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EFFECT OF PARTIAL SHADING AND REVIEW OF MITIGATION METHODS

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Abstract- The increasing need for energy sources has led to a rise in the application of photovoltaic systems. They can be used in a variety of ways and under a variety of conditions, such as stand-alone use with storage, grid-on and pumping. To get the maximum energy of these applications, certain environmental factors have a negative influence. Shading is the factor that most influences the efficiency of photovoltaic systems. It is a significant factor that can decrease the performance of photovoltaic panels. The main purpose of this article is to demonstrate the effect of partial shading on the power and current supplied by the panel. Using MATLAB/Simulink, the results are plotted and interpreted. To solve this problem, different methods are analyzed, like bypass diodes, Sudoku-based reconfiguration method, various PV array configurations, number place method, current injection method.

Keywords: Partial Shading, Photovoltaic Panel, Solar Irradiation, Methods to Mitigate.

1. INTRODUCTION

Photovoltaic is part of a range of unconventional energy sources that can be used to supply clean, abundant electricity. It offers several advantages, like free fuel, flexibility in terms of generation and demand, and cheap operating costs [1]. PV cells are an essential part of a photovoltaic (PV) system since they convert sunlight into electricity and can be assembled to form arrays or modules [2]. When some portions of a PV module or array are shaded while others remain exposed to sunlight, an uneven distribution of energy production can have an impact on system efficiency and lead to potential reductions. This can be caused by various factors, including nearby structures, vegetation, cloud cover, or even soiling of the PV panels themselves [3]. A PV module characteristic non-linear (*I*-*V*) and (*P*-*V*) characteristics, indicating that the module generates maximum power at only one PM point [4].

Under uniform irradiance conditions, these available methods can be categorized into two methods. In the first, a modification in the module configuration is used, and in the second, power electronics circuits like an MPPT controller are used. The MPPT controller allows the extraction and transfer of electrical energy from the solar photovoltaic module to optimize power consumption [5].

An easy bypass technique that significantly decreases the reverse voltage across cells that are shaded, thereby lowering cell temperature and power loss. These applications do not claim to totally reduce power losses brought on by shading [6].

2. MODELING OF A PHOTOVOLTAIC CELL

Modeling is based on the mathematical expression found in the solar cell's equivalent circuit. Many models have been developed and published in journal articles to explain the behavior of a photovoltaic cell. The reason why the single-diode model is commonly used is that it offers a simpler way of mathematically representing cell operation compared to the two-diode model [7]. Figure 1 represents the equivalent single-diode circuit.

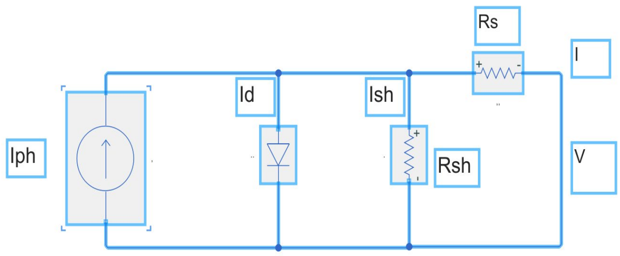

Figure 1. Equivalent single-diode circuit [8]

A single diode model uses a current source to simulate incident solar radiation, a diode to simulate polarization phenomena, and power losses represented by a series resistor and a parallel resistor. Using Kirchhoff's law, the cell's terminal current is determined as indicated below [8]:

$$I = I_{ph} - I_d - I_{sh} \tag{1}$$

The equation for diode current is shown as:

$$I_d = I_o \left[e^{\left(\frac{V+IR_s}{aV_t}\right)} - 1 \right] \tag{2}$$

The shunt current is expressed as:

$$I_{sh} = \frac{V + IR_s}{R_{sh}} \tag{3}$$

The output current equation is:

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$$I = I_{ph} - I_o \left[e^{\left(\frac{V+IR_s}{aV_t}\right)} - 1 \right] - \frac{V + IR_s}{R_{sh}} \tag{4}$$

Equation (4) is used to describe the electrical behavior of a photovoltaic cell as a function of various parameters. It is also used to simulate the performance of a photovoltaic module and determine the effect of partial shading.

3. SIMULATION IN MATLAB/SIMULINK

To demonstrate how partial shading impacts, the output of a PV system, we have employed MATLAB/Simulink software to simulate a model of a PV module. Figures 2 to 4 show the one-diode configuration simulation of a photovoltaic cell based on previously determined equations. This model was created from blocks located in the Simulink Library. This simulation is developed according to the parameters shown in Table 1.

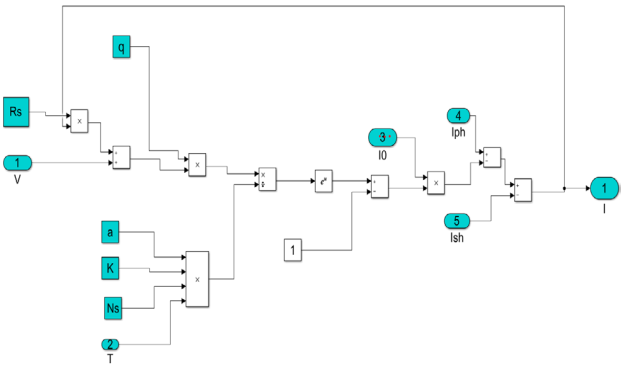

Figure 2. Current output sub block

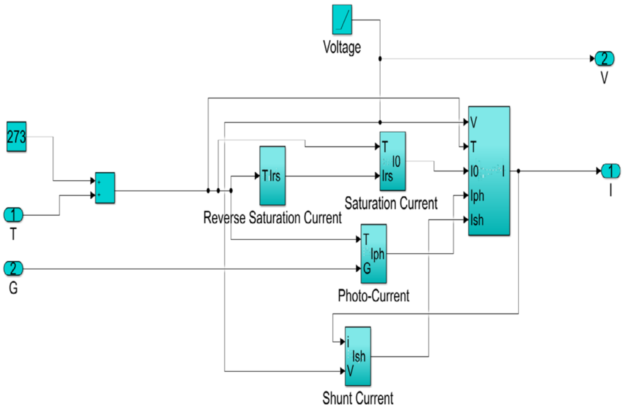

Figure 3. Voltage and Current output sub block

Figure 4 shows the final cell model with a single diode. The input parameters are T and G. The output parameters are current, power, and voltage. This model gives us the behavior of PV system characteristics in the event of partial shading.

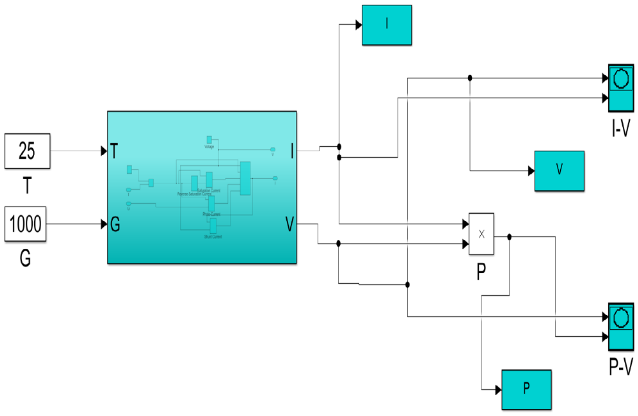

Figure 4. Simulink model for a single diode

Table 1. Electric properties of PV cell [9]

Parameters	Values
P_{max}	250 W
V_{mpp}	30.96 V
I_{mpp}	8.07 A
V_{oc}	37.92 V
I_{sc}	8.62 A
a	0.99132
R_{sh}	82.1161 Ω
R_s	0.098625 Ω
q	1.602e^{-19} C
K	1.38e-23 J/°K
N_s	60

3. RESULTS AND DISCUSSION

After having created the simulation on MATLAB/Simulink, the results are presented in Figures 5 to 10. These figures show the characteristic curves of a PV cell. Temperature was kept constant at 25 °C according to STC. Only different radiation values were entered, as this parameter is the one that will show us the effect of shading.

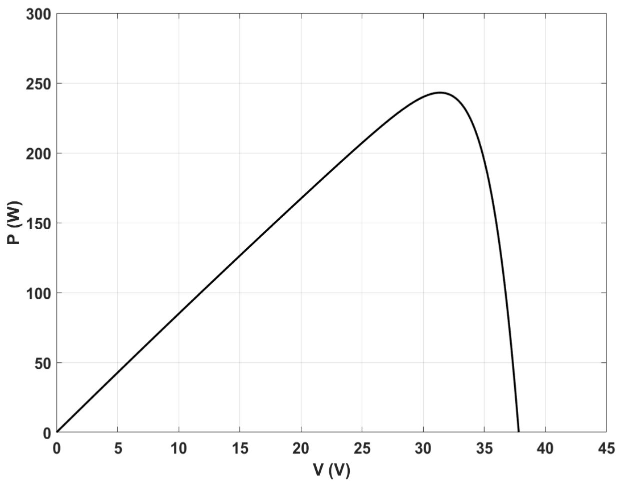

Figure 5. P-V characteristic at G=1000 W/m^2

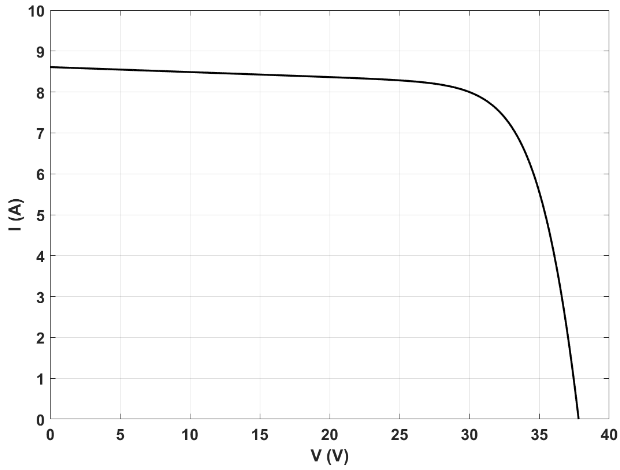

Figure 6. *I-V* characteristic at *G*=1000 W/m^2

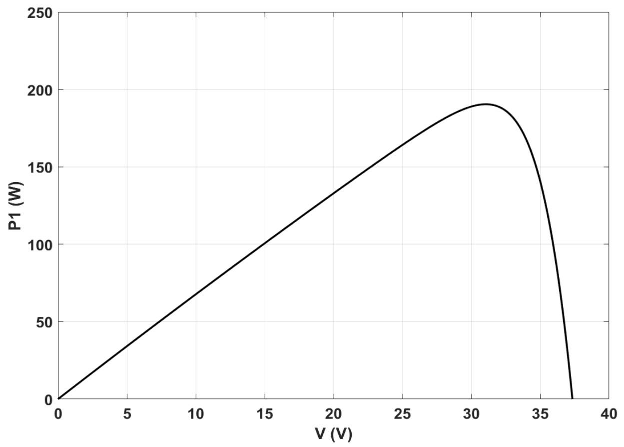

Figure 7. *P-V* characteristic at *G*=800 W/m^2

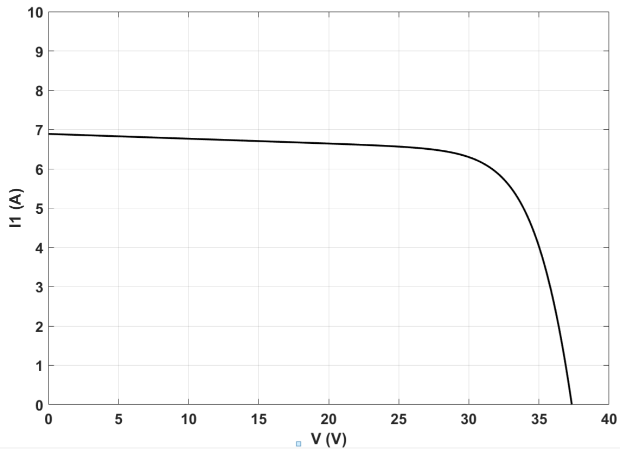

Figure 8. *I-V* characteristic at *G*=800 W/m^2

In Figure 11, the *P-V* characteristics are combined in the same bend to give a clear insight into the evolution of power under different values of solar irradiation. In Figure 12, the *I-V* characteristics are also combined to see the behavior of the current under various values of solar irradiation, and easily obtain a result. From Figures 10 and 11, it is clearly observed that performance decreases as sunlight intensity varies at a temperature of 25 °C. Table 2 provides the simulation results.

Output power and current correlate with irradiance. As solar irradiance decreases, current and power output decreases. It's been noticed that the current and power of a photovoltaic cell are affected by variations in solar irradiance. Partial shading is therefore one of the factors influencing a panel's energy production capacity.

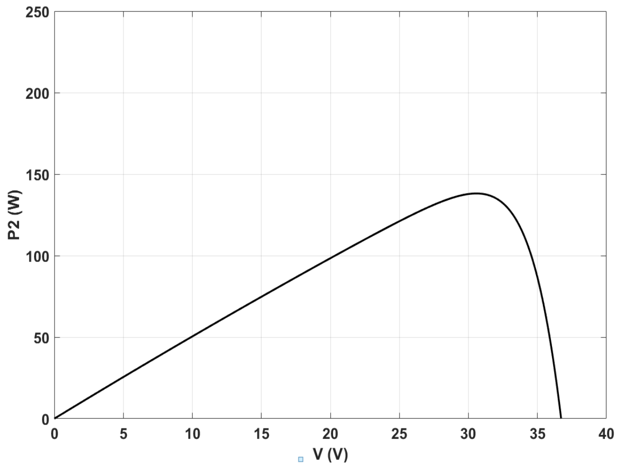

Figure 9. *P-V* characteristic at *G*=600 W/m^2

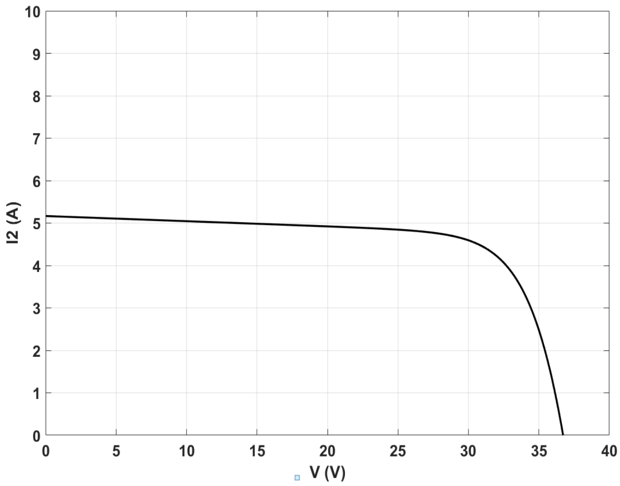

Figure 10. *I-V* characteristic at *G*=600 W/m^2

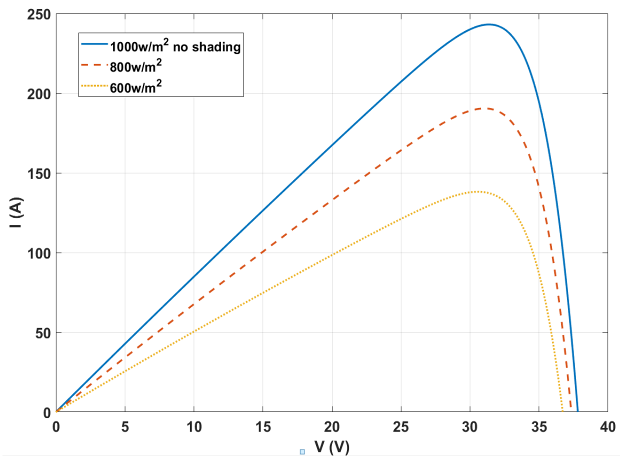

Figure 11. *P-V* characteristic at *G* =1000, 800 and 600 W/m^2

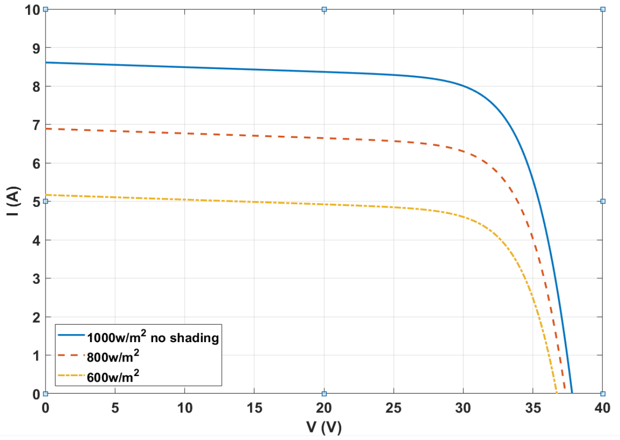

Figure 11. *P-V* characteristic at *G*=1000, 800 and 600 W/m^2

Table 2. Results of simulation

Solar irradiation (W/m^2)	Power (W)	Current (A)
1000	249	8.6
800	190	6.9
600	140	5.1

4. REVIEW OF MITIGATION METHODS

As previously demonstrated, shading can affect panel efficiency. In this part, it will summarize the solutions utilized by researchers to decrease the influence of shading. Masoum, et al. [10] study the consequences of shading on the solar electricity systems. They specifically focus on how (V, I) and (P, I) curve behaviors are affected in photovoltaic systems. The researchers also highlight limitations found in MPPT methods like CMPPT, VMPPT, and P&O when it comes to dealing with uniform shading. To tackle these challenges, they suggest a modification to the CMPPT method that uses tracking converters for each solar cell in place of bypass diodes. This study emphasizes the significance of adaptive MPPT approaches. It shows how the modified CMPPT method significantly enhances the yield of PV systems under both non uniform shading conditions [10].

Khatoon, et al. [11] examine the effects of series and parallel connections in modeling modules and panels. They investigate the current and power characteristics. Their findings suggest that series connections experience power losses when sunlight is uneven. To address this issue, they recommend using connections with bypass diodes, as each panel operates independently in this configuration [11]. Ahmad, et al. [12] introduce a technique for monitoring the MPP by temporarily disconnecting the PV array from the load and connecting it to an external capacitor. This method is straightforward to implement. Reduces the time needed to identify the MPP. Its objective is to overcome the difficulties caused by shading situations, thereby enhancing the efficiency of PV systems. Simulations conducted using Proteus software confirm its effectiveness when faced with varying levels of irradiation and shading conditions [12].

Jalil, et al. [13] present a new method called "Number Place" that enhances energy generation in photovoltaic systems and mitigates the impact of shading. Using this method, the modules are repositioned while the electrical connections remain intact. The findings demonstrate that this reconfiguration method remarkably boosts grid power output, resulting in an increase of up to 6.7%. Moreover, it effectively reduces peaks to a peak across all configurations utilizing the Number Place method [13].

Mamun, et al. [14] conducted an experiment to explore how partial shading affects a 90 W photovoltaic (PV) module under shading and irradiation conditions. Their findings revealed that increased shading has an impact on electricity production and efficiency. Specifically, they observed that a 10% increase in shading led to a decrease of 12.41 W in electricity production and a 2.3% drop in efficiency. Additionally, they noted that shading causes the temperature of cells to rise, with emphasis on horizontal shading patterns. The researchers emphasize the importance of implementing techniques to mitigate shading effects and optimize energy generation. Their study aims to provide insights for policymakers, manufacturers, engineers, and academics involved in this field [14].

Djalab, et al. [15] used bypass diodes to conduct MATLAB/Simulink simulations and analyze the impact of shading at radiance levels (100%, 75%, 50%, 30%, and 20%) on the characteristics of photovoltaic arrays current-voltage and power-voltage. The results demonstrated that the incorporation of bypass diodes can improve the performance of PV systems in certain conditions. Also, Partial shading was shown to reduce the energy generated by PV arrays, resulting in fluctuations in the output curves. The researchers concluded that shading has an impact on PV systems, emphasizing how bypass diodes play a role in mitigating these adverse effects [15].

Peter, et al. [16] ran simulations on MATLAB/Simulink using a two-model for photovoltaic systems to investigate arrangements of PV arrays. They analyzed the performance of various configurations (Series, Parallel, TCT, and HC) setups, comparing them under shading scenarios and considering the influence of bypass diodes. The results indicate that both TCT and HC configurations outperformed the others when it came to dealing with shading conditions. These configurations are suitable for stand-alone or grid-on PV systems as they offer higher power output, fill factor, and efficiency while minimizing power loss due to mismatching [16].

Thinh, et al. [17] propose a technique called Sudoku-based reconfiguration (SDK) to address the issue of shading in photovoltaic modules. However, recognizing the limitations of SDK's effectiveness, they introduce a biogeography-based algorithm to rearrange the connections between photovoltaic panels. They validate this approach using power voltage (PV) simulations and a PV model based on a diode. The results demonstrate a 19.3% reduction in power loss compared to PV array configurations and a slight 0.3% improvement compared to SDK based configurations. This new method, known as BBO SDK reconfiguration, holds promise for minimizing the impact of shading on large-scale photovoltaic systems [17].

Karmakar, et al. [18] have explored a solar array reconfiguration (DAR) technique as a solution. They acknowledge its limitations, particularly the requirement for expensive MPPT controllers. To address these shortcomings, they have introduced an injection (CI) based approach to enhance the DAR strategy. This CI-based method does not boost the power output of the grid beyond existing techniques. It also eliminates multiple fluctuations in the power voltage characteristics that occur during partial shading. The effectiveness of this approach is supported by results, which demonstrate its superiority over strategies for PV array reconfiguration. What's more, this CI-based approach enhances the performance of PV arrays under shading without relying on MPPT controllers, and a cost analysis supports the investment in inverters. All this research highlights that using current injection shows promise to maximize energy production in partially shaded PV arrays [18].

5. ANALYSIS OF THE METHODS

The studies discussed in Table 3 present a range of approaches to solving the challenges caused by partial shading in photovoltaic systems. One promising solution is the modified CMPPT method proposed by Masoum, et al., which incorporates tracking converters. This approach demonstrates performance in handling no uniform shading scenarios, resulting in enhanced overall efficiency of PV systems. Another practical insight comes from Khatoon, et al. investigation into series versus connections, which revealing that parallel configurations are superior in mitigating power losses under non-uniform shading conditions. Ahmad, et al. capacitor-based technique, involving a disconnection, offers a method to reduce scan time and enhance efficiency when dealing with partial shading situations.

Djalab, et al. focus on bypass diodes at radiance levels, which highlights the vulnerability of PV systems to shading and emphasizes the important role bypass diodes play in mitigating these adverse effects. Peter, et al. simulation-based exploration of PV array configurations establishes the superiority of cross tied (TCT) and honeycomb (HC) layouts as they offer higher power output and efficiency compared to other configurations. Lastly Thinh, et al. Sudoku based and BBO SDK reconfiguration methods provide solutions, with the BBO SDK approach showing a 0.3% improvement in reducing power loss compared to initial configurations. Karmakar, et al.'s approach to solar array reconfiguration, known as injection (CI), is remarkable due to its cost-effective nature. It achieves efficiency improvements without the need for complex MPPT controllers. In another study, Jalil, et al. implemented the number place method resulting in an increase in the grid's output power. This technique represents an advancement in optimizing the performance of PV systems.

Lastly, Mamun, et al. conducted experiments that shed light on the real-world effects of shading on electricity production and efficiency in a 90 W PV module. Their findings revealed a correlation between increased shading levels and reduced electricity generation. Together, these studies contribute significantly to efforts aimed at improving the efficiency, resilience, and practicality of energy systems under various shading conditions.

Table 3. Overview of shading methods

Paper	Methodology	Main Results
Masoum, et al. [10]	Modified CMPPT with individual tracking converters	The modified CMPPT method showcased improved performance in handling non-uniform shading scenarios, optimizing the PV system's overall effectiveness
Khatoon, et al. [11]	Series vs parallel connections	Parallel connections mitigate power losses in non-uniform shading
Ahmad, et al. [12]	Capacitor-based technique with brief disconnection	Reduced scan time, improved efficiency under partial shading
Djalab, et al. [15]	Bypass diodes under various radiance levels	The results underscored the sensitivity of PV systems to partial shading and highlighted the crucial role bypass diodes play in mitigating these adverse effects
Peter, et al. [16]	Simulation of various PV array configurations	TCT and HC configurations demonstrated higher power output, fill factor, and efficiency compared to series and series-parallel configurations
Thinh, et al. [17]	Sudoku-based and BBO-SDK reconfiguration	The BBO-SDK method showed a 0.3% improvement in power loss reduction compared to the initial SDK-based configurations
Karmakar, et al. [18]	Dynamic solar array reconfiguration using CI	The CI-based approach accomplished these gains without requiring costly and intricate MPPT controllers
Jalil, et al. [13]	Number Place method	Implementation of this reconfiguration technique led to a noteworthy increase in the grid's output power, with a maximum enhancement of up to 6.7%
Mamun, et al. [14]	Experimented with the impact of partial shading on a 90 W photovoltaic module	The findings revealed a direct correlation between higher shading levels and reduced electricity production, with a 10% increase in shading resulting in a significant 12.41 W drop in electricity production and a 2.3% decrease in efficiency

6. CONCLUSIONS

In conclusion, this paper emphasizes the challenge posed by the shading of solar panels. It has been observed through MATLAB/Simulink software simulation results that such shading can lead to a decrease in energy production and system efficiency. Extensive research has been conducted to tackle this issue, resulting in solutions like MPPT techniques, reconfiguration methods, and the use of bypass diodes. The objective of these methods is to reduce the impact of shading, improve energy extraction, and enhance the performance of photovoltaic systems when faced with shading. As the need for energy keeps growing, these advancements are crucial in maximizing the efficiency and dependability of photovoltaic systems. Ultimately, they help make these systems sources of energy.

NOMENCLATURES

1. Acronyms

PV	Photovoltaic
MPPT	Maximum Power Point Tracking
CMPPT	Current maximum power point tracking
VMPPT	Voltage maximum power point tracking
TCT	Total cross-tied
HC	Honeycomb
SDK	Sudoku-based reconfiguration
DAR	Dynamic solar array reconfiguration
CI	Current injection

2. Symbols / Parameters

I: Output current of PV cell
I_{ph}: Photocurrent
Id: Diode current
Io: Diode reverse saturation current
G: Irradiation
R_s: Series resistance
R_{sh}: Shunt resistance
V_t: Thermal voltage
$a.$: Diode quality factor
K: Boltzmann's constant
q: electron Charge
N_s: Number of cells in series
V: Output voltage of PV cell
T: Temperature
$P_{\max}$: Maximum power of PV cell
V_{mpp}: Voltage at maximum power
I_{mpp}: Current at maximum
V_{oc}: Open circuit voltage
I_{sc}: Short circuit voltage

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