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Research Article

Examination of the Effect of Shading on a Photovoltaic System Performance

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ABSTRACT

This study investigates the impact of shading on the performance of photovoltaic (PV) systems, a critical consideration for optimizing solar energy generation. Shading can occur due to various environmental factors, including nearby structures, vegetation, and atmospheric conditions, leading to significant reductions in energy output and overall system efficiency. Through a combination of experimental measurements and simulation modeling, we assessed how different shading scenarios affect the electrical performance of PV arrays. The findings reveal that even partial shading can cause substantial decreases in power generation, with shaded cells experiencing reverse biasing and increased thermal stress, resulting in potential hot spot formation. The analysis also highlights the importance of PV module configuration and orientation in mitigating shading effects. Additionally, the study highlights the functionality of bypass diodes in PV systems. By allowing current to bypass shaded or malfunctioning cells, these diodes help maintain optimal performance levels even when some cells are compromised. The analysis includes comparative assessments of PV systems with and without bypass diodes under identical shading conditions. Results demonstrate that systems equipped with bypass diodes exhibit significantly improved performance, including higher voltage and current outputs, thereby enhancing overall energy yield. This research underscores the necessity for site-specific evaluations during the design phase of PV installations to ensure maximum efficiency. The insights gained from this study contribute to a deeper understanding of shading dynamics in PV systems and provide practical recommendations for improving solar energy utilization. Ultimately, addressing shading challenges is essential for advancing the reliability and effectiveness of solar power as a sustainable energy solution. The findings deduce the importance of integrating bypass diodes in PV systems to mitigate the detrimental effects of shading, ultimately contributing to more effective utilization of solar energy resources.

Introduction

The increasing demand for renewable energy sources has intensified research into the efficiency and reliability of photovoltaic (PV) systems. As solar energy becomes a cornerstone of sustainable energy strategies worldwide, understanding the factors that influence the performance of PV systems is crucial. One of the significant challenges faced by PV installations is shading, which can dramatically affect their energy output and overall efficiency.

Shading can occur due to various environmental factors, including nearby buildings, trees, poles, clouds, leaves, or even dust accumulation on the panels Figure 1.

The impact of shading on PV performance is multifaceted; it not only reduces the amount of sunlight that reaches the solar cells but can also lead to uneven heating and increased resistance within the system. This phenomenon can result in a substantial decrease in energy production, sometimes exceeding 50% under certain conditions. Consequently, it is essential to investigate how different shading scenarios affect the operational efficiency of PV systems.

Figure 1. Environmental shading.

There have been many studies which have highlighted the importance of understanding shading effects, that consider various shading patterns and their implications for different types of PV technologies [1-2]. For instance, one of the research demonstrated that shading from dust and varying positions significantly impacts the electrical properties of grid-connected PV systems, emphasizing the need for localized studies to evaluate performance under specific conditions [3-6]. Furthermore, investigations into partial shading effects have revealed that different configurations and orientations of PV modules can lead to varying degrees of efficiency loss, suggesting that optimization strategies must be tailored to individual installations [7-10].

To eliminate the negative effect of partial shading, bypass diodes are employed in PV systems as a protective measure [11-12]. These diodes are connected in parallel with individual cells or groups of cells and serve to redirect current around shaded or malfunctioning cells, thereby preserving the functionality of the rest of array. Bypass diodes play a crucial role in enhancing the resilience and reliability of PV systems under partial shading conditions. They allow unshaded cells to continue producing electricity while preventing reverse current flow through shaded cells. This capability significantly mitigates power losses and prevents thermal damage, thereby prolonging the lifespan of the solar panel [13].

Moreover, advancements in maximum power point tracking algorithms have been developed to mitigate losses due to shading by dynamically adjusting operational parameters to maximize energy extraction under non-uniform solar irradiance conditions [14].

This study investigates the performance of a PV system under shading conditions using both experimental and simulation methods. By analyzing the impact of shading on energy yield, the research explores the role of bypass diodes in mitigating power losses. Various system configurations and shading scenarios are examined to assess how bypass diodes enhance energy output in solar installations. The findings offer valuable insights for optimizing PV system design and improving efficiency in real-world applications where shading is inevitable.

PV Array at Partial Shading Conditions

PV arrays are typically mounted on rooftops and sloped surfaces that face northward, while having minimal exposure to the south. Various environmental elements, such as adjacent buildings, trees, and cloud cover, can lead to complete or partial shading of one or more solar panels. This shading results in reduced efficiency for the affected panels, subsequently decreasing the overall power output of the entire system.

PV power generation systems consist of multiple PV cells linked together either in series to boost the voltage output or in parallel to enhance the total current. Ideally, a PV system operates most effectively when all panels within the array receive uniform solar exposure. However, if sunlight is obstructed by leaves, trees, buildings, or antennas, some cells may be subjected to different solar conditions, leading to inconsistencies among cells or panels.

When certain cells within a panel are shaded, the series-connected cells become reverse biased. This prevents current from flowing around the shaded cells, resulting in excess power dissipation in these areas. Consequently, this overheating can create hot spots, leading to a noticeable decline in the module's output power. In cases of partial shading, the affected PV cell acts like a load, negatively impacting the system's efficiency, reliability, and safety.

As a cell becomes shaded, its current output decreases in proportion to the extent of shading. Since strings of panels are generally wired in series, the overall current in that string is constrained by the performance of the weakest cell, as illustrated in Figure 2. If one PV panel is partially shaded 20%, then the current through that panel reduced approximately 20% this cause 20% output power reduction. If one panel is 80% shaded, the output power generation become ≈80%. If few panels are partially shaded and the most shaded cell is 25%, then, approximately 25% of output power reduction is observed.

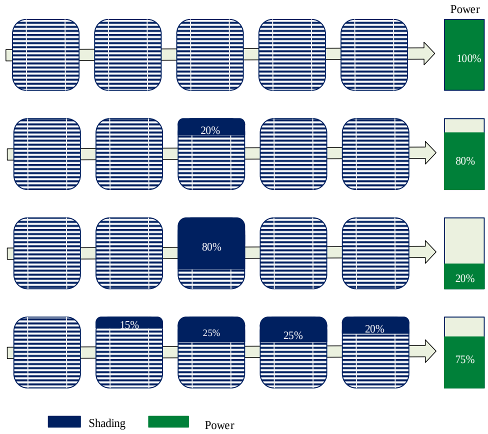


Figure 2. Effects of partial shading on PV panels [15].

A simulation system is implemented using 10W Tommatech polycristal panels whose parameters are obtained from the producer and listed in Table 1. It is observed from the simulation results of the two identical PV panel, connected in series, that if two panels are under uniform solar irradiation, then full power generation is achieved. If one PV panel is partially shaded 40%, then the current through that panel reduced approximately 40% this cause 40% output power reduction.

Table 1. PV Module Parameters.

Parameter	Value
Module	Tommatech TT10-36P
Maximum Power (W)	10Wp
Cells per module (Ncell)	36
Open Circuit voltage Voc (V)	21.1
Short circuit current Isc (A)	0.718
Voltage at max. power point Vmp (V)	17.3
Current at max. power point Imp (V)	0.578

Figure 3 shows the I-V and P-V characteristics of the two series connected panel under different solar irradiation.

If the solar irradiation is decreased 80%, then, approximately 80% of output power reduction is observed. As it is seen in the P-V characteristic, the decrease in solar radiation results approximately the same amount of decrease in the produced power.

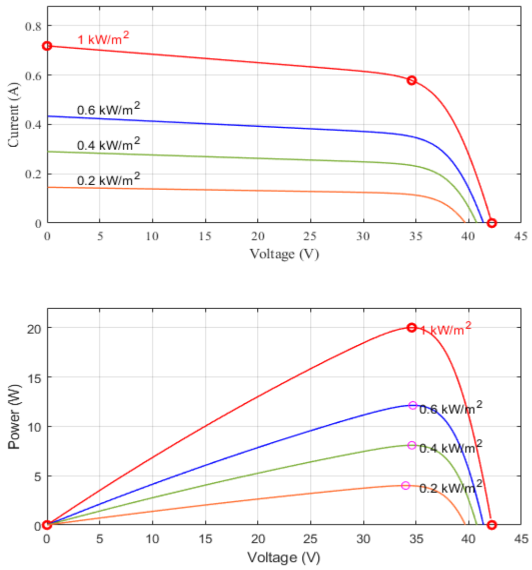


Figure 3. I-V and P-V characteristics of PV system under different uniform shadings.

The similar results were obtained experimentally when two identical PV panels are used as given in Figure 4 and the results of shading effect test system are listed in Table 2.

The experiments were made in a sunny day. An artificial shading condition is realized by blocking the sun light from the PV panel. It has been observed that even a small amount of shading on the panel reduces 37% output power of the solar system.

Table 2. Results of shading effect test system.

Test system	Results
a	V=42,5V, I=0.21A, P=9W
b	V=39,2V, I=0.19A, P=7.4W
c	V=36.3V, I=0.18A, P=6,4W
d	V=36.3V, I=0.18A, P=6,4W
e	V=38.4V, I=0.19A, P=7,3W
f	V=38.4V, I=0.19A, P=7,3W
g	V=34.1V, I=0.17A, P=5,7W

Figure 4. Shading effect test system.

To overcome partial shading effect a bypass diode is connected parallel to the strings with opposite sign as in Figure 5. The performance of the PV module is influenced by the presence of bypass diodes. These diodes play a significant role in managing the operational characteristics of solar cells, particularly under short-circuit and open-circuit conditions.

Open-circuit condition occurs when the solar cell is not connected to any load, resulting in the maximum voltage output known as the open-circuit voltage (V_{OC}). Under standard test conditions, V_{OC} is a crucial parameter that indicates the potential voltage a solar cell can deliver when no current flows through it [16-17]. Short-circuit condition occurs when the solar cell terminals are directly connected, allowing maximum current to flow, referred to as short-circuit current (I_{SC}). The I_{SC} value is critical as it represents the highest current output from the solar cell under illumination [18-19].

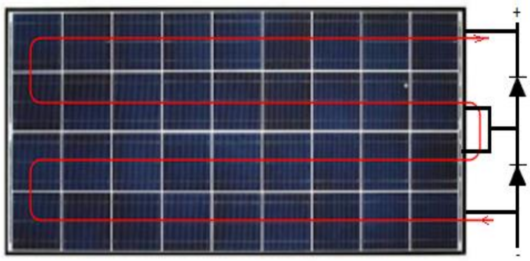


Figure 5. PV panel with bypass diodes across the strings.

Bypass diodes are integrated into solar panels to mitigate the effects of shading and enhance overall performance. Their primary function is to provide an alternative pathway for current when one or more cells in a series string become shadowed or malfunctioning. This capability significantly impacts both open-circuit and short-circuit conditions.

When bypass diodes are employed, they allow current to bypass shaded or faulty cells, thereby maintaining a higher overall voltage across the remaining operational cells. In scenarios where shading occurs, without bypass diodes, the affected cells could reverse bias and lead to a reduction in VOC. However, with bypass diodes in place, these cells are effectively isolated from the circuit, preserving the voltage output from unshaded cells. This action prevents significant drops in VOC, ensuring that the solar panel can still produce useful voltage levels even under partial shading conditions. In short-circuit conditions, bypass diodes also play a crucial role. If one cell in a series string becomes shaded or damaged, it can limit the total current flowing through that string. Without bypass diodes, this limitation can lead to reduced ISC for the entire panel. However, with bypass diodes installed, they allow current to flow around the affected cells. This mechanism ensures that most of the solar panel continues to operate at or near its maximum short-circuit current level, thereby optimizing performance even when some cells are compromised.

Simulation Results

The effect of bypass diode is examined using two panel each parallel connected to a bypass diode. Solar panels generate electricity when exposed to sunlight, but at night or in low-light conditions, there is a risk of current flowing backward from the battery or load into the panels.
Normally a blocking diode is connected in series with a solar panel or a string of solar panels to block the reverse current from the battery to the panel or the string at night or when the panel or the string is not producing enough power. It also prevents energy loss and potential damage to the panels.

A simulation model, as shown in Figure 6, is developed in Matlab Simulink environment. The solar PV panels are modelled with the manufacturer supplied data given in Table 1.

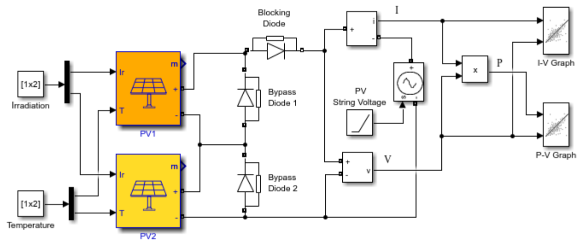


Figure 6. Simulink model for examination of shading effect.

Figure 7 illustrates the power-voltage (P-V) and current-voltage (I-V) characteristics of two PV arrays connected in series, with their parameters detailed in Table 1.

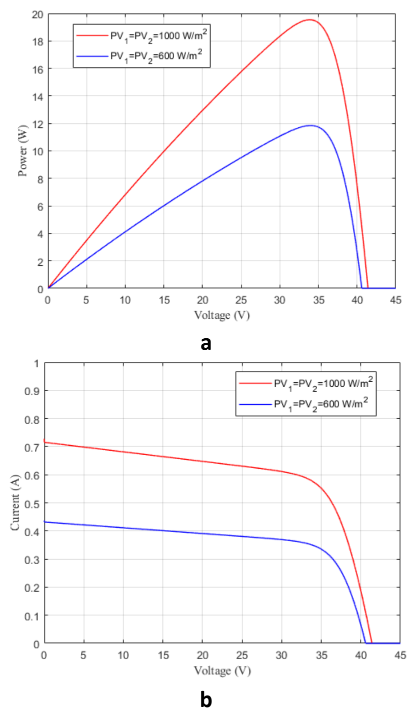
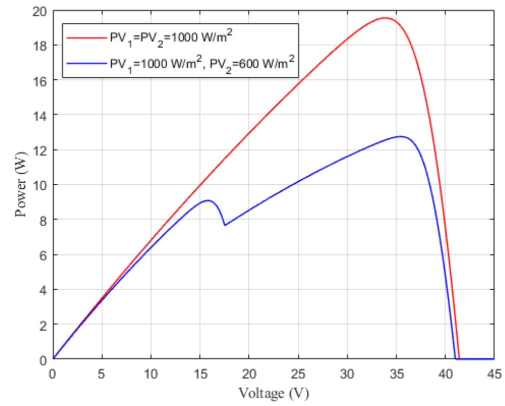


Figure 7. Characteristics of two series connected panel with uniform shaded/unshaded conditions **a.** P-V **b.** I-V.

The blue line depicts the scenario where both PV_1 and PV_2 are exposed to identical solar irradiance levels of 1000 W/m². In contrast, the red line represents the situation in which both PV_1 and PV_2 experiences a solar illumination of 600 W/m².

Figure 8 (a) presents the P-V characteristics, while Figure 8 (b) displays the I-V characteristics of two PV arrays connected in series, both with bypass diodes, under various irradiation conditions.

The red line indicates the scenario where both PV_1 and PV_2 are subjected to the same solar irradiance of 1000 W/m². The blue line represents the situation where PV_1 has 1000 W/m² of solar illumination and PV_2 receives 600 W/m². As seen in the figure, the integration of bypass diodes alters the I-V and P-V characteristics of PV arrays under shading, resulting in multiple peaks in the characteristic curves.



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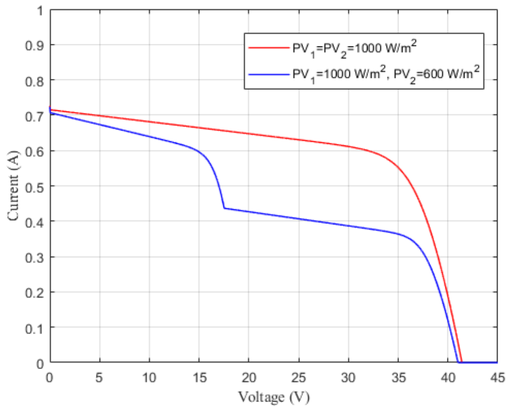


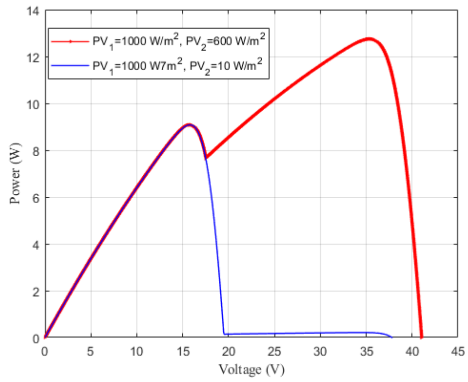
b

Figure 8. Characteristics of two series connected panel with by-pass diode under full and partial shaded conditions **a.** P-V characteristics **b.** I-V characteristics.

Figure 9 displays the P-V and I-V characteristics of two PV arrays connected in series, both with bypass diodes, under various irradiation conditions.

The red line indicates the scenario where PV1 receives solar irradiance of 1000 W/m² and PV2 are subjected to solar irradiance of 600 W/m². The blue line represents the situation where PV1 has 1000 W/m² of solar illumination while PV2 receives no illumination at all.

The simulation results indicate that shading not only affects the individual performance of the impacted cells but also creates mismatches within the entire array, leading to reverse biasing and potential hot spot formation.



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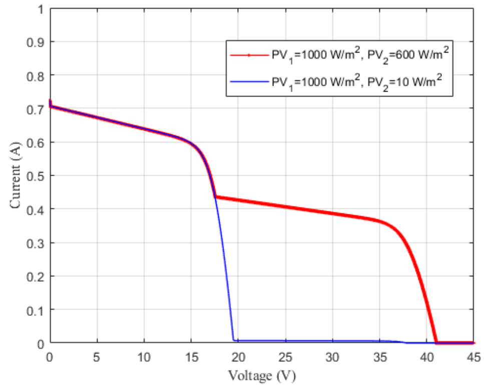

b

Figure 9. Characteristics of two series connected panel with by-pass diode under full and partial shaded conditions **a.** P-V characteristics **b.** I-V characteristics.

The simulation results clearly demonstrate that when a PV module experiences partial shading, the current output from the affected cells decreases significantly. In the absence of bypass diodes, this reduction in current can severely impact the overall performance of the module. Since all cells in a series-connected string must conduct the same current, a drop in the output of shaded cells constrains the entire string, leading to considerable power losses.

This limitation is evident in the I-V curve, which shows a noticeable drop in short-circuit current under shading conditions. However, when bypass diodes are integrated into the PV system, they provide an alternative path for current to flow around shaded or malfunctioning cells. These diodes activate when the voltage across a shaded cell falls below a specific threshold, allowing them to conduct and redirect current, thereby preventing significant power losses. As a result, the I-V curve maintains a more stable current output, ensuring that unshaded cells continue to operate efficiently without being hindered by the shaded ones.

One notable effect of bypass diodes in partial shading conditions is the emergence of multiple peaks in the I-V and

P-V characteristic curves. This phenomenon arises because different sections of the PV array receive varying levels of illumination, creating multiple operating points where power output can be optimized. Identifying and tracking the global maximum power point (MPP) in such scenarios becomes essential for improving the system's energy efficiency.

Furthermore, when bypass diodes are activated, they effectively short-circuit the shaded cells, leading to a localized drop in voltage. This voltage reduction corresponds to the sum of the voltages of all bypassed cells, along with the forward voltage drop of the diodes themselves. While the overall system voltage may decrease slightly due to shading, it remains significantly higher than it would be without bypass diodes, where shaded cells could enter reverse bias and drastically reduce system voltage.

By enabling unshaded cells to continue generating current, bypass diodes play a crucial role in maintaining a consistent and reliable power output under partial shading conditions. Their presence helps mitigate shading-induced power losses, enhances system stability, and ensures that PV arrays operate more efficiently in real-world environments where shading is often unavoidable.

Conclusion

This study has thoroughly examined the effects of shading on the performance of PV systems, revealing significant implications for energy output, efficiency, and overall system reliability. It has provided a comprehensive examination of the effects of shading on the performance of PV systems. Through a combination of experimental measurements and simulation analyses, it has been demonstrated that shading significantly impacts the energy output and efficiency of PV arrays.

The findings indicate that shading can drastically reduce the voltage and current generated by PV modules, leading to diminished power output and efficiency losses. These effects are particularly pronounced in configurations where multiple cells are connected in series, as shading on any single cell can impact the entire string's performance. Importantly, the integration of bypass diodes emerges as a critical strategy for mitigating the adverse effects of shading. By allowing current to circumvent shaded or malfunctioning cells, bypass diodes help preserve the operational integrity of the remaining cells in a series connection. The results from the comparative analysis demonstrate that PV systems equipped with bypass diodes consistently outperform those without them under identical shading conditions. This enhancement manifests as higher voltage and current outputs, which translates to increased overall energy yield from the system. Moreover, the presence of bypass diodes not only improves performance during partial shading events but also enhances the reliability and longevity of PV systems. By preventing reverse bias conditions in shaded cells, bypass diodes reduce the risk of thermal runaway and potential damage, thereby contributing to a more robust system design.

Moreover, this research underscores the importance of conducting site-specific assessments when planning PV installations. Since shading conditions vary based on geographical location, surrounding structures, vegetation, and seasonal changes, a thorough evaluation of these factors is crucial. By integrating advanced shading analysis techniques and simulation tools, stakeholders can develop more accurate predictions of energy yield and implement design strategies that minimize shading-related losses.

As solar energy continues to play a critical role in the transition toward sustainable and renewable energy sources, addressing shading challenges becomes essential for maximizing the efficiency and reliability of PV systems. A deeper understanding of shading effects not only contributes to improving system performance but also supports the development of optimized panel layouts, strategic placement of bypass diodes, and the adoption of innovative mitigation techniques. By refining PV system design through such insights, solar energy solutions can be made more resilient, cost-effective, and aligned with global energy sustainability goals, ultimately accelerating the widespread adoption of clean energy technologies.

Ethics committee approval and conflict of interest statement

There is no conflict of interest with any person / institution in the article prepared.

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