



INNOVATIVE TRANSITION UNIT FOR VOLTAGE REGULATION IN SOLAR PANEL SYSTEMS

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<https://doi.org/10.30572/2018/KJE/170122>

ABSTRACT

Partial shading continues to pose a substantial obstacle in photovoltaic (PV) systems, frequently resulting in substantial decreases in system efficiency and energy output. One of the techniques used to mitigate the effect of partial shading is the hierarchical dynamic reconfiguration. It is based the combination scheme of PV panels as the elemental building block. This paper, introduces a simple adaptive PV panel combiner called the Transition Unit (TU) to control the configuration of PV panels in real-time based on shading conditions. The proposed TU system is practically implemented and tested under different shading conditions. The results show that it is capable to produce a more stable and higher output as compared to conventional parallel combiner and microcontroller (MC) based systems by 21% and 6%, respectively. The TU system does not involve MCs and hence ignores hardware and software complexity, which emphasizes its significance with respect to MC based counterparts. Therefore, the proposed TU system can be considered as an effective and sustainable approach to enhance the efficiency of the PV systems subjected to partial shading.



KEYWORDS

Partial Shading, PV Systems, PV Configuration, MPPT, Adaptive Control.

1. INTRODUCTION

Clean energy, particularly solar-based energy, is a meaningful response to the increasing global energy dilemma. As the globe faces the negative implications of fossil fuel dependency, such as environmental pollution and climate change, the move to cleaner, renewable energy resources becoming more crucial. Solar energy sources like a PV, in particular, provides a widely available and sustainable source of power, which is essential for lowering carbon emissions levels and supplying energy to remote places (Al-Jabari et al., 2022). The development of solar-based energy techniques, such as photovoltaic panels for electricity production and solar-powered irrigation systems for desert farming, shows how solar-based energy may be used to respond to major concerns in both energy and water scarcity (Ghazi et al., 2021).

Solar-based power plants generate power using natural airflow, advancing a better future. To fully realise the potential of renewable energy and drive global sustainable development, it is critical to address the sector's problems, particularly efficiency and affordability (Abbood and Abbas, 2021). These systems are beneficial in tapping solar based energy, which is stated to be plentiful, clean and renewable. However, certain environmental variables may interfere with the performance of the PV technique depending on which location they are installed thus the variation in intensity of the sun, presence of shade and variations in temperature (Jakhongir Turakulugli, n.d.). Their presence may cause large variations in the direct current (DC) and voltage available from solar PV panels. This voltage is essential for efficient energy conversion procedures and for allowing the steady connection to power networks (Mekhilef et al., 2011). Traditional approaches like Maximum Power Point Tracking (MPPT) algorithms which include Perturb and Observe (P&O) beside the Incremental Conductance (IC), have been used in previous and many studies to enhance and increase power production (Dhanalakshmi and Rajasekar, 2018). However, these techniques do not give a steady voltage supply, which is very vital in many applications such as grid-connected inverters and power storage systems (Palpandian et al., 2021). Partial shadowing (PS) is one of the important overall difficulties and challenges encountered by PV-Panels systems. It happens when objects like high-buildings, trees or any formation block the sun light and directions from falling directly on the system of solar panel. This makes only one part or section of the PV panel receives direct sunlight while the other sections and parts is shaded (Pachauri et al., 2020). If not properly managed, these effects and factors can greatly reduce the capability of the whole system and may lead to cause damage to PV modules, including hot points (spot) formation etc (Bouselham et al., 2021). To address these challenges and difficulties, many different reconfiguration techniques have been

constructed with the intention of levelling the impact of shading across the area of the PV array as well as enhancing the output power particularly when the shading is partial (Bizon, 2016). Technological advances over the latest decade have made it capable to implement dynamic reconfiguration technologies that are able to altering the electrical connections between the PV panels on the fly (F. Ameen et al., 2024) This makes it capable to minimize the overall impacts of shading and optimizing the output power. These dynamic reconfiguration schemes entail the use of sensors, programmable logic controllers and complex switching matrices. Moreover, machine learning (ML) based algorithms are utilize to improve the decision making performance of dynamic reconfiguration. However, the performance improvement achieved by using these techniques is at the expense of rising system complexity in terms of hardware and software (Ameen et al., 2024). In addition, while focusing on maximizing output power, these systems show a variation in output voltage level (Siddiq et al., 2023). This issue can have negative effects of the efficiency of back up battery charging.

In this paper, a simple and yet efficient switching unit is proposed to control the connection of PV panels in order to produce output voltage with least variation. The proposed scheme dynamically reconfigurations the connection of the PV panels according to the imposed partial shading condition. It is designed to be simple so that its implementation avoids the use of programmable controllers and large number of switches as the case in conventional and ML-based schemes. The performance of the designed system, in terms of output voltage stability, is evaluated under non-uniform shading. It is compared with the elemental unit in PV arrays which is the parallel connection of PV panels. The results show the superiority of the designed system in maintaining less variation in output voltage.

The rest of this paper is organized as follows. Section 2 provides a review of similar works that are concerned with the dynamic reconfiguration of PV arrays. In Section 3, the model of the proposed system together with the design details and test methodology are presented. The practical implementation, tests, results and related discussions are presented in Section 4. Finally, Section 5 concludes the obtained finding and comments.

2. SIMILAR WORKS

For the problem of ensuring constant output voltage in PV systems under partial shading conditions, many works have analysed approaches based on dynamic reconfiguration techniques and high-level MPPT algorithms. In (Mohammad et al., 2020) a hierarchical reconfiguration model was introduced which applies Serial Parallel- Total Cross-Tied (SP-TCT) transformation together with a switching matrix that toggles the panel configuration. This approach has been known to provide an efficiency enhancement of up to 50% in large-scale PV

panels systems through decreasing mismatch losses at the expense of relatively high system complexity (Mao et al., 2020). As a simplify approach, the Automatic Switching Block (ASB) was introduced in (Namuq et al., 2023). The ASB adjusts the electrical inter-connections of photovoltaic panels by using relays to change connection status. The ASB technique is specifically useful for mitigating the effect of partial-shading and has been developed to increase the power output by 12% more with the proposed technique over the conventional Sudoku and Futoshiki puzzle patterns.

Advanced control schemes have also applied the main methods of MPPT tracking along with a significant contribution in maintaining stability of output voltage. A number of sophisticated control strategies such as neural networks (NNs), fuzzy logic and ML algorithm based MPPT have been proposed to improve the efficiency and convergence of the algorithm. For instance, (Lu et al., 2020) presents an MPPT scheme based on a convolutional neural network (CNN) that aims at balancing the short-circuit currents of the PV arrays under partial shading condition. This method provides great enhancement in power output as the result that improvement is more than 25% in case study. In the same context, optimistic and recursive algorithms have been applied to improve the voltage and current characteristics in real-time, which makes the output power stable even under complicate shading (Mohammad et al., 2020). These approaches have been further improved through optimization methods like dynamic programming which offers a structured approach of handling the switching operation in large PV arrays while at the same time maintaining high efficiency and less operational complication (Ngoc et al., 2019).

One of the primary issues in the optimization of the PV system is the conflict between the size of the system and the configurational flexibility of the system especially when it comes to dynamic reconfiguration. There are many combinations that integrate SP and TCT topologies which have been identified to be flexible and efficient in large scale developments. Arguments from comparative study, as in (Mao et al., 2020), represent that hybrid concepts offer more than pure static and dynamic strategies especially if it comes to comprehensive shading scenarios in large PV fields. The hierarchically based reconfiguration solution that involves both SP and TCT methods has been quite efficient in handling a substantial number of panels present in utility-scale solar farms. To address this, these systems apply a two-level structure as the lower-level handles with the reconfiguration of SP topology for the systems within a group and the upper-level deals with the interconnecting structures by TCT for different groups, thus enabling them to perform efficiently under various operating conditions (Lu et al., 2020). Apart from these methods, other strategies such as Coyote Optimization and Genetic Algorithms have also

been used more frequently in PV panel reconfiguration systems. These algorithms are aimed at searching the global MPP by changing the type of connections between the panels in real time mode including such complex scenarios as the presence of the shading. As shown by the works presented in (Ahmed et al., 2021; Bonthagorla and Mikkili, 2020; Meerimatha and Rao, 2020), these metaheuristic approaches can be incorporated into the reconfiguration system to enhance the level of power output greatly. These techniques are best useful in large installations where it is almost impossible to physically reconfigure the systems and where shading conditions fluctuate. Furthermore, these algorithms have been interfaced with monitoring systems to enhance real-time optimization of the operation of the PV system, claiming maximum efficiency despite variable environment factors.

However, even though dynamic reconfiguration and intelligent MPPT offer major benefits, but they still suffer from some implementation issues such as real-time operation, scalability and hardware complexity. Therefore, as reported in (Ameen et al., 2024) the hierarchical structure of PV array provides many useful features. In hierarchical PV arrays the design problem is reduced to the design of the elemental building block of the parallel combination of two PV panels (or sets of PV panels). By fixed parallel connection, partial shading cause variation in output voltage and weak panels act as electrical loads on unshaded panels. On the other hand, when the connection is controlled by programmable microcontrollers, then the effect of mismatches can be effectively reduced. However, the use of microcontrollers adds to the system complexity. Therefore, to address this problem, the transition unit has been proposed in this paper to be a simpler effective alternative PV panel combiner to facilitate effective dynamic reconfiguration in hierarchical PV arrays subjected to partial shading.

3. SYSTEM MODEL

The proposed PV panel combiner is called the transition unit. This is due to its primary function which is to control the states of switches (relays) that determine the connection of two identical PV panels, as shown in Fig.1. The connection scheme is dynamically updated according to the productivity of the PV panels.

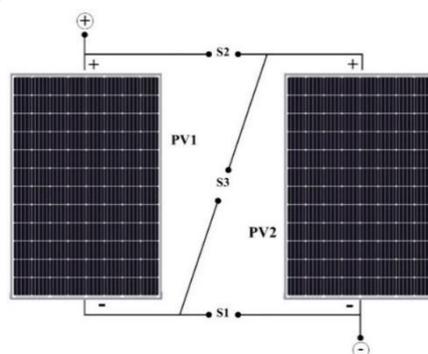


Fig.1. Scheme of Connection

The system works as follows, during standard operational conditions, with both panels receiving complete illumination and no interference from shading; the system sets a parallel connection between the panels by turning ON the first and second relay (S1 and S2) as shown in [Table 1](#), where (1) means unshaded and (0) is for shaded PV panel.

This configuration provides the best scenario to maximize current output, as the outputs from the two panels are integrated at a constant voltage level. Next, when one of the PV panels is shaded and the other remains under full illumination, the system adapts to this by isolating the shaded panel and operating on the unshaded panel fully. Thus, for the case when the first panel PV1 is occluded, S1 will be turned OFF while S2 remains ON, allowing the system to draw power from the second panel PV2 exclusively. Conversely, if PV2 is shaded and PV1 remains in the sun, this selective connectivity approach will always make sure that the system is biased towards the photovoltaic panel that has the highest energy production, hence minimizing the associated shading losses. Finally, in the case of both PV panels are under shading, the switches are set to the series configuration. This is achieved by turning both S1 and S2 OFF while S3 is turned ON. A PV panel is considered as shaded if its output voltage falls below 50% of its maximum.

Table1. Truth table of Transition Unit

PV1	PV2	Connection Type
1	1	PV1 & PV2 in Parallel
0	1	PV2 Only
1	0	PV1 Only
0	0	PV1 & PV2 in Series

The detailed connection diagram of the designed transition unit is shown in [Fig.2](#). Each one of the PV panels has a nominal maximum output voltage of 7 Volts under unshaded conditions. For the designed controller to be able to work properly with different PV specifications, a voltage divider is used to take a sample of the PV output to be compared with the threshold voltage, 3.3 Volts, which is generated by a Zener reference voltage. The voltage divider circuit should be designed to produce a range of voltage suitable to be compared with the predetermined threshold to identify the shading condition of each panel. The panel threshold serves as the determining factor to establish whether a panel is illuminated or shaded. The comparators control the switches through a photo-couplers to setup the proper.

Panel configuration as given in [Table 1](#). The optocoupler is used to isolate the control circuitry from the primary power circuit. In the designed Transition Unit circuit Shown in [Fig.2](#), the transistor acts as a primary electronic switch that turns ON and OFF according to the signal it gets from the opto-coupler. In this case, when it is turned ON, the transistor activates the relay, which connects or disconnects the corresponding solar panel according to its shading condition.

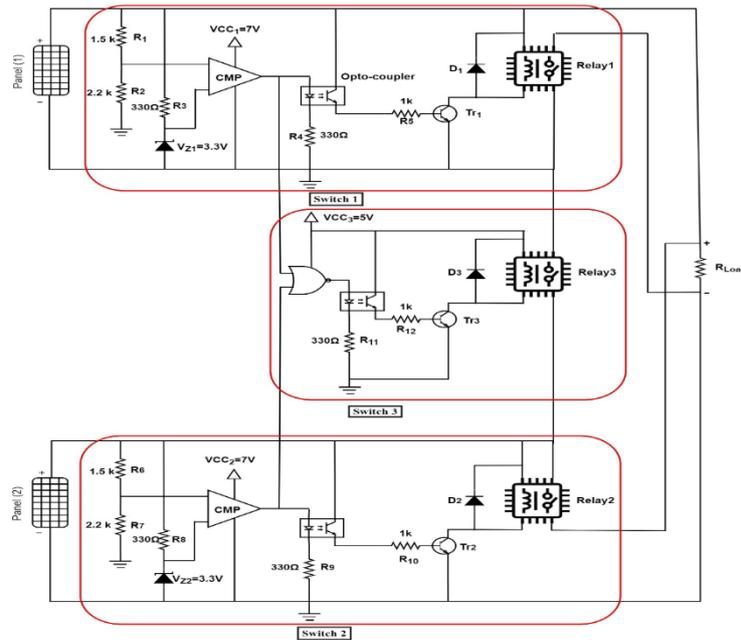


Fig.2. Designed Transition Unit circuit

These relays are connected in order to regulate the interconnectivity of the panels in parallel, series, and a single panel-based configuration by logic circuit through the truth table, given in [Table 1](#). The truth table spells out the conditions where a relay would need to be OFF or ON to ensure that at any given time, the panels are connected in such a way as to provide stable output voltage. The Transition Unit circuit involves the NOR gate, which functions as the control of the third relay in the system. This NOR gate takes its input from the comparators that are connected to both panels. If both of the panels are masked (shaded), this NOR gate generates a signal to switch on the third relay, and the configuration switches from parallel to series. The configuration change has a particular added advantage at low levels of illumination in that a series arrangement can allow maintenance of higher output voltages, despite the smaller total current. This switching ability allows the system to track full maximum power point tracking, even under conditions where the shading can change quite rapidly during the day.

By dynamically changing the configuration of PV panels with input from real-time shading measurements, the system attains maximum energy output at a consistent performance level. The integration of electronic components like comparators, Zener diodes, opto-couplers, and logic gates allows for fine-tuned control over the operation of the system, and hence it becomes a useful tool to maximize the efficiency of photovoltaic systems where partial shading cannot be avoided and in a wide range of operating scenarios.

4. RESULTS AND DISCUSSION

The main aim of this study is to assess the effectiveness of the proposed Transition Unit (TU) in producing stable output voltage under different partial shading conditions. The TU was

practically implemented, as shown in Fig.3, and its performance in terms of output voltage stability was evaluated in comparison with the conventional parallel configuration and microcontroller based dynamic reconfiguration system.

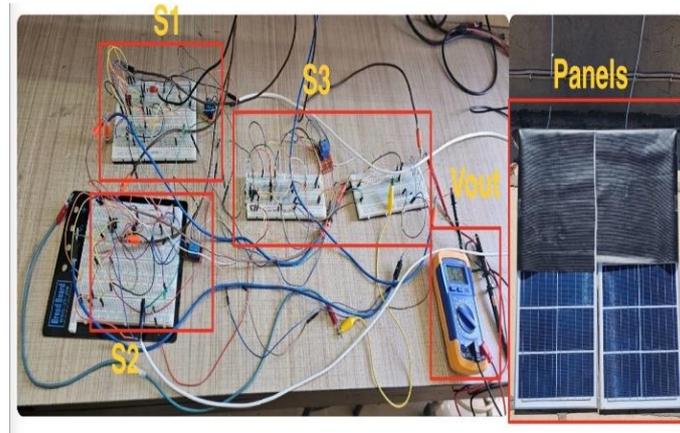


Fig.3. Practical implementation of the Transition Unit

The results in Table 2, provide the output voltages under eight different shading scenarios. The irradiation levels of PV1 and PV2 were deliberately manipulated to replicate real-life shading conditions. The performance assessment is based on the output voltage which holds significant relation with the efficiency of energy extraction and the stability of the PV system especially during partial shading conditions.

Table 2. Shading Conditions and Output Voltages

Shading cases	PV1 Irr Percentage	PV2 Irr Percentage	Parallel configuration voltage (V)	Microcontroller based voltage (V)	Transition Unit voltage (V)
1	100	100	6.3	6.3	6.3
2	16.7	100	4.2	5.2	5.6
3	33.4	100	4.9	5.2	5.6
4	50	100	5.1	5.2	5.6
5	100	16.7	4.5	5.5	5.8
6	100	33.4	5	5.5	5.8
7	100	50	5.4	5.5	5.8
8	50	50	2.5	5.1	5.3

Under normal conditions with full irradiation, the difference in output voltage among the compared methods was insignificant. The traditional parallel configuration, the microcontroller (MC) based system and the TU, produced 6.3 Volts, where all of these methods realize a simple parallel connection under this condition. These results indicate that the tested approach were able to produce comparable outputs.

In the second test situation, PV1 had a significant reduce in irradiation, dropping to 16.7%, while PV2 remained completely lighted. As a result, the output voltage from the parallel technique decreased significantly to 4.2V. Conversely, the TU and the MC methods sustained a significantly greater output of 5.6V and 5.2V, respectively. In test situations three and four,

as the level of shade grew, the irradiation of PV1 decreased to 33.4% and 50% respectively. The parallel approach faced challenges in maintaining a consistent output, resulting in voltages of 4.9V and 5.1V, respectively. Meanwhile, the TU approach maintained a constant voltage of 5.6V under these conditions. The stability of this method showcases its durability and capacity to dynamically adjust to changing light condition without experiencing a substantial decrease in efficiency of the system. The performance of MC approach is similar to the TU but with a simple less value. This is due to losses in generated power used to feed the electronic components of the system.

Moreover, scenarios five through eight incorporated shading on PV2, either separately or in integration with shading on PV1. In scenario five, PV2 saw a decrease in irradiation to 16.7% while PV1 remained fully lighted. The parallel approach resulted in an output of only 4.5V, but the TU method yielded a stronger output of 5.8V. As shading intensified in scenarios six through eight, the conventional parallel approach increasingly struggled, especially in scenario eight where both panels were subjected to 50% shading. In this case, the output of the parallel approach significantly decreased to 2.5V, while the TU method continued to generate a more effective output of 5.3V.

The results place emphases on the significance of the suggested approach in terms of the average output voltage generated under the different test conditions. That is, the implemented TU generated an average of 5.73V while the parallel and MC based system generated 4.7V and 5.4V, respectively, when tested under the same irradiance conditions. Moreover, the implemented TU system shows more and better stability and less deviation from the average value in all different test cases in contrast with the parallel combiner, as shown in Fig.4.

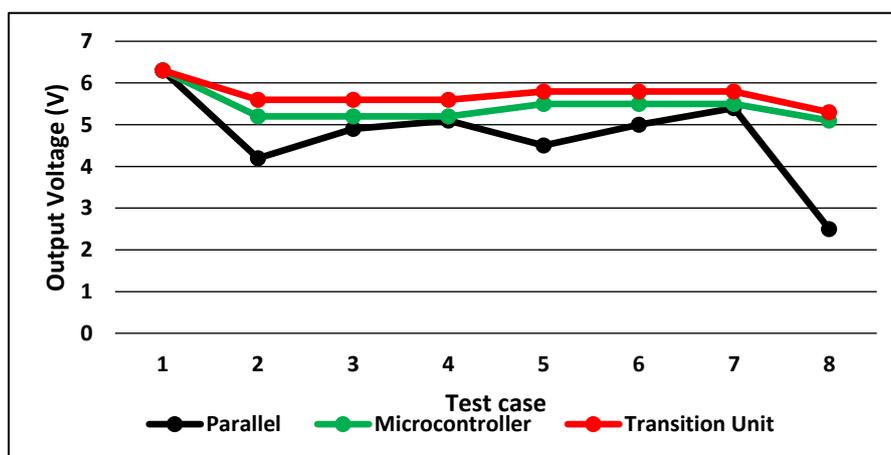


Fig.4. Output Voltage Comparison

It worth mentioning that an necessary feature of the proposed TU system is its ability to disengage a PV panel from the circuit when its irradiance and sunlight falls below 50%. By employing this approach, the system circumvents the inefficiency of extracting energy from a

panel that is severely shaded. This shading would otherwise undermine the overall effectiveness of the array. Alternatively, the circuit cleverly prioritizes extracting output voltage from the panel that is experiencing superior light exposure, hence maximizing energy extraction. This characteristic proved to be very advantageous in scenario eight, as both panels were partially shadowed lead to connect them in series to keep constant and stable outcome voltage. In contrast to the parallel technique, which yielded unsatisfactory outcomes due to the cumulative influence of shading, the TU method demonstrated the ability to adjust and sustain a more consistent level of performance by placing greater reliance on the panel with less shading.

Another advantage of the TU system is that it does not include software algorithms and other controls developed with the use of microcontrollers. It is a fully electronic circuit and it can prove responsive to the activity of the panels in real time. In its configuration, it is simple to scale up and can be integrated at a large scale without a need for software update or even reprogramming of the controller.

5. CONCLUSION

This paper addresses the problem of obtaining a stable output voltage from the combination of two PV panels in a hierarchically structured PV array exposed to non-uniform shading patterns. The proposed TU circuit sets the connection of the panels through controlling relays according to the current shading condition. The results showed the superiority of the proposed TU over the conventional parallel configuration and the MC-based approach. The TU ignores the need to complex algorithms or microcontrollers. It is able to directly track the panel irradiation and ensure that there is consistently and higher voltage despite the challenges posed by shading conditions. Moreover, the designed TU system gets power output from only well illuminated panels while avoiding those that are heavily shaded, as they have irradiance of far less than 50%. However, there are some limitations that have to be considered. The primary limitation of the method may be the fact that certain aspects of PV systems may require precise adjustment of specific hardware characteristics. Also, it is important to note that the circuit performs to an incredibly high standard in most of the tentative shading conditions; but in the occasions where the voltage for both panels is less than 30%, the system is unable to supply the required DC power on the comparator IC of the circuit, which causes a definite hitch. This is even more important in environments which have very low illumination since there is likelihood that the circuit may not work as intended. In fact, despite these drawbacks, the TU method is quite pragmatic, efficient, and can be scaled to increase the performance of the photovoltaic systems in areas that experience partial shading often.

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