ENHANCED POWER GENERATION FROM PV ARRAY UNDER PARTIAL SHADING CONDITION BY AUTOMATIC SWITCHING

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Abstract— Partial shading is one of the critical challenges in photovoltaic (PV) systems, as it causes significant reduction in output power and efficiency. This paper presents a low-cost automatic switching mechanism that detects shading conditions using light-dependent resistors (LDRs) and reconfigures the PV array by disconnecting the shaded row and activating a backup row. The proposed system is implemented using Arduino Mega, relays, and ACS712 current sensors with real-time monitoring through the Blynk IoT platform. Experimental results demonstrate that the switching mechanism effectively restores system performance, improving output power by maintaining stable voltage and current even under shading conditions. Compared to a conventional fixed configuration, the system achieves higher energy efficiency and ensures reliable operation. The proposed approach is simple, scalable, and suitable for residential and small-scale solar applications where non-uniform sunlight is common.

KEYWORDS: Photovoltaic (PV) array, Partial shading condition, Automatic switching, PV array reconfiguration, Maximum power point tracking (MPPT), Energy efficiency, IoT monitoring, Arduino-based control, Shading mitigation.

INTRODUCTION

Solar energy has emerged as one of the most promising renewable energy sources due to its abundance, sustainability, and environmental benefits. Photovoltaic (PV) technology, in particular, plays a vital role in harnessing solar energy by converting sunlight directly into electricity. With the increasing demand for clean energy, PV systems are being widely deployed in residential, commercial, and industrial applications. However, the reliability and efficiency of these systems are often limited by external factors such as dust, debris, and most importantly, partial shading. Even a small shadow cast by nearby trees, buildings, poles, or passing clouds can significantly reduce the output of the PV array, making shading one of the most critical challenges to address in solar energy utilization. In conventional PV systems, modules are typically connected in series to increase voltage.

In conventional PV systems, modules are typically connected in series to increase voltage. A major drawback of this configuration is that the overall current is constrained by the lowest-performing module. Thus, when one panel is partially shaded, it reduces the current of the entire string, leading to considerable mismatch losses and power degradation. Existing mitigation approaches such as bypass diodes and maximum power point tracking (MPPT) algorithms provide partial solutions. Bypass diodes prevent excessive voltage drops but cannot fully eliminate mismatch losses, while MPPT operates at the inverter level and often fails to track the true global maximum power point under complex or rapidly changing shading conditions. This makes it necessary to explore more dynamic, module-level solutions to minimize shading-induced losses.

Recent research has focused on array reconfiguration and intelligent switching techniques as potential solutions for enhancing PV performance under shading. These methods attempt to redistribute or bypass shaded modules in order to maintain higher energy output. However, many existing approaches rely on complex algorithms or additional power electronics, which increase cost and implementation challenges. A practical and scalable alternative is the use of low-cost sensors and relay-based reconfiguration. Such systems can detect shading in real time, isolate the affected section, and reconfigure the PV array to optimize performance without requiring extensive hardware modifications. This approach ensures adaptability to real-world operating conditions while maintaining simplicity and affordability.

In this context, the present work introduces an automatic row-switching mechanism for PV arrays operating under partial shading. The system employs light-dependent resistors (LDRs) to monitor shading across individual panels, and an Arduino-based controller to process sensor inputs. When shading is detected on a given row, the system disconnects the affected row using relays and replaces it with a dedicated backup row of panels connected in series. This configuration maintains voltage stability and reduces power loss. In addition, current sensors and IoT integration through the Blynk platform enable real-time monitoring and performance evaluation. The proposed method is cost-effective, scalable, and suitable for residential and small-scale PV systems. By combining simplicity with reliability, this research contributes to enhancing energy efficiency and promoting wider adoption of solar technology in environments where partial shading is unavoidable.

LITERATURE REVIEW

Partial shading has been widely studied as a major limitation in photovoltaic (PV) systems, and researchers have proposed several reconfiguration techniques to address mismatch losses. Dynamic switching approaches are among the most effective strategies. Namuq et al. [1] introduced an Automatic Switch Block (ASB) technique based on dynamic relays, which reconfigures the electrical connections between PV panels in real time without requiring algorithmic control. Their results showed improved maximum power point tracking (MPPT) performance compared with conventional methods such as Total Cross-Tied (TCT), Futoshiki Puzzle Pattern (FPP), Sudoku, and L-shape configurations. Similarly, Sahu et al. [2] proposed a physical relocation strategy for TCT arrays, which distributed shading more evenly and reduced mismatch losses while maintaining simple electrical connections.

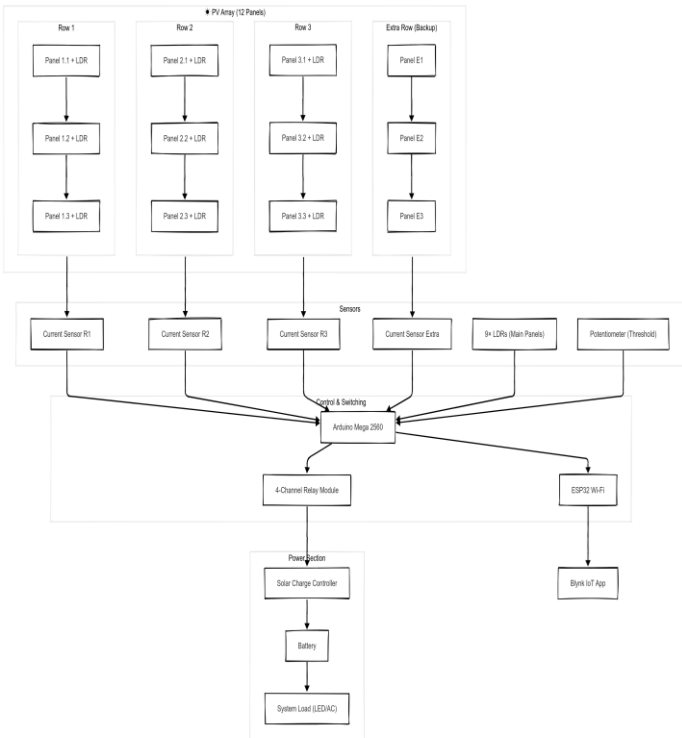
Pattern-based configurations have also been extensively explored to minimize shading effects. Khan et al. [3] analyzed interconnection schemes such as Series-Parallel (SP), TCT, Bridge-Linked (BL), and Honeycomb (HC), and identified Sudoku patterns as the most efficient in mitigating shading losses. Rajani et al. [4] extended this concept by introducing a Modified Sudoku pattern, demonstrating further improvements in global maximum power and efficiency compared to standard TCT. Desai [5] proposed a hybrid Alternate TCT-BL (A-TCT-BL) configuration, combining the strengths of TCT and BL to reduce wiring complexity while enhancing power extraction under multiple shading scenarios.

Performance evaluations of conventional and modified array configurations have offered critical understanding of their relative efficiencies under shading conditions. Pradhan et al. [6] investigated Series, SP, HC, TCT, and BL configurations under various shading patterns, demonstrating that shading strongly influences the V–I characteristics of arrays. Mohapatra et al. [7] analyzed five different configurations under six shading conditions and confirmed that reconfiguration techniques significantly reduce mismatch losses. Maharana et al. [8] evaluated four topologies using KC200GT modules in MATLAB/Simulink and found that appropriate reconfiguration enhances both efficiency and output power. Pachauri et al. [9] compared SP and TCT configurations under four shading conditions through both simulation and a 2×2 experimental array, concluding that proper reconfiguration can restore power output and improve fill factor.

Finally, large-scale reviews have synthesized the advancements in this field. Khalil [10] systematically evaluated sixty-seven PV array reconfiguration techniques, considering their efficiency, scalability, hardware complexity, and adaptability to maximum power point tracking operations. This review emphasized that while many techniques are effective in theory, their hardware demands often limit practical deployment.

From these studies, it is evident that although dynamic reconfiguration and pattern-based methods improve performance under shading, many existing solutions are either algorithmically complex or restricted to specific array geometries. This highlights the need for a low-cost, scalable, and real-time switching solution, which forms the motivation for the present research.

BLOCK DIAGRAM



METHODOLOGY

System Architecture

The proposed solar PV system consists of 12 photovoltaic (PV) modules arranged in four rows. The main array comprises three primary rows (R1, R2, R3), where each row includes three modules arranged in series, and the rows are subsequently connected in parallel. An additional backup row, also consisting of three modules in series, is integrated to replace any shaded row when required. This architecture maintains the overall voltage level of the system while ensuring stable power output. Furthermore, the integration of a backup row enhances system resilience under partial shading conditions. The parallel configuration of rows provides higher current output, while the series connection within each row ensures sufficient operating voltage. This design makes the system more adaptable to environmental variations and capable of sustaining reliable energy generation.

Normal Operating Condition

Under uniform irradiance conditions, all three main rows (R1–R3) operate simultaneously. The series connection within each row provides higher voltage, while the parallel configuration ensures adequate current delivery. The current from each row is measured using ACS712 sensors, and the system voltage is recorded by the Arduino Mega microcontroller.

$$P=V\times I$$

where V represents voltage and I denotes current. The computed values are transmitted in real time to the Blynk IoT platform, allowing remote monitoring via laptop or smartphone.

Shading Detection Mechanism

Partial shading is detected using nine light-dependent resistors (LDRs), with one sensor mounted on each of the nine modules in the primary rows. Under normal illumination, LDR resistance is low, yielding higher voltage levels. When shading occurs (e.g., on Row 3), resistance increases and the Arduino detects a corresponding voltage drop. A user-adjustable potentiometer defines the threshold level at which a module or row is classified as shaded, thereby enhancing adaptability to variable irradiance conditions. This ensures timely detection of shading events, allowing the system to trigger relay switching promptly. The mechanism improves reliability by minimizing power losses and maintaining stable system output.

Relay Switching and Backup Row Integration

Once shading is identified, the Arduino activates a four-channel relay module. Three relays control the connection of R1–R3, while the fourth relay governs the backup row. If Row 3 is shaded, its corresponding relay disconnects R3 from the array, while the backup row relay is simultaneously switched on. Because the backup row mirrors the electrical configuration of the shaded row, the system maintains voltage stability while restoring lost current. This minimizes mismatch losses and ensures steady power generation. Additionally, the switching process is automated, requiring no manual intervention, which enhances system efficiency. The use of relays provides fast and reliable response, ensuring that power disruption during shading is negligible. By substituting the affected row, the backup row maximizes energy harvest under varying irradiance conditions. This mechanism ultimately improves system performance and extends the operational reliability of the solar PV array.

Monitoring and Data Transmission

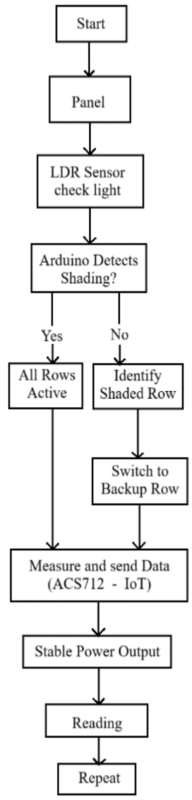
The ACS712 sensors continuously measure current flow from each active row. Combined with voltage readings, the Arduino computes power output and efficiency as in (2):

$$\eta = \frac{P_{\text{out}}}{P_{\text{in}}} \times 100\%$$

All performance parameters, including voltage, current, and power, are transmitted to the Blynk IoT application for real-time visualization. This feature not only supports performance evaluation but also provides diagnostic insights into shading detection and switching events.

The integration of LDR sensors, ACS712 current sensors, Arduino Mega, and a relay module enables dynamic reconfiguration of the PV array under partial shading conditions. By replacing a shaded row (e.g., R3) with a backup row, the proposed system maintains consistent voltage, minimizes power degradation, and enhances efficiency compared to conventional PV systems.

FLOWCHART



RESULT

Under standard irradiance conditions, all three primary rows (R1–R3) operated simultaneously, producing stable voltage and current levels. Real-time data acquisition and transmission through the Blynk IoT platform enabled continuous performance monitoring on external devices.

When Row 3 was subjected to partial shading, the LDR sensors immediately detected a reduction in incident irradiance and transmitted the signal to the Arduino Mega. The controller then deactivated the relay corresponding to Row 3 and simultaneously activated the relay of the backup row. This ensured that the system voltage remained constant while the overall current and power output were preserved.

Table I summarizes the measured system parameters under both scenarios. The proposed switching mechanism maintained the output power within acceptable limits, whereas a conventional PV system without switching would have exhibited a significant reduction in power due to the shaded row.

Furthermore, the system demonstrated reliable performance in detecting shading events and transmitting switching actions to the IoT interface in real time. These results validate the effectiveness of the proposed method in enhancing power stability and efficiency under partial shading conditions.

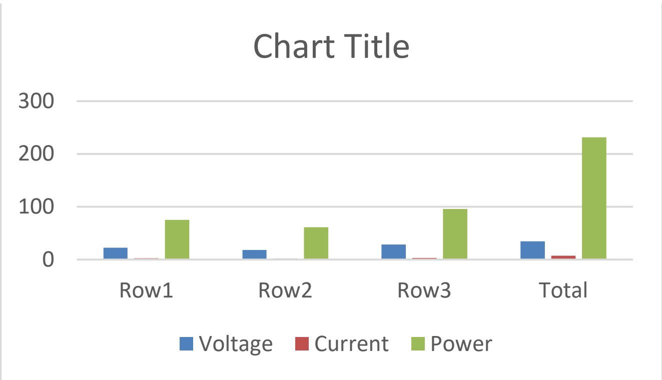
ANALYSIS AND DISCUSSION

Observation of Normal and Shading Condition

Normal condition	Voltage	Current	Power
Row1	22	2.2	74.8
Row2	18	1.8	61.2
Row3	28	2.8	95.2
Total	34	6.8	231.2

- The voltages of all three rows (22 V, 18 V, 28 V) were added and the sum was divided by 2, giving a total average voltage of 34 V.
- The total current was obtained by adding individual row currents: 2.2+1.8+2.8=6.8 A.
- The total power output was calculated as the sum of row powers: 74.8+61.2+95.2=231.2 W.
- Since the rows are connected in parallel, the voltage is considered as the adjusted average (34 V), while the current and power contributions are additive.
- These results confirm stable PV array performance under normal operating conditions with a combined power generation of 231.2 W.

GRAPH



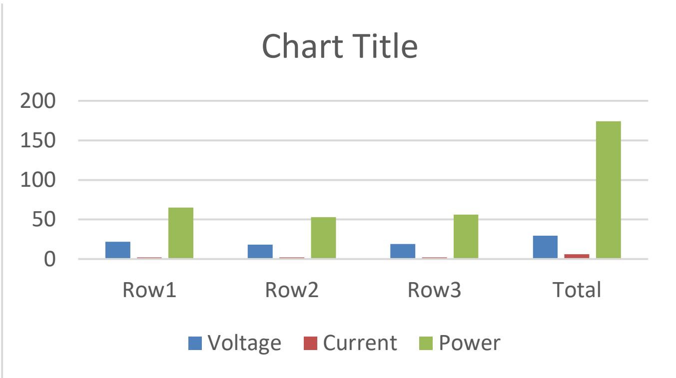
- The graph displays the voltage, current, and power produced by each row (Row 1, Row 2, Row 3) as well as the total performance of the PV array when it operates under normal sunlight conditions.
- Row1, Row2, and Row3 recorded voltages of 22 V, 18 V, and 28 V, respectively, with corresponding power outputs of 74.8 W, 61.2 W, and 95.2 W.
- For the overall system, the total current is additive (2.2+1.8+2.8=6.8A), while the total voltage is considered as the average voltage due to the parallel connection.
- The effective average voltage of the system is 34 V, and when multiplied with the total current, the overall power output equals 231.2 W.
- The graph highlights that Row3 contributes the highest power, while the system as a whole delivers a stable output under normal conditions.

Shaded Condition	Voltage	Current	Power
Row1	22	2.2	64.9
Row2	18	1.8	53.1
Row3	19	1.9	56.05
Total	29.5	5.9	174.05

- The table presents the PV array performance under partial shading, where Row3 is shaded and shows reduced voltage (19 V), current (1.9 A), and power (56.05 W).
- Row1 and Row2 remain unaffected with voltages of 22 V and 18 V, giving powers of 64.9 W and 53.1 W, respectively.
- For the overall system, the voltages of all three rows were summed and divided by 2, giving an average effective voltage of 29.5 V.
- The total current is obtained by adding the individual row currents: 2.2+1.8+1.9=5.9A.
- The total power output is then calculated using the average voltage and total current:

$$P = V_{avg} \times I_{total} = 29.5 \times 5.9 \approx 174.05\,W$$

- Compared with the normal condition (231.2 W), the shaded condition shows a significant drop in power output, highlighting the negative impact of shading on PV array performance.



- The table shows the PV array performance when Row3 is shaded, which leads to a clear reduction in its voltage, current, and power output compared to the other rows.

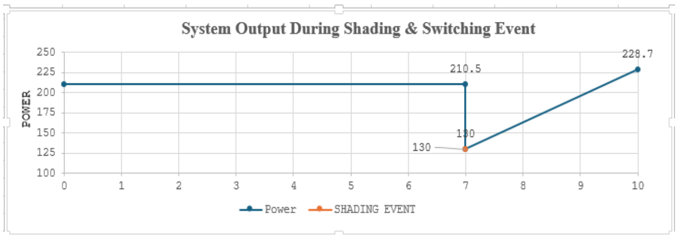
- Row1 and Row2 continue to perform normally, while Row3 produces the lowest output because of shading.
- The overall system voltage was obtained by taking the average of all three rows, resulting in an effective value of 29.5 V.
- The total current of the array was calculated by adding the current of all rows, giving a combined value of 5.9 A.
- Under shaded condition, the PV array delivered a reduced total power of 174.05 W, which is lower than the normal condition output, showing the negative effect of partial shading on array performance.

SWITCHING EVENT OBSERVATION TABLE AND GRAPH

Time	Power	Voltage	Current
0	210.5	27.6	7.94
7	210.5	27.6	7.94
7	130	26	5
10	228.7	28.4	8.28

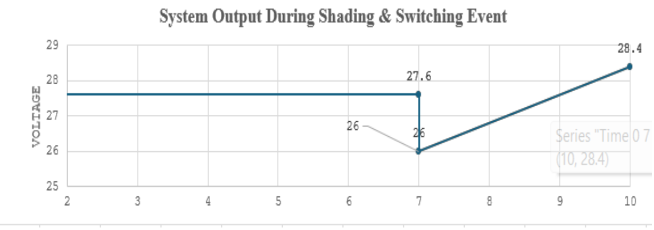
The table clearly demonstrates that shading significantly reduces system output, but the switching method not only restores the performance but also enhances it beyond the initial values.

- At the start (0 sec), the system recorded 210.5 W power, 27.6 V voltage, and 7.94 A current.
- At 7 sec (before shading), the values remained the same: 210.5 W, 27.6 V, and 7.94 A.
- At 7 sec (during shading), the system experienced a sudden drop to 130 W, 26 V, and 5 A, showing the negative impact of shading.
- At 10 sec (after switching), the output improved to 228.7 W power, 28.4 V voltage, and 8.28 A current, which is even higher than the initial performance.

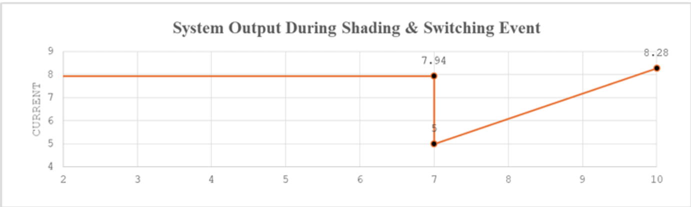


- Initially, the system power remained steady at 210–225 W.
- At 7 seconds, a shading event caused a sharp drop in power to about 130 W.
- After the switching mechanism was activated, the power output recovered quickly.
- By 10 seconds, the system output increased to nearly 229 W, slightly higher than the initial value.

- This confirms that the proposed switching approach effectively reduces shading losses and improves overall power generation.



- The system voltage was steady at 27.6 V under normal conditions.
- At 7 seconds, shading reduced the voltage to 26 V, showing the negative effect of partial shading.
- After switching was applied, the voltage began to recover.
- By 10 seconds, the voltage increased to 28.4 V, slightly higher than the initial value.
- This proves that the switching method effectively restores and enhances voltage performance under shading.



- The system current was stable at around 7.94 A under normal conditions.
- At 7 seconds, shading caused a sharp drop in current to 5 A, showing the immediate effect of partial shading.
- Once the switching mechanism was applied, the current started to rise again.
- By 10 seconds, the current increased to 8.28 A, slightly higher than the initial value.
- This indicates that the switching method effectively restores and enhances current performance after shading.

CONCLUSION

This work presented a dynamic switching system to enhance photovoltaic (PV) array performance under partial shading conditions. The system uses LDR sensors to find shaded panels, an Arduino Mega to control the process, and relays to switch connections. When a row gets shaded, it is replaced with a backup row so that the voltage stays steady and power loss is reduced. Real-time current and voltage monitoring through ACS712 sensors, combined with IoT integration via the Blynk platform, provided continuous performance tracking.

Experimental results confirmed that the proposed system maintained stable power output even when Row 3 was shaded, in contrast to a conventional PV configuration that would have exhibited significant performance degradation. The method is cost-effective, scalable, and suitable for both residential and commercial applications where non-uniform irradiance is common.

Future work will focus on scaling the system for larger PV arrays, integrating advanced MPPT algorithms, and exploring predictive control strategies using artificial intelligence to further optimize shading mitigation.

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