration.

3. SYSTEM CONFIGURATION

Photovoltaic systems target solar energy, which is renewable energy and is abundant in almost every place. By using this energy, homeowners can reduce their dependence on conventional fossil fuels, reduce pollution, contribute to sustainability, and reduce their carbon footprint. Economically, the use of solar energy produces significant reduction in the bills of electricity in prospective long term. In this work, a PV system of 5 kW for home purposes has been suggested as shown in Figure 1.

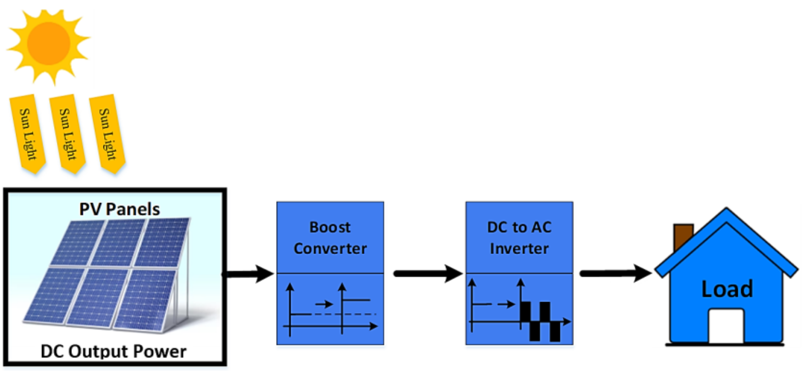

Figure 1. PV system for home application

3.1. PV panels

In order to supply 5 kW in uniform shading conditions, 20 PV panels are connected as 5 PV panels in series with 4 such groups in parallel, as shown in Figure 2. The output (I-V) and (P-V) curves for each panel with irradiance of 500 and 1000 W/m^2 are shown in Figure 3. Table 1 describes the specification of each panel.

In order to obtain the desired power production under consistent shading conditions, the PV system is constructed with panels connected in series and parallel. For maximum efficiency, each panel runs at its ideal voltage and current levels. In order to ensure that the system can satisfy the power requirement, the series setup raises the total voltage while the parallel connection improves the current output. Temperature changes affect the panels' performance by slightly decreasing voltage and slightly increasing current, underscoring the significance of thermal management. The system's performance curves show how well it adapts to varied sunshine situations and how reliable it is at various irradiance levels.

3.2. DC to DC boost converter

The converter is a significant stage between both the PV panels and the inverter. The boost converter here has to raise the PV output voltage to values of inverter input voltage and in this stage, the MPPT controller is design to provide a suitable duty ratio (D) to the converter to extract maximum power from PV panels during the day, as shown in Figure 4. The parameter of such a converter in this work is shown in Table 2.

In order to maximize the PV system's power and achieve optimal performance, maximum power point tracking is a necessary prerequisite. Because of its fundamental structure, a number of researchers have used the perturbation and observation (P&O) and incremental connectivity (IC) methods for MPPT modeling. Compared to the P&O MPPT method, the IC-MPPT algorithm can track changing conditions more quickly; however, it requires a costly and complex controller and generates somewhat unsteady output power. In contrast, the P&O algorithm's output power varies around MPPT. A perturb and observe (P&O) control algorithm is proposed in this study. It requires fewer parameters, is inexpensive, simple to deploy, and readily adaptable to increase efficiency. It is necessary to maintain the operating point (voltage and current) of the PV array at the maximum power point (MPP) by modifying the duty ratio of the boost converter using the P&O technique. This is because the continuous variation of irradiance throughout the day results in supply adjustable values of both voltage and current from PV cells.

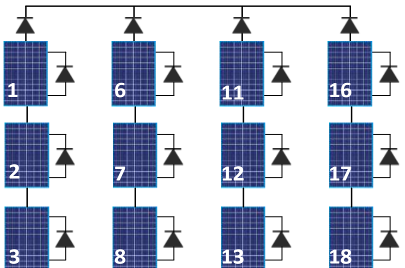

Figure 2. (5*4) PV panel system

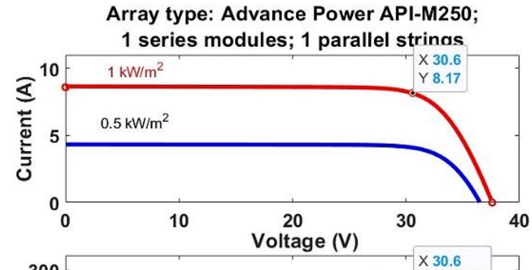

Figure 3. I-V and P-V curves of PV panel at irradiance of 500 and 1000 W/m^2

Table 1. PV panel parameters

(PV panel) parameter	Value
Maximum power (PMAX)	250.002 W
Voltage at maximum power (Vmp)	30.6 V
Current at maximum power (Imp)	8.17 A
Open circuit voltage (Voc)	37.62 V
Short circuit current (Isc)	8.59 A
Temperature coefficient of Voc (Kv)	-0.3564%/ºC
Temperature coefficient of Isc (Ki)	0.053725%/ºC

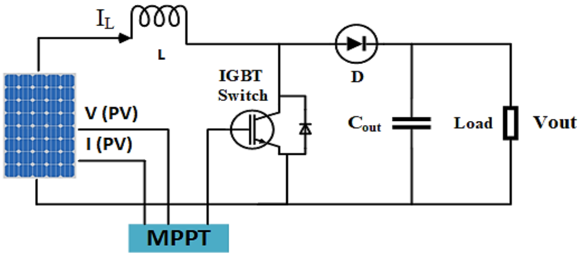

Figure 4. Boost converter with (P&O) MPPT algorithm

Table 2. Boost converter parameters

Boost converter parameters	Values
Inductance (L)	2.294 mH
Capacitor	100 µF
DC–link capacitor	700 µF
Switching frequency	5 kHz

3.3. DC to AC inverter

When obtaining an AC power signal from renewable energy sources (such as a battery or solar panel), the inverter is thought to be the most crucial component. DC/AC inverters can be configured with a half or complete H-bridge topology, depending on the geometry of the power electronic switches. This work used single phase universal bridge inverter with power of 5 kW, input voltage of 400 volts, and output voltage 223 volts. The inverter converts the DC boost converter voltage to an AC voltage applied to the load. The main circuit of the two-stage load-connected PV system is described in Figure 5.

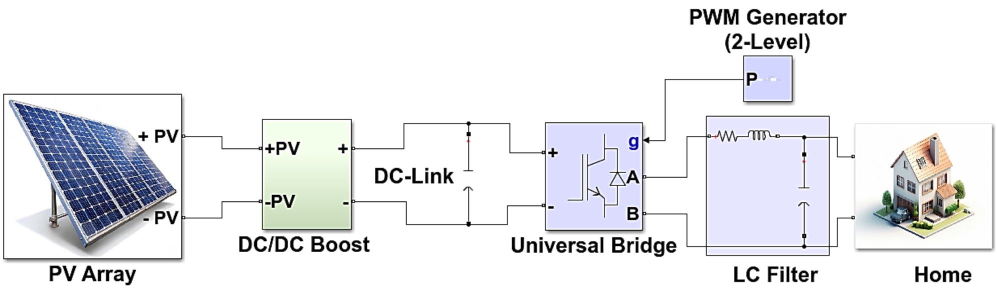

Figure 5. PV system model in MATLAB

4. PV ARRAY UNDER PARTIAL SHADING

The system of solar cells can provide sufficient amount of energy for home application in standard uniform irradiance conditions. This kind of energy can be affected directly by shading conditions and its duration during the day. Obviously, the solar array is exposed to shadow, which negatively affects the solar panel electrical power output. A PV array typically consists of many modules connected to one another in both series and parallel configurations. PV arrays are said to be under photovoltaic shade control if many cells inside a module are shaded. Partial shading lowers the current for PV cells that are shaded while producing high currents for the other unshaded cells since each PV cell's current within a module is dependent on the sun's brightness. As demonstrated in Figure 6, the cells under shading function in the reverse bias zone and maintain the same current as the non-shaded modules since the current flow through every module connected in series must be equal.

The reverse voltage across the PV module's cells causes them to absorb energy when they are shaded. As a result, the array's output power is decreased. This energy is transformed into heat, which could lead to the shadowed cells' thermal breakdown and the creation of a hotspot. The PV string that is shaded may have an open circuit due to cell breakdown brought on by this type of heat breakdown. With bypass diodes, this hotspot effect can be avoided. Bypass diodes are used to stop negative voltage from manifesting. The main reasons for partial shading occurrence can list as follows [25], [26]:

i) Physical obstacles: nearby building objects, trees, or structures that cast their shadows on the solar panels. It is possible for the shading to be complete or partial, as this situation is likely to occur at a certain time of the day.
ii) Module mismatch: Every PV system may consist of many PV panels connected in series to reach the desired voltage, if shading happened one panel, then the string performance will be affected where the string current will be limited to a value of the current of the weakest panel that was most exposed to the shadow.
iii) Cell configuration: The configuration of solar panels is usually consisting small cells and if shading taken place on single or more cells that's lead to reduction in panel output power.

A well knowing of such causes can guide researchers to design PV systems that are more resilient to partial shading and maximizing their overall efficiency and energy production. Partial shading causes reduction in efficiency of PV system. The shaded cells produce less power than the unshaded cells, which leads to reduce the overall output power of PV system. Several mitigation strategies have been suggested to reduce the impact of shading; PV systems can be constructed with bypass diodes, optimum configuration of PV panels, or even with micro-inverters that manage each panel independently [25], [27].

In this work, multi cases of shading (with a shed irradiance of 500 W/m^2) on the PV array system has been suggested as shown in Figure 7. First case 1, the shading accrues on the first left column of PV system array. The second case 2 of shading is on the complete upper row of the system. A case of spotted shad case 3 is suggested to be on the middle of PV system with 6 shaded panels. While case 4 described the shading on two corners of the system one of them is the upper right corner and the other one is its opposite. The last case is a random selection of 8 modules to be shaded, and the modules are (2, 4, 8, 11, 14, 16, 18, and 20). Test such cases provide indication how the system is performed under these shading cases. Most important signs to measure the performance of PV system explain as follows [8], [18].

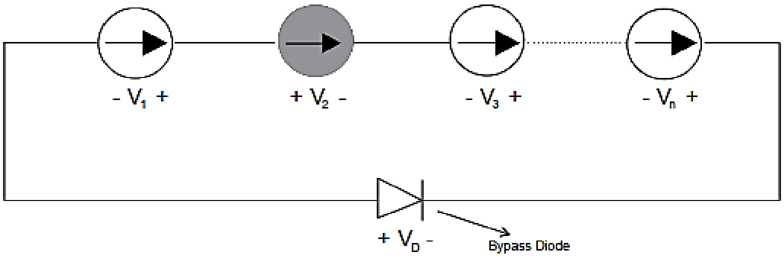

Figure 6. One solar cell is shaded when a bypass diode is connected in parallel with them

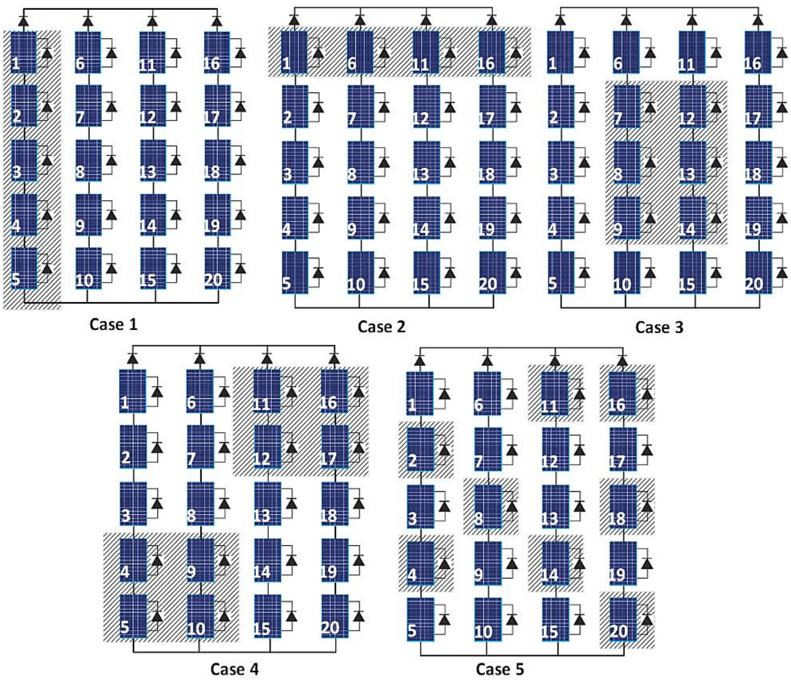

Figure 7. Several patterns of shading on the PV system

4.1. Mismatch loss (ML)

PPSC represents the power generation at specific PSCs, while Pmp is the fraction of difference between the maximum power generation under uniform irradiance conditions. The global maximum power point (GMPP) at each PSC's maximum voltage (Vmp) and maximum current (Imp) can be multiplied to determine the PPSC.

$$ML = \frac{Pmp - Ppsc}{Pmp} \times 100 \tag{1}$$

4.2. Fill factor (FF)

Determining the output efficiency of solar PV systems under non-homogeneous (partial shadowing) irradiation conditions is connected to the FF parameter. The FF of a solar PV system is defined as the percentage of maximum electrical output power generated in a non-homogeneous irradiation scenario to maximum rated capacity.

$$FF = \frac{(Vmp * Imp) at\ respective\ PSC}{Voc * Isc} \times 100 \tag{2}$$

In (2), V_{OC} and I_{SC} represent the open circuit voltage of PV array and short circuit current of PV array, respectively.

4.3. Performance ratio (PR)

PR is defined as the maximum generated output power during a non-homogeneous (partial shading) irradiation situation. It is compared to the maximum generated output power during a homogeneous (uniform) irradiation situation.

$$PR = \frac{Pmax(non-homogenous)}{Pmax(homogenous)} \times 100 \tag{3}$$

The performance ratio (PR) is an important indicator for evaluating the efficiency of a solar system under realistic operating conditions, especially when there is partial shading. It helps compare system performance under varying conditions with ideal irradiance, revealing potential operational losses. It is also used to optimize the design and maintenance of solar systems to ensure the highest possible output.

5. RESULTS AND DISCUSSION

To evaluate the performance of a two-stage home (5×4) PV system, a topological SP was proposed, and the characteristics of this system were tested under different partial shading conditions and the effect of these conditions on the performance of the entire system was observed. This system was implemented using MATLAB/Simulink. From the simulation result, as shown in Table 3, we note the output of the photovoltaic array under standard conditions and its output under the influence of multiple cases of partial shading.

In different partial shading cases, we absorption that the capacity of the photovoltaic system is not affected, except for the case 1, which led to a reduction in the short circuit current (Is.c) of the system to (30.2955 A) due to the effect of partial shading on an entire column (5 panel) with a value of (Ir = 500 W/m^2). Figure 8 shows the (P-V) characteristic of PV array under various partial shading conditions; we notice a decrease in the value of the maximum power provided by the photovoltaic system from its value under standard conditions (4981.81 W) when exposed to various partial shading situations. When the PV array is operating at standard test condition (STC) (uniform irradiance condition), the (P–V) characteristics curve of the array exhibits a single maximum power point. but, during partial shading conditions, the (P-V) curves show a more complicated characterized by several local and one global maximum power point. The results show that the number of panels exposed to partial shading and their location play an important role in the decrease that occurs in the value of the maximum power of the photovoltaic system. In cases 4 and 5, partial shading occurred on the same number of models (8 panels). The global maximum power point in case 4 decreased by (41%) from its value in STC, while the global maximum power in case 5 decreased by (44.8%) from their values in STC due to the difference in the locations of the models under the influence of partial shading.

For the performance analysis of the PV array characteristic under a partial shading situation, several factors of FF, ML, and PR were relied upon. A PV array of size (5×4) produces less output power. The PV array's increased power loss is the cause of this dropped output power. As seen in Figure 9, this type of power loss is expressed as ML. The kind of shading pattern has a significant impact on ML. During STCs, the ML was nearly zero, the least ML as 12.4% was found in case 1 with single GMPP at 4362.17 W, the worst case is at case 5 with global max power point as 2749.49 W, where the ML increased to 44.8%.

Figure 10 shows the effect of different partial shading conditions on the fill factor (FF) of a PV system. In the normal state (no shading), the fill factor reaches its highest value at 76.5%. With shading applied to certain columns or rows, the fill factor gradually decreases, reaching 67% for column shading and 60.8% for row shading. Performance deteriorates further with shading at the center or corners, reaching its lowest value with random shading at 42.2%. The figure demonstrates that the shading pattern and location significantly impact the efficiency of a PV system, necessitating the design of systems that minimize the effect of shading, as shown in Figure 10.

Figure 11 shows the effect of different partial shading conditions on the performance ratio (PR) of a photovoltaic system. Under normal conditions, without shading, the system achieves a peak performance ratio of 100%. With partial shading, this ratio gradually decreases, reaching 87.5% for single-column shading and 79.4% for single-row shading. The PR decreases further when the center or corners are shaded, reaching 58.9% and 55.19% for random shading. The figure demonstrates that shading distribution directly affects the efficiency of a photovoltaic system, and the more irregular the shading or the more critical areas, the greater the performance loss.

Table 3. PV array parameters under partial shading cases

Partial shading cases	$V_{o.c}$ (V)	$I_{s.c}$ (A)	V_{max} (V)	I_{max} (A)	P_{max} (W)
STC condition	188	34.6	152.918	32.57	4981.81
Case 1: PSC at column 1	188	30.2955	152.958	28.518	4362.17
Case 2: PSC at row 1	188	34.6216	121.437	32.59	3958.56
Case 3: PSC at center	188	34.6176	155.228	24.51	3805.21
Case 4: PSC at corners	188	34.6183	89.9154	32.64	2935.2
Case 5: PSC at random	188	34.6174	163.942	16.77	2749.49

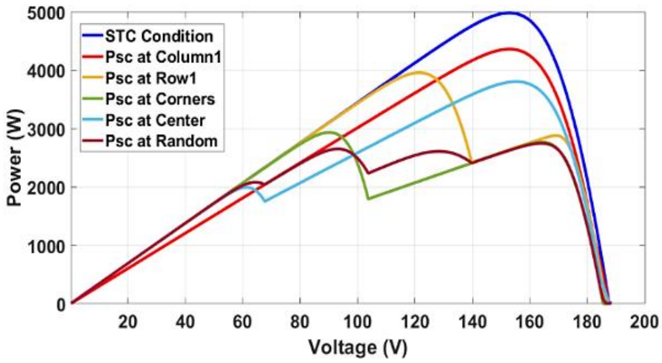

Figure 8. P-V characteristic under partial shading cases

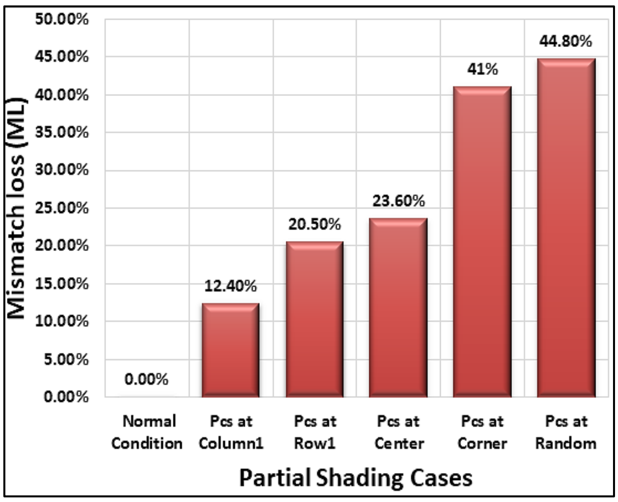

Figure 9. Mismatch loss for partial shading cases

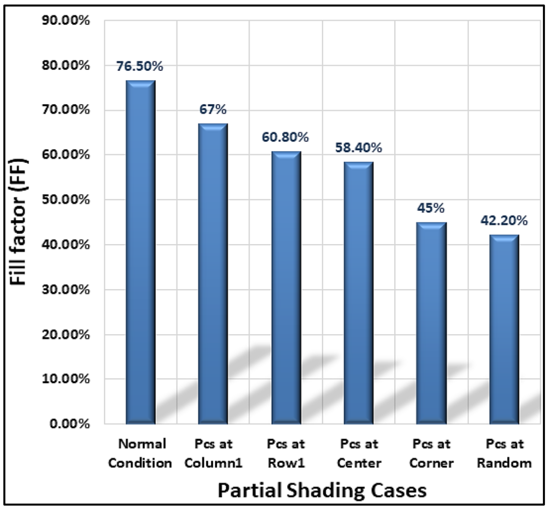

Figure 10. Fill factor loss for partial shading cases

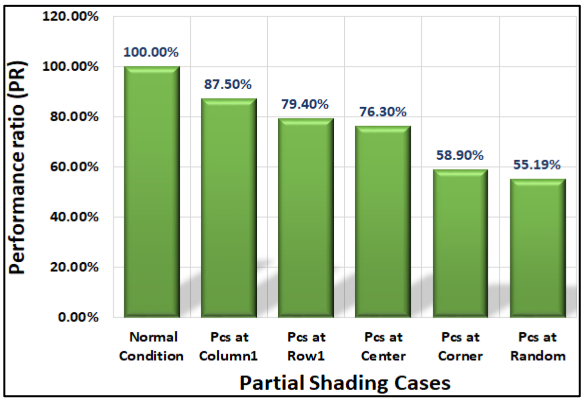

Figure 11. Performance ratio for partial shading cases

The photovoltaic system was connected to the single-phase 5 kW (R-L) home load. Table 4 shows the effect of the various partial shading situations at (Ir = 500 W/m^2). At STC, since the PV array system is operating at full capacity, the load operates with a high efficiency estimated at 92.17%. However, when the PV array system is exposed to different cases of partial shading, the load power in the system is affected. Partial shading means a decrease in the value of the current supplied by the PV array system to the load, as well as a voltage drop, which in turn affects the amount of power supplied to the load. This has led to a decrease in the overall efficiency of the system by different percentages according to the partial shading condition to which the solar system is exposed.

Through the results obtained when partial shading was applied, it was found that the highest efficiency of the system was when partial shading (Ir = 500 W/m^2) was applied to one column (5 panels) as 82.84%, while the worst and least equipped case was when the shading was applied to the corners and random shading at (8 panels), where the efficiency decreased to approximately 39.24% and 40.64% respectively. Figure 12 shows the load voltage output, load current, and load power at STC. Figure 13 shows the behavior of voltage, current, and power for home load at applied partial shading at one column (case 1), and Figure 14 shows the behavior of voltage, current, and power for home load at applied partial shading randomly (case 5).

Table 4. System output for partial shading cases

Partial shading cases	V_L (V)	I_L (A)	P_L (W)	Efficiency (%)
STC condition	223.2	23.51	4609	92.17
Case 1: PSC at column 1	211.6	22.29	4142	82.84
Case 2: PSC at row 1	185.9	19.58	3193	63.87
Case 3: PSC at center	197.2	20.77	3596	71.91
Case 4: PSC at corners	145.9	15.35	1962	39.24
Case 5: PSC at random	148.5	15.62	2032	40.64

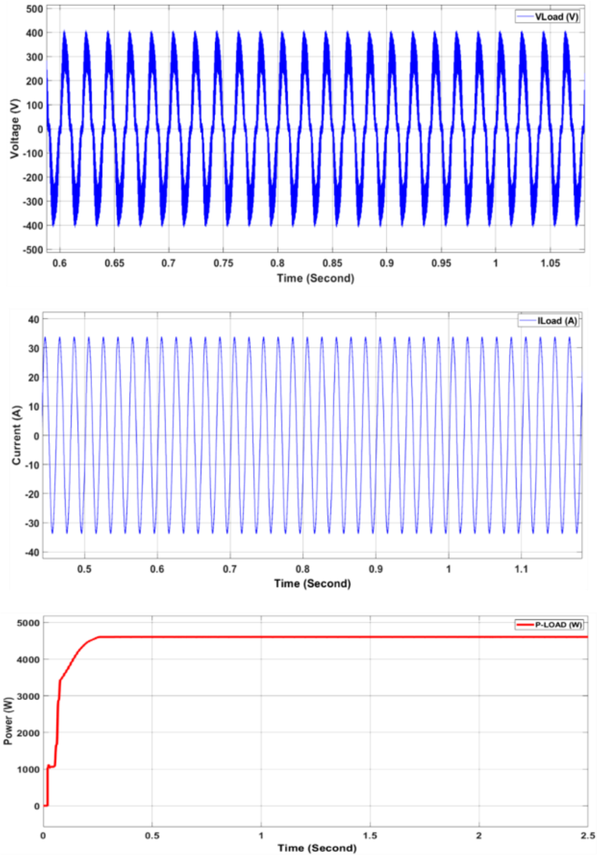

Figure 12. System output at normal condition

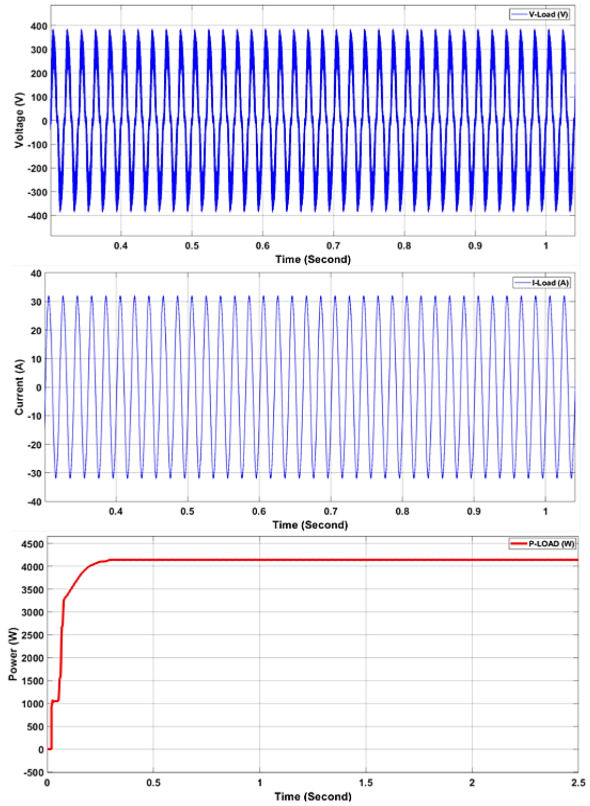

Figure 13. System output at case 1

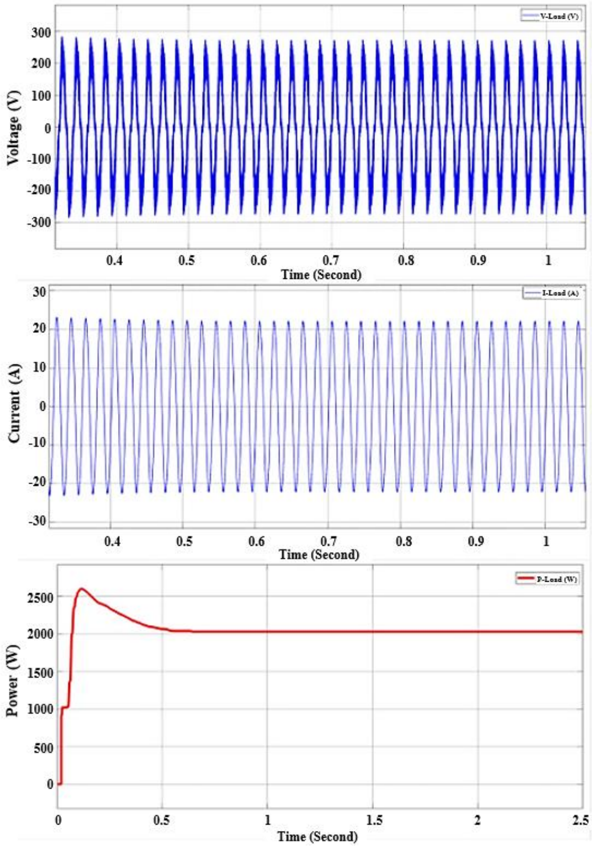

Figure 14. System output at case 5

6. CONCLUSION

The effects of particular shading patterns on residential solar energy systems are examined in this study in a unique way. It finds that partial shading that only covers one column (5 panels) maximizes system efficiency at 82.84%, whereas shading that covers corners significantly reduces system efficiency to about 39.24%. In order to ensure accuracy in evaluating system performance under various shading scenarios, such as random shading applied to eight panels, which showed efficiency as low as 40.64%, the findings are validated by empirical data collection and analysis. The study illustrates the significant influence of shade, quantifies performance losses, and identifies configurations that preserve higher efficiency even in difficult circumstances by examining energy output, efficiency metrics, and reliability. A cogent understanding of system behavior under various shading conditions is made easier by the research's methodical presentation of results for all shading configurations, which clearly contrast optimal and suboptimal cases. The findings give homeowners and policymakers vital information for attaining greater efficiency and dependability in actual solar installations by highlighting the significance of carefully planning and positioning solar panels to reduce shading losses. By tackling real-world issues while upholding technical rigor, this thorough study promotes solar technology and guarantees its applicability to both academic and real-world settings.

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AUTHOR CONTRIBUTIONS STATEMENT

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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