Traditional and hybrid solar photovoltaic array configurations for partial shading conditions: perspectives and challenges

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ABSTRACT

The role of photovoltaic (PV) array in converting solar energy to electrical energy is very much important to get maximum power. Current challenge in solar PV systems is to make them energy efficient. Partial shading conditions (PSCs) is one of the main causes for performance degradation of PV array. It not only effects the shaded region but also effect the overall output of the PV array. Proper selection of configuration is essential to overcome such type of challenges. There exist various types of traditional configurations such as series (S), parallel (P), series parallel (SP), total-cross-tied (TCT), bridge-link (BL), and honeycomb (HC). Hybrid configurations also available such as series-parallel-total-cross-tied (SPTCT), bridge-link-total-cross-tied (BL-TCT), honey-comb- total cross-tied (HC-TCT), and bridge-link-honey-comb (BL-HC). This paper presents an overview on various types of configurations available with their merits and demerits under various partial shading situations. This paper also insights recent advancements in PV array configurations with their future trends to benefit the researchers working in this domain.

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1. INTRODUCTION

Due to continuous increase in oil prices and energy consumption, solar photovoltaic (PV) based power generation is becoming very much important [1]. The performance of PV systems has been remarkable, and they are now widely used in the electrical grids of many nations.The semiconductor technology growth and advancements leads to increase in usage of photovoltaic energy as a dependable non-conventional energy source. Due to a number of positive features, including rooftop installation, openness to solar radiation, and environmental friendliness, PV technology is currently becoming more and more popular. The PV based power generation has the advantages of being stable, environmentally favorable, easily accessible, reliable, and emission-free, making it the primary source of renewable energy generation globally [2], [3]. The energy produced by a PV system is limitless and capable for supplying a safe and reliable power source. Environmental factors like ambient temperature and solar irradiation have a significant impact on the energy generated by PV modules [4]. Maximum power point tracking (MPPT) is crucial for PV power generation in order to generate as much solar energy as possible [5]. A significant challenge is partial shadowing (PS), which inhibits the PV system from supplying the load with the causes formation of hotspot formation and power loss [6]. PS is an instance where the special array modules received a different level of radiation due to shadow. This shadow may be the result of unusual circumstances, such as a nearby building or tree, or it may be clouds. The PS conditions (PSC) have a direct impact on the (P-V) and (I-V) characteristics of PV modules

[7]. Though there are various factors, PS is one of the main factors that affects power generation [8]. Figure 1 shows various sources of PSC. Broadly the main causes of PSC are classified as natural and artificial causes. Natural causes are again classified as environmental factors, various dust types factors, installation site and associated factors. Artificial causes are classified as building shadow and telecom towers. Exploring different methodologies is vitally needed to find the solutions for these PSC problems. Modifying the electrical connections of PV modules in array topologies is also one of the finest approaches [9]. Karatepe *et al.* [10] looked into various sizes of PV array topologies, such as SP, TCT, BL, and HC affected by partial shadowing. Performance is evaluated in terms of minimum power losses and FF. The experimental study to investigate the effects of shading on S and SP configurations of PV array has been done in [11].

MPPT algorithms are challenged by the output power curve's multi-peak phenomenon and the variable I-V characteristics of each array row brought on by the activation of bypass diodes under PSC. Additionally, this shading is dynamic and essentially difficult to forecast prior. The phenomena of PSCs has been extensively investigated in literature due to its impact on power generation, and the issue is well understood. To lessen the effects of PSC and increase output power under PSC, researchers have developed a number of PV array reconfiguration strategies. This paper thoroughly and methodically evaluates a number of PV array reconfiguration options and offers a full summary from multiple angles in order to close the gaps. It might therefore be regarded as a cutting-edge review resource for reconfiguration of PV array. Future researchers interested in this field can gain some insights from this review. Using the shortcomings of previous evaluations as a foundation, this article offers a close examination and evaluation.

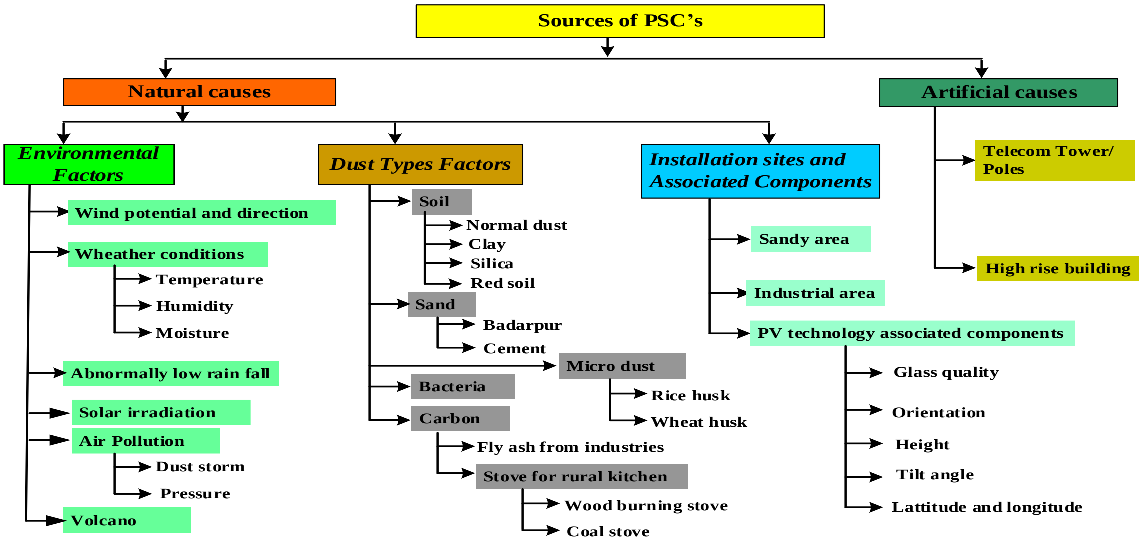

Figure 1. Various sources of occurring PSC's

2. PV ARRAY CONFIGURATIONS

In order to provide the appropriate output current and voltage as required by the load, huge PV arrays are typically built by connecting a multiple of modules in series and parallel [12]. To reduce the hotspot's heat stress on the array's output voltage, the bypass diodes are also positioned in parallel with the PV modules [13], [14]. Figure 2 shows various types of solar PV array configurations. The PV array topologies typically use different channels for the current generated by unshaded modules to flow in order to reduce the mismatch loss across modules during partial shading. This paper comments the performance of various types of PV arrays, including basic or conventional, hybrid, and advanced configurations. The traditional topologies for PV arrays are SP, BL, HC, and TCT [15]. Under partial shading, TCT is proved as most efficient and ideal method for reducing power loss in PV arrays [16].

In order to reduce the power loss caused over by partial shading, the reconfiguration strategies expand the shade effect across the array, through one row to every possible row in the PV array. An electrical array reconfiguration (EAR) has been created to dynamically change the connections in between arrays. Electric vehicles have used this technique to enhance performance at specific driving speeds, particularly low, mid, and high speeds. Several articles have employed dynamic reconfiguration to increase the PV array's PSC power production. Switches, sensors, and switching algorithms are not needed for the static reconfiguration technology, often known as physically array reconfiguration (PAR). According to Krishna and Morger [17], the PV array utilize the static reconfiguration technique and the SuDoKu pattern. When operated under PSC the output power is increased. The placement of PV modules should be in such a way that the rows "sum of irradiances (SIR)" is as near together as possible. In a PV array as a one-time arrangement, authors employed an array pattern dubbed "magic-square" to reduce the disparity between the maximum value of SIR and the minimum value of SIR. The magic square was created by enhancing the power production under PSC using genetic algorithms (GA).

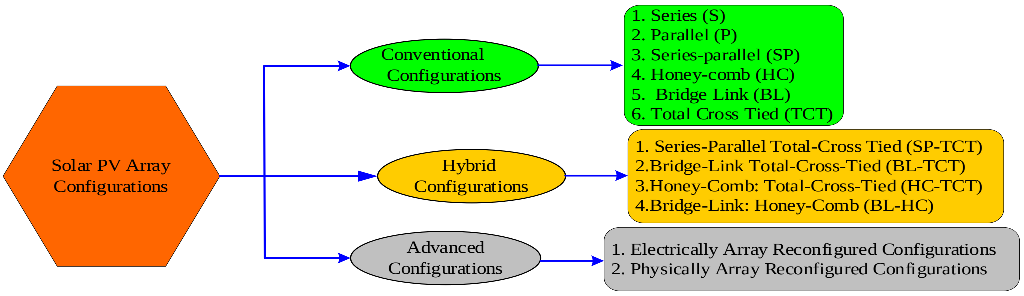

Figure 2. Classification of solar PV array arrangements

3. COMPARISON OF VARIOUS CONFIGURATIONS

In this section comparison of various PV array configuration has been done along with pros and cons of each configuration. Various researchs examined the effects of partial shading and ways to minimize PS losses using different PV systems and topologies. Table 1 gives the major conclusions drawn by previous authors when PV array are connected in basic and hybrid configurations across various situations. The TCT configuration has a greater maximum power and less fluctuation in the MPP voltage than the BL and SP versions. Because there are more modules in series with each other in the HC design than in the TCT and BL configurations, the mismatch losses will be larger. Because there are fewer modules coupled in series, the mismatch losses in the series and SP configurations are reduced.The GMPs are improved over traditional SP, BL, and HC configurations by the hybrid SP-TCT, BL-TCT, HC-TCT, and BL-HC configurations. The configurations of TCT and BL-HC therefore offer the greater performance in all areas under this shading situation, but due to the higher cost of wiring, BL-HC can be recommended over TCT. All configurations in descending order of performance are TCT, TT, BL-HC, BL-TCT, HC-TCT, BL, SP-TCT, HC, and SP.

Table 1. Comparison between basic and hybrid configurations

References	Array advised	Merits	Demerits
[18]	Series	– The functions of series are well described along with shunt resistance. – Eight different irradiation levels are used to test the module.	– Only the module level is considered in the analysis. – There is no consideration of temperature effect.
[19]	Parallel	– There is a twofold increase in power. – Facilitates in the efficient MPPT for various shading conditions. – A bypass diode is not necessary.	– Only suitable for low-voltage applications – There is a requirement of power converters.
[20]	Series-parallel	– Temperature and resistance variations are taken into account in a two-diode PV model. – The results are compared to data that has been measured.	– Only nonoverlapped bypass diode-based SP configurations are tested with the model.
[21]	Bridge link	– I and V relation of single solar cell is examined. – Three distinct array setups are investigated.	– Computational process is complex. – Unclear presentation of algorithm.
[22]	TCT	– Partial shading situations have the least effect on the TCT topology performance, then BL topology. – Experimental valuated the simulated results.	– Only three topologies (SP, BL and TCT) are considered. – HC configuration is not taken into account.
[23]	BLHC, BLTCT, and HCTCT	– Research on various fictional and realistic shade patterns, which have not before been taken into consideration, using various PV array topologies.	– TCT has best performance and hybrid configurations deliver the satisfactory performance under all PSC
[24]	TCT	– Under PSC, TCT has the greatest GMPP, %O/P, and lowest %MP for the PV array under consideration with experimental study.	– For the least irradiating case VIII and most irradiating case IX, NSD has maximum power extraction
[25]	TCT	– T-C-T configuration generated highest GMP compared to B-L and H-C configurations.	– Wiring losses in T-C-T reconfiguration due to more number of cross ties.

The following conclusions are drawn from this Table 1.

- Under the uniform irradiation condition, it has been determined that all conventional and suggested hybrid PV designs produce an equal maximum power with a single peak. Multiple power peaks are generated in PSC, which lowers output power and raises mismatching losses.
- The majority of the shading patterns produce the greatest GMPP values when the A-TCT-BL PV arrangement is used [26]. In comparison to other PV configurations under consideration, it also lowers mismatching losses in the majority of PSC. In four out of eight PSC, the A-TCT-BL PV configuration produces fill factor and efficiency figures that are higher than those produced by other PV configurations. In majority of the shading patterns taken into consideration, it also produces fewer output power peaks.

In EAR method PV arrays have been segregated into two main parts fixed and adaptive. Owing to the PSC, GMP, and output power has reduced. EAR method mostly works on the irradiance or current equalization principle. In this method, electrical connections of PV arrays in the adaptive part have changed through a switching matrix and it has Table 2. gives the major conclusions drawn by previous authors when PV array are connected in electrically array reconfigured configurations across various situations.

Table 2. Comparison of electrically array reconfigured configurations

References	Array	Merits	Demerits
[27]	Adaptive	– Array power attainment is enhanced by shadings. – Model-based sorting's algorithm speeds up computation.	– It is necessary to have (2m+1) numbers of sensors. – $2m^2$ measurement switches needed.
[28]	ANN based APVA	– PV array accuracy has been significantly improved under extreme shadowing conditions.	– The presentation of the methodology is unclear. – There is no indication of the switch count.
[29]	IE	– Produced 3% more power compared to the standard one.	– 2 Npv m throws switches are required. Sensors are also required.
[30]	Fuzzy based APVA	– Reduces the need for DC-DC converters and various sensors. – Replaces shaded modules with unshaded modules.	– There is no indication of the switch count. – Parameter values are not displayed.
[31]	Reconfigured configuration	– Both configurations, SP and TCT, are compatible with the described reconfiguration scheme.	– Every PV string needs a set of current sensors. – Switches needed to rearrange the TCT setup
[32]	Scanning algorithm based APVA	– When there are shadings, the PV module power output is maximised by 37%. – Needs a minimum quantity of sensors.	– Needed 2xmxm electronic switching components.
[33]	GA based APVA	– More appropriate for real-time tasks. – Faster than other methods.	– Complex shading conditions are not taken into consideration.
[34]	topology reconfiguration method	– Up to 4-6% more output power is generated. – PV power has reduced costs.	– PV array electrical behaviour is not presented.
[35]	IE	– A new switching network based on DPDT is utilised. – Relative to other lower switch counts.	– Not suitable ideal for prolonged training. – Twenty-four relays are used.
[36]	PCT	– Easy implementation. – Up to 11.9 percent more output power.	– Noisy electrical activity. – Switches, sensors are required.
[37]	GOA	– The greatest percentage of 10.9 generated power over GA. – Only GMPP was produced.	– Intricate panel circuitry.
[38]	PSO	– The use of complicated shading patterns. – The annual total of energy extracted is examined.	– An increase in the price of installing PV power units. – More iterations involved.

Under all types of shade situations, these strategies provide the maximum power, but they all require a significant number of control algorithms, switches, and sensors, raising the system's cost and complexity. Furthermore, the above approaches appropriateness and dependability for massive PV arrays working in shaded situations have not been discussed. It has been suggested to use a bubble sort-based shade dispersion approach in adaptable PV systems, however its implementation necessitates different sensor configurations and has switching limits that prevent it from dispersing all types of shading. Table 3 gives the merits and demerits of various physically array reconfigured PV arrays which were proposed by earlier researchers.

A variety of static relocation solutions based on permanently moving the position of modules have been developed to decrease losses and increase power output from PV arrays under varied PSC. With the help of a proposed algorithms, PV module modules have their attention focused on the shade dispersion positioning (SDP) technique [50]. Similar to this, it has been recommended to arrange PV modules physically using the SuDoKu puzzle pattern [51] to maximise the PV output power by reducing the shade of modules in any row. In order to obtain higher power attainment than conventional topologies, a column index-based one-time relocation strategy that reconfigures the modules using the column index method has been created.

Table 3. Comparison of physically array reconfigured configurations

References	Array	Merits	Demerits
[39]	SuDoKu	– When measure to traditional TCT setup, RTCT configuration results in power losses that are 23.6% lower.	– There is no analytical analysis performed. – Wiring is complex.
[40]	Novel approach	– Makes sub arrays easier to use.	– It is only implied for PV arrays built on asymmetric array.
[41]	MS	– This method is based on just three basic rules. – Up to 44.3 percent more power in a TCT setup.	– The lengths of wires are increased. – Big size PV arrays present a complex implementation.
[42]	OSDK	– Low power losses. – Superior to SuDoKu.	– Real-time hardware validation is not taken into account.
[43]	NS-1 and NS-2	– Eight alternative PV array configuration types are taken into account. – Guidelines for formation are given.	– Not applicable for arrays based on an even number of rows.
[44]	FS	– The hourly shading circumstances are taken into account. – Experimentally validated the findings.	– It can be challenging to select a good puzzle pattern. – A more complicated circuit.
[45]	ZZ	– Effective for arrays of any dimension type. – Eight distinct types of parameters are used to evaluate the performance of PV arrays.	– The PV modules located in the first column are fixed.
[46]	CDV	– Shade-related problems are reduced. – A 23.9 percent increase in output power. – There are no local peaks to be discovered.	– Circuit complexity is increased. – The need for switches of any kind is decreased.
[47]	KKSP	– It produced 6.81 percent more power than SuDoKu. – 18.86 percent fewer wire losses were experienced.	– Complex formation rules exist.
[48]	Two phases	– Interconnections with fewer ties. – Scalability to huge solar panel arrays. – Achieve maximal power.	– The method is challenging – More phases are introduced.
[49]	LS	– When compared to TCT, the LS-TCT arrangement produces the most power and FF.	– Investigations based on fixed irradiation and constant temperature is reported.

4. PERSPECTIVES AND CHALLENGES

Although solar array reconfiguration has major research value, there are still a number of problems that need to be addressed, such as the following:

– There are still no practical solutions and successful examples that can be used to apply simulation techniques to the management of big PV systems.
– Because several reconfiguring methods described in recent years have similar results, significant innovation should be encouraged.
– Complex variable adjustments in the current reconfiguration methods need to be simplified.

Additionally, the following suggestions for upcoming research in the field of solar array reconfiguration:

– Hybrid algorithms, which combine the benefits of several different AI algorithms and primary algorithms, are widely used in a variety of engineering practices. Therefore, in PV array reconfiguration, more attention should be placed on the enhancement or fusion of numerous potent individual algorithms. In addition, further research is needed to optimise the right "weighting" factors for AI algorithms.
– More focus than was given in past research needs to be placed on striking a balance between increasing power generation and reducing switch operation periods. Future study should also take into account the return on investments index in order to efficiently minimise costs and maximise revenues, which is of considerable significance for real-world engineering applications.
– More hardware experiments should be conducted in addition to simulation and hardware testing to confirm the practical performance of different algorithms.
– Most of the studies are verified at normal room temperature, which has a big effect on power production. It is critical to carry out further study on PV array reconfiguration under various temperature range in order to offer more practical suggestions for different field temperature situations.

– Furthermore, more reliable experimental algorithms need to be created. Additionally, these algorithms will undergo experimental testing and be modified for use with larger PV arrays, more complex shadow scenarios.

5. CONCLUSION

This article attempts to give a comprehensive overview of several PV array reconfiguration techniques. For each of the PV array reconfiguration strategies, the various indicators, such as power enrichment, control variable, rate of shadow spread, control algorithm complexity, employed array size, shadow pattern, response speed, merits/demerits, and are compared. This study compares several PV reconfiguration options using more pertinent criteria, ensuring that decisions are reasonable and appropriate. Each technique's fundamentals, possible applications, and test results are all described in detail, which can provide relevant researchers and engineers with practical working recommendations. A general summary of the main conclusions drawn is provided: i) static methods are difficult to apply in real-world circumstances, while having an easier controller. Since most PV panel installations are permanent, moving the location of PV panels is difficult; ii) due to their short response times and high adaptability, dynamic approaches are still the most promising ones for reconfiguring PV arrays despite too many sensors, switches, and integrated electronics; and iii) meta-heuristic algorithms produce better results as compared to simple static approaches. They have consequently attracted the most focus in recent publications.

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