Strategies for Enhancing Photovoltaic System Efficiency Under Partial Shading Conditions

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***Abstract*— Partial shading in photovoltaic (PV) systems, caused by factors like clouds, trees, buildings, or dirt, can significantly diminish power output and overall system efficiency. Traditional PV setups face challenges such as mismatch losses and the limitations of bypass diodes, particularly under uneven irradiance. This paper investigates the mitigating effects and advanced methods to counteract the negative impacts of partial shading. Key strategies include optimizing through maximum power point tracking (MPPT) algorithms, employing system design techniques such as Series Parallel (SP) reconfiguration. This paper presents work explores a combination of optimized array configurations to mitigate shading impacts by using the simulation results of MATLAB/SIMULINK. The investigation underscores the importance of hybrid configuration solutions to enhance solar energy harvesting in sub-optimal environmental conditions. Optimal PV array interconnections by using the combination of (SP), when rows, columns, corners and diagonally partially shaded simulation results demonstrate the performance when these strategies are implemented.**

Keywords* — *energy efficiency, photovoltaic effect, partial shading, maximum power point tracking, TCT, SP topologies, differential power processing (DPP)

I. Introduction

World is finding new techniques to overcome the scarcity of power, efficient and environmentally friendly energy alternates, renewable energy sources are at forefront of the research. Furthermore, renewable energy will not run out, whereas current sources of energy are being depleted. Nevertheless, the renewable technologies are cleaner and have lower environmental impact in comparison to other available sources of technologies. Thus, there is a huge future potential, especially within the research area of solar system. The research on PV Technology for Sustainability, Energy, & Environment in the discipline of Electrical & Electronic Engineering will not only be beneficial to potential customers to overcome the scarcity of power with an alternate system, but also it will incentivized the investors to capitalize the financial feasibility. Furthermore, the extensive usage of MATLAB simulation package during the research will enhance the skills which will be a steppingstone of the research.

Fig. 1. demonstrates energy flows from the solar panel to the charge controller, then to the battery. From the battery, energy can either go directly to a DC load or through the inverter to an AC load.

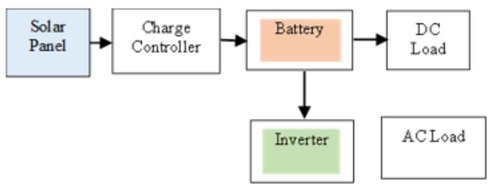

Fig. 1. Basic block diagram of solar power system [1].

This study optimize the array of configurations to understand the adverse effects of partial shading. Through extensive computer simulations, the research highlights the advantages of hardware-based design strategies. Furthermore, the incorporation of various partial shading predicts and analyse a system performance under uniform and non-uniform irradiance.

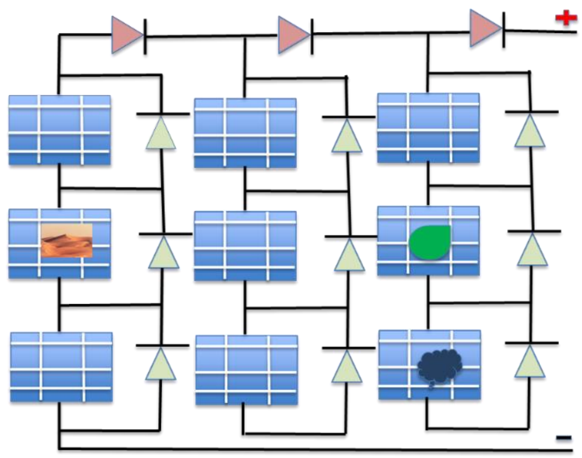

Fig.2. PV array in series parallel combination with bypass and blocking diodes under uniform and non-uniform irradiance [3] .

Fig.2 illustrates the effect of different types of partial shading on a 3x3 solar PV array. Each row in the image shows a distinct type of obstruction or environmental factor that causes partial shading, leading to uneven energy production across the solar panels. Each obstacle (sand, leaf, cloud) represents a real-world environment that causes non-uniform irradiance [2]. Shaded cells/panels act as bottlenecks, which may trigger hot spots or reduce the overall efficiency. This type of analysis is crucial for MPPT (Maximum Power Point Tracking) and reconfiguration strategies in PV systems. First row represents the ideal condition where each panel receives uniform irradiance, which means that there is no shading and no mismatch in output, hence it generates maximum power generation. Furthermore there are blocking diodes in brown colour to prevent the reverse current flow from the battery or from the load into the solar panel during night time when the panel is not generating power. Moreover, green diodes works as a bypass to maintain the energy production even during the partial shading.

II. LITERATURE REVIEW

A. Existing Solutions

A. Existing Solutions

Shading not only affects the photo voltaic (PV) output, but also generates heat[4]. The heat is generated due to the underperforming module. According to some experts, homeowners could be losing as much as 40 percent of the potential output of their solar PV installation because of shade. Just 10 percent shading of a solar PV panel can result in a 50 percent decline in efficiency according to some reports [5]. This is due to the way the solar cells in an array are connected within the system. Traditional solar panel arrays are connected in a series of parallel 'strings'. If one array is affected by shade, then the losses are passed onto the rest of the chain of cells. Thus, a solar panel changes from being an electrical generator to an electrical load. This means that instead of producing power, it consumes power. Shaded panel starts drawing power from other panels in the string and therefore pulls down the output of the whole channel.

To prevent all the cells failing completely, the designer usually includes bypass diodes. These then reroute the current, bypassing the underperforming cells [6]. Bypass diodes are a very simple circuit with a very low accuracy. They tend to operate on a threshold of around 20-30 percent and are aimed more at ensuring safety more than any attempt at increasing system efficiency. A traditional solar system consists of a string inverter and one or more strings. These strings are highly susceptible to mismatch issues between the panels, which may also be caused by manufacturer tolerances, shading, or soiling [7].

Photovoltaic (PV) cells or modules connected in series for the higher voltages required by the applications but experience severe power decrease due to mismatch in the PV cell's electrical characteristics. Thus, developing new techniques and control methods are required to enable PV arrays to achieve high efficiency and power output, under partial shading conditions (PSCs) with low cost.

Various array configurations have been discussed [8] to understand the effects of partial shading on PV arrays by interconnecting the PV modules in different ways, forming numerous arrays. Active research has been pursued in a conventional configurations include Series (S), Parallel (P), Total-Cross-Tied (TCT), Bridge-Linked (BL), and Honey-Comb [9-11]. Recent research has compared the performance of new variants under partial shading. It has been found that parallel arrays are more resistant to shading effects and less susceptible to mismatching losses than other arrangements . However, their low output voltage may render them impractical. In contrast, series connections of PV modules are highly vulnerable to significant power loss due to mismatching effects. Therefore, mixed Series and Parallel (SP) connections have been simulated as demonstrated in the section of results & discussions.

Photovoltaic systems are highly sensitive to partial shading, which leads to reduced power output due to mismatch losses and local maxima in the power-voltage curve. Traditional MPPT algorithms, such as Perturb & Observe (P&O) and Incremental Conductance (INC), often fail to identify the global maximum under these conditions. Recent studies have explored advanced MPPT techniques, including Particle Swarm Optimization (PSO), Genetic Algorithms (GA), and Artificial Neural Networks (ANN), each demonstrating improved tracking accuracy. Additionally, alternative array configurations such as Total Cross Tied (TCT) and Sudoku layouts have been discussed to minimize shading losses [4].

Partial shading mitigation methods fall into three main categories. Array interconnection methods aim to spread out shading effects. Reconfiguration strategies adapt the layout to minimize shading losses and Integration of power electronic converters, MPPT algorithms and Differential power processing (DPP) enhance energy harvesting from partially shaded panels. Summarized below are various approaches for mitigating partial shading effects:

1) Optimal PV Array Interconnections

- Traditional:
  - o Series (S)
  - o Parallel (P)
  - o Series-Parallel (SP)
  - o Total-Cross-Ties (TCT)
  - o Bridge-Linked (BL)
  - o Honey-Comb (HC)
- Hybrid:
  - o SP-TCT
  - o BL-TCT
  - o BL-HC

2) Reconfiguration Strategies of PV Array

- Dynamic Reconfiguration:
  - o Electrical Array Reconfiguration (EAR)
  - o Adaptive Array Reconfiguration (AAR)
  - o Irradiance Equalisation (IE)
- Static Reconfiguration:
  - o Sudoku
  - o Dominance Square
  - o Competence Square
  - o Zig Zag
  - o Magic Square
  - o SDP-Area Dispersion
  - o Odd-Even
  - o Fibonacci

o Skyscraper

3) Integration of Power Electronic Converters

- Full Power Processing (FPP):

o Centralised System

o Module Integrated Converters (MIC)

o Distributed Series MICs

o Distributed Parallel MICs

o Distributed Sub-MICs System

- Differential Power Processing (DPP):

o Series DPP

o Parallel DPP

o Series-Parallel DPP

- MPPT Control Algorithms:

o Perturb & Observe (P&O)

o Particle Swarm Optimisation (PSO)

o Fuzzy Logic Controller (FLC)

o Artificial Neural Network

B. *Research Gap*

Although PSO-based MPPT has demonstrated superior results compared to traditional methods, there is limited research on its performance when combined with reconfigured array topologies, such as Sudoku or Magic Square, under varying shading conditions. This study seeks to delve deeper into this hybrid approach. Furthermore, integrated solution combining intelligent MPPT algorithms with dynamic reconfiguration remain limited, particularly under real-world shading patterns.

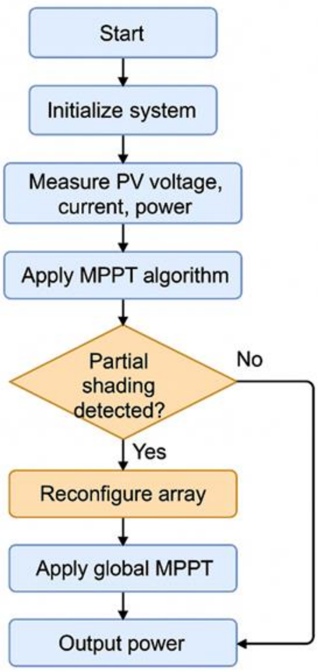

Fig. 3. Flow chart of extracting maximum power

III. MTHODOLOGY

The methodology outlines the approach to solve the problem, with the techniques or tools employed, and the evaluation process. For a PV system experiencing partial shading, this includes designing the PV system, implementing mitigation strategies, and assessing system performance through simulations.

Fig. 3 of flow chart outlines the process of managing a photovoltaic (PV) system with Maximum Power Point Tracking (MPPT).

1. Start: The process begins.
2. Initialize System: PV system set up and ensure all components are ready for operation.
3. Measure PV Voltage, Current, Power: Monitor and measure the voltage, current, and power output continuously.
4. Apply MPPT Algorithm: Use the MPPT algorithm to optimize the power output by adjusting the operating point.
5. Partial Shading Detected?: Check if partial shading is affecting the PV system.
   - If No: Return to step 3 and continue measuring PV voltage, current, and power.
   - If Yes: Proceed to step 6.
6. Reconfigure Array: Adjust the configuration of the PV array to mitigate the effects of shading.
7. Apply Global MPPT: Implement a global MPPT algorithm to optimize the power output for the reconfigured array.
8. Output Power: The optimized power output is delivered to the load.

This flow chart helps to maintain the power optimization of the PV system without the user's intervention, despite the changes of shading, by updating the system configuration and operation point all the time. However, this is an overall flow chart according to a general MPPT method, and the other switching will be used to realize a global MPPT to escape local MPP.

A. *Shading Scenario of various Array Reconfiguration Techniques to analyze partial shading*

To reduce mismatch loss, different array configurations are tested: Series, Parallel, Series-Parallel (SP) are being considered as a baseline model, Diagonal shading, Corner Shading. The array of configurations demonstrate different shading impact. Each configuration is compared under identical shading patterns.

Various shading patterns are simulated: Uniform shading, Series patch shading, Parallel patch, Series Parallel (SP) patch shading, Diagonal shading and Corner shading. These are applied to a 3x3 array layout. The effect is observed on the I-V and P-V characteristics. A Ablytek 6PN6A225-A0 solar panel is being utilized in this study, and the electrical characteristics are shown in Table 1.

B. *Simulation Setup*

- Number of modules 9 (3x3 array)
- Irradiance1000 W/m² (unshaded), varies for shaded
- Temperature 25°C (STC)
- SoftwareMATLAB/SIMULINK (2021b)
- Simulation Time 10s real-time equivalent

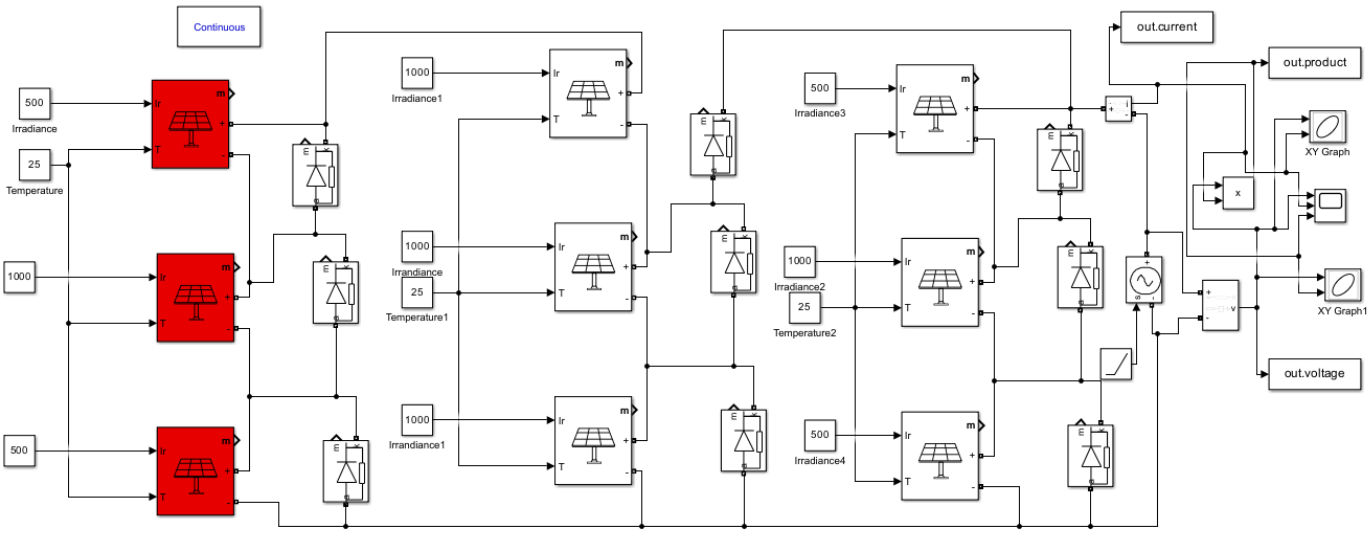

Fig. 4 A matrix of 3 x 3 array simulation.

TABLE I Electrical parameters of the Ablytek 6PN6A225-A0

Maximum Power P mpp	224.9856 W
Short Circuit Voltage Voc	36.24 V
Voltage at MP Vmpp	30.24 V
Short Circuit Current I sc	8.04 A
Current at MP I mpp	7.44 A
No. of Cells Ns	60
Shunt resistance	136.1896 Ω
Series resistance	0.19316 Ω

IV. RESULTS & DISCUSSIONS

Fig. 4. shows a MATLAB/Simulink model simulating a solar photovoltaic (PV) array under partial shading conditions with multiple irradiance.. The model is divided into three PV sub-arrays, each with different irradiance inputs, representing partial shading scenarios: Left section (sub-array 1) with irradiance of 1000 W/m^2, temperature of 25 ℃. Each PV modules are connected in a series parallel configuration. Middle section (sub-array 2) with irradiance of 800 W/m^2, simulating partial shading, temperature = 25 ℃ , and connected again in series parallel configuration, whereas right section (sub-array 3) with irradiance of 200 W/m^2 representing a heavy shading section. All these sub-arrays are connected are combined to DC output currents and voltages to create a non-linear I-V and P-V characteristics due to shading. These values are plotted on XY graphs to visualize the I-V and P-V curves as demonstrated below.

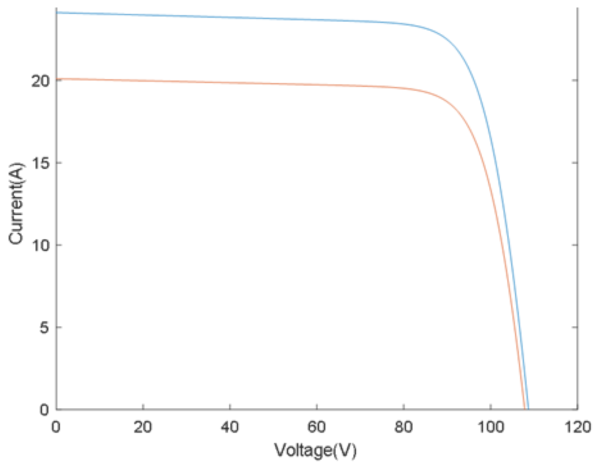

Fig. 5. IV curve of unshaded (blue) , shaded (orange) first column with 500 W/m^2.

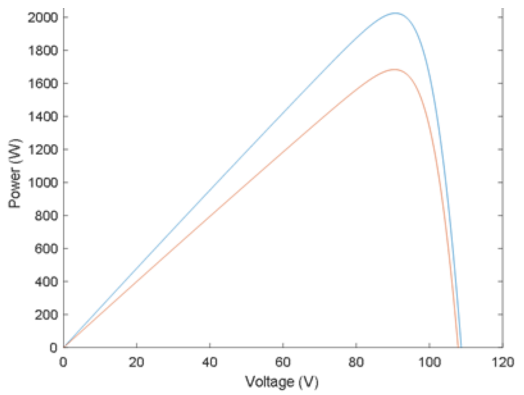

Fig. 6. PV curve of unshaded (blue), shaded (orange) first column with 500 W/m^2.

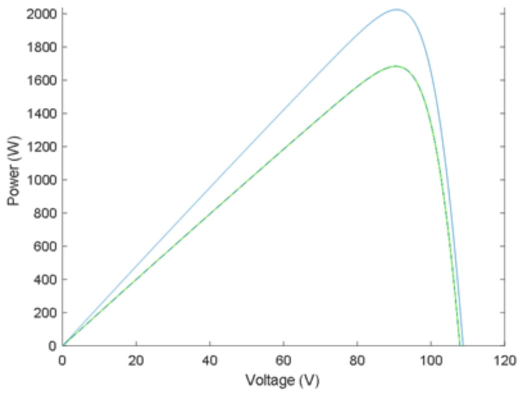

Fig. 7 PV curves unshaded (blue), superimposed (green) 1st, 2nd 3rd columns 500 W/m^2.

Fig. 5, 6 and 7. show Current–Voltage (I-V) and Power-Voltage (P-V) characteristics of a solar photovoltaic (PV) array under two different conditions corresponding to uniform irradiance vs partial shading. This demonstrates the effect of shading when columns are shaded. The blue curve represents the PV array under uniform sunlight (1000 W/m² across all panels). The power increases with voltage, peaks near 90–100 V, and then drops sharply. This curve shows the Maximum Power Point (MPP) under ideal conditions. Green curve the represents partial shading. Additionally simulation illustrates that partial shading reduces considerably the output power of a PV array.

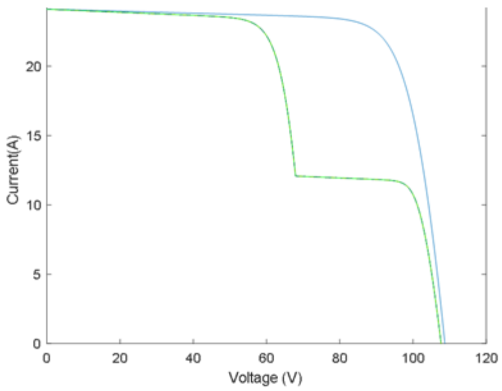

Fig. 8. IV curves unshaded (blue), superimposed shaded (green) 1st, 2nd 3rd rows.

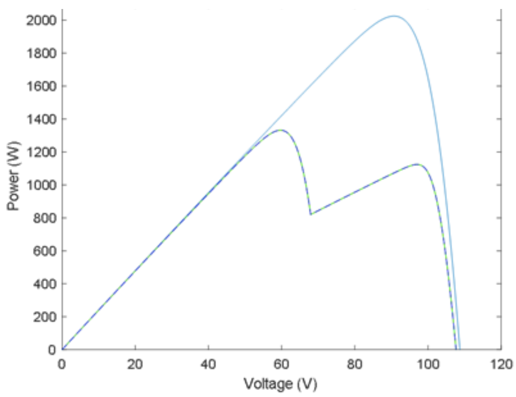

Fig. 9. PV curves unshaded (blue), superimposed (dashed) shaded 1st, 2nd, 3rd rows.

Fig. 8, & 9. Show Current–Voltage (I-V) and Power-Voltage (P–V) characteristic curves of a photovoltaic (PV) array under partial shading, where multiple peaks are visible, and demonstrates a classic example of complex partial shading conditions. Without intelligent MPPT, the system may stuck at the local peak and miss the global peak, leading to significant power loss. The blue curve (PV array output) increases in power with voltage under uniform irradiance. Nevertheless, there is a clear dip followed by a second rise, forming two distinct power peaks under a non-uniform irradiance of dotted curve. This is indicative of partial shading, where mismatched irradiance across PV modules causes multiple local maxima. The higher peak (~2000 W) is the Global Maximum Power Point (GMPP). The lower peak (~1400 W at ~65–70 V) is a Local Maximum Power Point (LMPP) caused by shaded sections of the array.

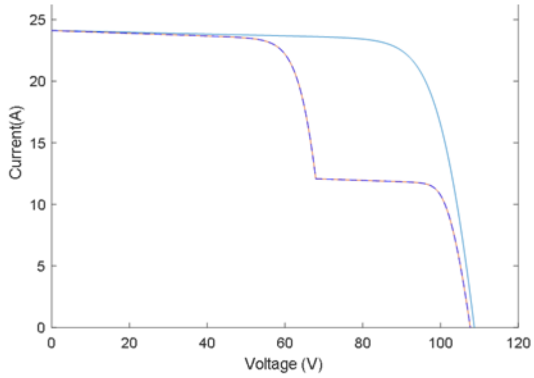

Fig. 10. IV Curves unshaded (blue), superimposed shaded (dotted) diagonally.

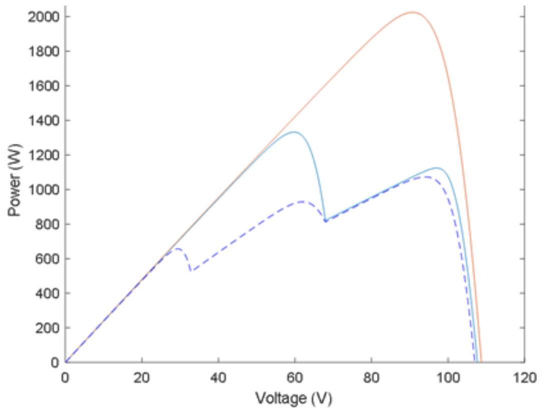

Fig. 11. PV curves unshaded (orange), superimposed shaded (blue &dotted) diagonally both ways 500 W/m^2.

Fig. 10 compares two IV curves under uniform and non-uniform irradiance, and Fig. 11. shows a PV curve with three different plots. The x-axis represents Voltage (V) ranging from 0 to 120 V, and the y-axis represents Power (W) ranging from 0 to 2000 W. The image provided shows a graph comparing the performance of a photovoltaic (PV) system under different shading conditions. Orange curve represents the unshaded PV performance. Blue solid curve represents the PV performance under diagonal shading at 500 W/m². Blue dashed curve represents another diagonal shading scenario at 500 W/m². Diagonal shading reduces the power output compared to the unshaded scenario.

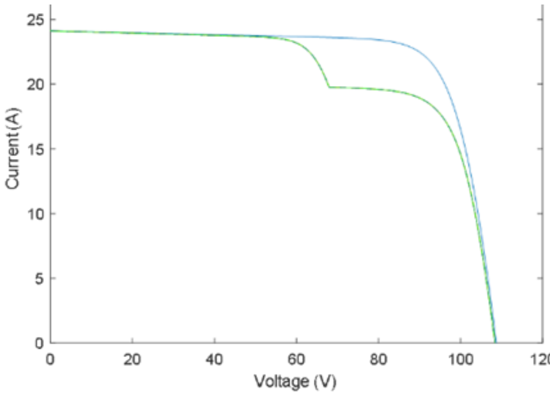

Fig. 12. IV curves unshaded, superimposed 4 corners shaded 500 W/m².

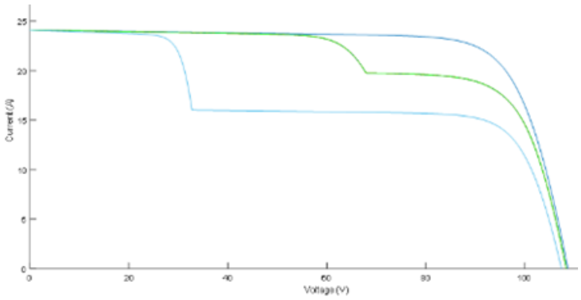

Fig.13. IV curves, unshaded (blue), superimposed (blue dotted) 4 corners and one corner (green dotted) each altogether 500 W/m ² .

Fig.13. the blue curve shows the IV characteristics of the PV system when it is unshaded. Green curve represents the IV characteristics when the PV system is shaded at four corners, either all together or one by one. Voltage (V) on x-axis shows the voltage range from 0 to 120 V. Current (A) represents the y-axis shows the current range from 0 to 30 A. Shading reduces the current output at a given voltage, as shown in the lower green curve compared to the blue curve. Different shading patterns (all corners together vs. one by one) affect the PV system's performance differently, moreover, 500 W/m² indicates the irradiance level used in the simulation.

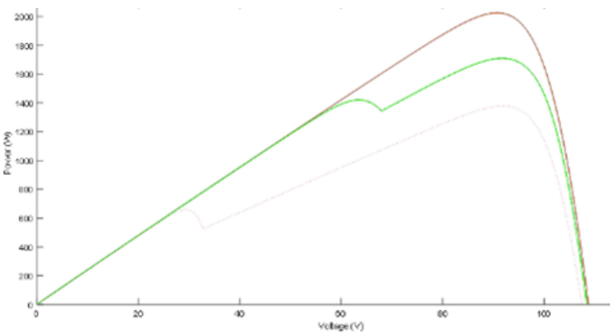

Fig. 14.PV curves unshaded (orange), superimposed one corner (green) and four corners (orange dotted) altogether 500 W/m².

Fig. 14. represents the PV performance without any shading. Superimposed one corner shaded shows the PV performance when one corner of the PV module is shaded. Four corners shaded altogether represents the PV performance when all four corners of the PV module are shaded. The irradiance of 500 W/m² used in the simulation. Different shading patterns (one corner vs. four corners) affect the PV system's performance significantly diminishing the output power of a PV array.

Partial shading significantly affects the performance of photovoltaic (PV) arrays by reducing overall power output, thus creating multiple local maxima in the power-voltage (P–V) characteristic curve potentially misleading traditional MPPT algorithms to lock onto a local maximum rather than the global maximum power point (GMPP) This leads to inefficiency and energy losses, especially in large or urban PV installations where shadows are common.

V. Conclusion

Partial shading has a dramatic effect on the output power and overall efficiency of the photovoltaic (PV) system. In this study, shading options are investigated, and it shows the negative impact of shading. However, optimized arrays and conventional MPPT screw potential load-curve scanning. Regarding the above case scenario, the algorithm scan on one local peak and it does not consider multiple peak and only count on one peak and that peak may not be maximum local peak. Furthermore, traditional setups, limited by mismatch losses and bypass diode constraints, often fail to perform efficiently under non-uniform irradiance. Nevertheless, switches and sensors will be used to overcome partial shading. The P&O method operates on a trial-and-error basis, whereas the Fuzzy Logic Controller is an intelligent control strategy. While both have their respective advantages and disadvantages, the latter will be used for tracking the global maximum power point

Simulation results from MATLAB/SIMULINK demonstrate Series-Parallel (SP) reconfiguration of hardware-level solutions (layout), when intelligently applied under complex shading scenarios such as row-wise, column-wise, diagonal, and corner shading offers substantial improvements in energy harvesting. Hybrid designs of hardware-level and combination of software-level intelligence smart MPPT control reduce the impact of localized shading without major changes.

This provides a cost-effective way to boost PV system reliability and output. The proposed techniques are adaptable and scalable to various real-world scenarios. These findings offer valuable insights for future PV system design under partial shading. Further simulation/experimental validation and field implementation are recommended for broader adoption.

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