Review of Different Solar Photovoltaic Array Configurations for Minimization of Power Loss Under Partial Shading Conditions.

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Abstract
Environmental conditions strongly determine the performance and quality of the power generated by the photovoltaic (PV) system. Partial shading condition (PSC) is a commonly occurring phenomenon which deteriorates the efficiency and effectiveness of the PV system and can also reduce its lifespan. Altering the PV array configuration is a good solution to reduce the negative impact of PSC on PV system. Hence many different types of configuration and reconfiguration techniques have attracted the attention of the researchers. In this paper, a comprehensive review of different configurations of PV array present in the literature has been presented. The advantages and challenges for different configurations have also been discussed.

Keywords: Solar Photovoltaic, array configuration, partial shading condition

1. Introduction

The ever-growing demand for electrical energy and the adverse impact on the environment is leading to a gradual shift from conventional to renewable energy resources like solar, biomass, wind and hydro. With technological improvements and rapidly declining costs, renewable energy sources are gaining popularity globally, with governments and industries all across the world investing heavily in these energy resource. Of the various renewable power technologies, solar photovoltaic electricity generation is the most important and has received increased attention because it is abundant, clean, doesn't include any moving part, has a low operating cost and can be installed almost anywhere with different capacities.

Solar Photovoltaics (SPV) is a simple process of conversion of solar energy into electrical energy directly. Solar cell is the basic unit for this conversion. Many solar cells are connected together to form a PV module, which are further interconnected to constitute solar PV arrays. Partial shading (PS) of SPV system is a serious problem which can drastically reduce its output energy generation [1],[2]. PS refers to situations where only a portion of PV array is shaded while the remaining portion is exposed to sunlight. Such conditions occur commonly due to shadow created by close by building, poles, trees, moving cloud, fallen leaves, accumulation of dust and snow, bird droppings, soiling, overhead transmission etc. [3]-[5]. A very fine solution to reduce the power loss due to PS is by implementing different configurations of PV array. Output performance and behaviour of a partially shaded PV array is dependent not only on the pattern and location of shade but also on its configuration. Many different types of PV array configuration have been proposed, tested and analysed by the researchers over a period of time for the mitigation of power loss due to shading. The present paper reviews the different types of PV array configurations present in the literature and their performance under PS conditions. The advantages and challenges for different configurations have also been discussed. Moreover, the paper also highlights the mode of conduct of these previous studies.

2. Different array configurations

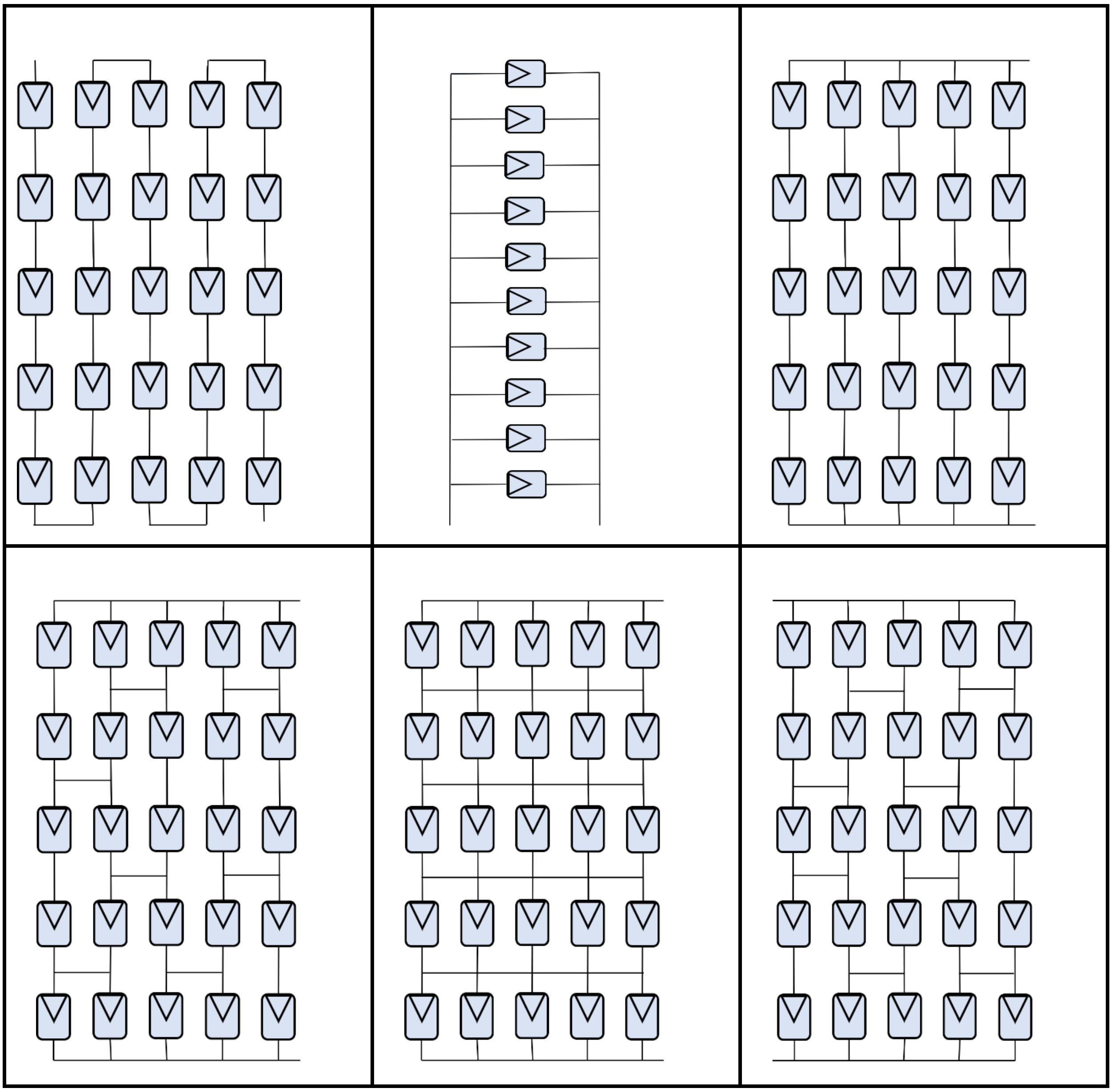

Figure 1. PV Array Configurations (a) Series (b) Parallel (c) Series parallel (d) Bridge linked (e) Total cross tied (f) Honey comb.

Array configuration means the design in which PV cells/modules are interconnected within the array. Several array configurations like series (S), parallel (P), series-parallel (SP), and cross-tie configurations, where ties are linked among strings of PV modules, such as bridge linked (BL), honey comb (HC), total cross tied (TCT) configurations are present in the literature [6-10]. The schematic of these configurations is presented in Fig. 1.

Standard series configuration (S), presented in Fig. 1 (a), is the basic configuration of PV array where all modules are connected in series string. It has low output current and high output voltage.

Parallel configuration (P), presented in Fig. 1(b), is the other basic configuration of PV array where all modules are connected in parallel. It has high output current and low output voltage, which makes it unsuitable for many PV applications.

In **Series-parallel (SP)** configuration several modules are connected in series to form a string to obtain the required voltage, and many such strings are further connected in parallel to obtain required current, as shown in Fig. 1 (c).

Bridge linked configuration (BL), shown in Fig. 1 (d), has modules interconnected in bridge rectifier fashion. Four modules constitute the bridge where two modules are connected in series and then they are connected in parallel with other two series connected modules.

Total Cross Tied configuration (TCT) is obtained from simple SP configuration by connecting ties across each row of junction, as shown in Fig. 1 (e). All modules in each row are connected in parallel and all such rows are connected in series. It has the highest interconnection redundancy.

Honey Comb configuration (HC), presented in Fig. 1 (f), is constituted by making some modification in BL configuration. It has a greater number of series connections compared to TCT and BL configuration and has less series connections compared to S and SP configurations.

3. Performance of different configurations under PSCs

3.1 Basic Series and parallel PV configurations

Series and parallel are the basic configuration which are very simple to implement. The advantage of S configuration lies in its simplicity, without the need of significant wiring, thereby curtailing wiring losses. However, S configuration is severely impacted by PS and is also most sensitive to the power loss due to aging [11]. Ramabadran & Mathur, 2009, investigated the effect of partial shading on the series and parallel configuration of PV array using PSPICE simulations [12]. The authors concluded that series configuration suffers substantial power loss due to partial shading and it is the parallel configuration which is dominant under partial shading conditions. Similar results were also obtained by Gao et al. 2008, who concluded that P configuration produce more power than S configuration under similar shading conditions [13]. However, to manage high current and low output voltage a proper power conditioning system and a suitable DC-DC convertor is required [14].

3.2 Other Interconnected PV Configurations

A lot of studies using different methodologies aimed at comparing the performance of different configurations under PSCs have been conducted.

Gautam and Kaushika in year 2002 used probability theory to evaluate the reliability of SP, BL and TCT SPV system to determine their operational lifetime. In this study the basic series and parallel configuration was not considered. The authors on basis of their computational results, concluded that cross-tied TCT or BL arrays are superior to SP array. SP configuration has greater proclivity towards mismatch loss and gives inferior performance than other cross-tie configurations under PSCs [15].

Ramaprabha and Mathur, 2012, developed a generalized MATLAB M-code to investigate and analyse the effects of partial shading conditions on different PV array configurations (S, P, SP, TCT, BL, HC) of varied sizes [16]. The authors concluded that TCT is the best configuration if the array size is symmetrical. HC configuration delivers better performance if the array sizes are asymmetrical or where the number of columns receiving same insolation is greater than the number of rows.

In another study conducted by Moballegh and Jiang, 2014, it has been demonstrated that under severe shading conditions TCT is the most efficient configuration, while for less severe conditions, SP is the most efficient. Performance of BL configuration lies between SP and TCT configuration [17].

Simulation based studies using MATLAB / Simulink platform have been conducted by many researchers to compare various configurations under different shading scenarios. Belhachat and Larbes, 2015, conducted a comparative study of 6x4 PV array of S, P, SP, TCT, BL, HC configurations under different partial shading conditions in terms of maximum power delivered and percentage power loss. The authors have used Bishop model for modelling different PV array configurations and implemented using MATLAB / Simulink platform [10]. The authors concluded that under partial shadings performances of the PV array configurations vary and depend strongly on the intensity, pattern, location of the shade, and the type of shading (uniform or not). For shading scenarios such as, where the shading covers completely and unevenly the PV array, shading covers partially and unevenly the PV array, or when columns of the array are completely and unevenly shaded, TCT configuration provides highest maximum power and lowest relative power losses. While for scenarios when one or two rows are completely and either evenly or unevenly shaded, S, SP, TCT, BL and HC provide the same maximum power. when one or two columns are completely and uniformly shaded, SP, BL, TCT and HC provide the same maximum power.

Pendem and Mikkili, 2018, further compared these configurations of array size 5x5 under various shading scenarios such as uneven column, uneven row, diagonal, short and narrow, short and wide, long and narrow, long and wide, and random shading patterns, using Matlab / Simulink platform [7]. The performance assessment of PV array topologies was carried out with respect to the comparison of open-circuit voltage, short-circuit current, global maximum power point (GMPP), local maximum power points (LMPPs), corresponding voltages and currents at GMPP and LMPPs, mismatching power loss, fill factor and efficiency of the PV array topologies. The authors found that TCT configuration followed by BL shows least mismatching losses due to PSC. Similar results were also obtained by Bingöl and Özkaya, 2018, who again, using MATLAB/Simulink platform, compared the performance of different configurations of a 6x6 sized array under six different shading cases in terms of shading loss, mismatch loss, and fill factor. The obtained results demonstrated that though shading loss is the same for all configurations for each shading cases, it is the TCT configuration which has the lowest mismatch loss and maximum fill factor [18].

Mohammadnejad et al., 2016, presented the mathematical analysis of 2x2 TCT configuration of PV array and validated through Matlab/Simulink. Further, using simulations, the authors compared TCT with SP, BL and HC configurations and established its superiority in terms of maximum power output and power dissipation percentage [19].

Experimental studies in real operating conditions, though only few, have also been conducted in this regard. Bana and Saini, 2017, conducted the experimental study on SP, TCT, BL, HC, and a novel configuration of 4x5 PV array under real operating conditions. For the purpose of investigation, uniform and 14 nonuniform shading scenarios were considered. The experimental results demonstrated that for partial shading conditions and uniform shading condition with static deviations, TCT configuration outperforms other configurations [20]. Satpathy et al., 2018, investigated the power generation and mismatch power loss of 3x3 and 5x5 sized SP, TCT and BL configurations using a prototype field experiment and Matlab/Simulink environment, under different irradiances and shading cases [21]. It was again demonstrated that TCT configuration minimizes the mismatch power loss and enhances PV output power generation under different shading patterns.

3.3 Hybrid configurations

Hybrid configurations i.e., combination of two configurations in a PV array have also been tested by some researchers. The objective is to reduce the number of cross ties as well as use the advantages offered by both the configuration to enhance power of PV array under PSC. Jha and Triar, 2019, analysed the performance of conventional and hybrid configurations such as SP-TCT, BL-TCT and HC-TCT under PSCs. The authors concluded that under PSCs, best performance is displayed by TCT configuration. Hybrid configurations are more economical than TCT configuration and also performs satisfactorily [22]. Premkumar et al., 2020, compared the performance of SP, HC, TCT, BL and ladder (LD) configurations with hybrid configuration like BLTCT, SPTCT and BLHC under static and dynamic shading patterns. The authors concluded that under shading conditions, TCT followed by BLHC is the optimum configuration [23]. Sarayu et al., 2023, proposed triple-series parallel-ladder (T-SP-L) configuration. The structure is obtained by joining the cross ties in the SP PV array for every three stings gap and long cross ties for every three rows [24]. Though the configuration has lesser cross ties than TCT, but in most of the shading cases considered by the authors, power generated by T-SP-L is less than TCT.

3.4 Array reconfiguration techniques

The reconfiguration strategy aims to optimize the PV yield by dispersing shade over the array to equalize the generated currents by different electrical rows. Array reconfiguration technique has also been adopted by many researchers for further maximizing output power of TCT array under PSC [25]. Pareek and Dahiya, 2016, proposed interconnection schemes according to shadow pattern to increase the power output of TCT connected PV array [26]. The method though provides multiple solutions to reconfigure photovoltaic array to improve energy yield under partial shading conditions, but is applicable for only fixed and easy to predict shadow patterns.

Reconfiguration can be either static reconfiguration or the dynamic reconfiguration [27]. In static reconfiguration the physical location of the panels is changed keeping the electrical connection same. In dynamic reconfiguration physical location of the panel remains the same but electrical connection are changed. In static reconfiguration technique, physical location of the PV modules in TCT configuration are changed within array on the basis of mathematical puzzle like Sudoku [28],[29], optimal sudoku [30],[31], magic square puzzle [32], dominance square [33], skyscraper puzzle [34]. Tatabhatla et al., 2019, reconfigured the conventional TCT array used arrow sudoku puzzle pattern which a variant of original sudoku puzzle. The authors compared the performance of proposed reconfiguration with the conventional configurations (SP, TCT, BL, HC) and hybrid configurations (SP-TCT, BL-TCT and HC-TCT) under different continuous dynamic shading conditions. The proposed configuration demonstrated better results others in terms of maximum output power, mismatch power loss and utility factor [35]. However, the reconfiguration is obtained by physical relocation of PV modules which implies lot of laborious interconnections, increase in complexity and length of interconnecting wires thereby increasing line losses, especially when implemented on larger PV system.

Various dynamic reconfiguration methods have also been proposed in the literature such as electrical array reconfiguration (EAR) [36],[37] adaptive array reconfiguration (AAR) [38]-[40] and optimal AAR [41]. Though dynamic reconfiguration has been found to be useful in extracting maximum power from partially shaded array, it employs great number of switches, sensors and control algorithms which increases the cost and complexity of the system.

Prince Winston et al., 2020, proposed connecting a current source across each row of TCT array which can inject current equal to the corresponding row's mismatch current during partial shading conditions [42]. The simulated results for a 4x4 TCT array have shown that the modified TCT topology improves the output power ranging from 5% to 105% under different considered PSCs. However, implementation of the proposed method requires additional circuit components like buck converter, programmable load, pulse generator which would escalate the cost of the system. The authors in another work have presented a technique of nullifying the mismatch losses under partial shading is by connecting converters with each row of TCT PV array. The purpose is to extract the mismatch power and store it in battery bank, which can feed the power to the grid during night-time [43]. Though the results show zero mismatch loss and decreased power loss, again the implementation of the proposed method requires additional circuit components which would increase the system cost.

4. Discussion

The review of the relevant literature demonstrates that the configuration of the PV array has a significant role to play in its output performance under PSCs. Static configurations like S, P, SP, BL, TCT, and HC are the commonly studied configurations. Series and parallel are the basic PV array configurations. Series is simplest configuration design to implement but most susceptible to power loss due to shading and ageing. Parallel configuration though doesn't suffer from these drawbacks, is not suitable for practical implementation owing to high current and low output voltage. Series-parallel is the therefore the most commonly used array configuration. Using this arrangement, both the voltage and current of the PV array can be increased. However, under PSCs, the performance of SP configurations significantly deteriorates. Therefore, many other configurations have been proposed and tested by the scientist so that the power loss under PSCs can be reduced significantly. Many studies have compared the performance of SP, BL, HC and TCT configurations using different ways and methods. Though lot of studies have been conducted either theoretically or using simulation, lesser number of studies have been done experimentally especially in real outdoor conditions. Nevertheless, these studies demonstrate that TCT configuration generally has superior performance in comparison to other configurations under shaded conditions. The performance of basic TCT configuration can be further enhanced by using reconfiguration methods. Dynamic reconfiguration methods disperse the shade on PV array using additional switching devices, sensors, and a complex control algorithm. This increases the cost and complexity of the PV system. The static reconfiguration though doesn't need sensors and switches for shade dispersion, requires physical relocation of the modules to disperse shade on PV array. This makes the system very complex due to strenuous interconnections using long interconnecting wires. This can also increase the line losses.

5. Conclusion

Partial shading results in huge power loss and is a big hindrance in the efficiency and reliability of solar photovoltaics as it. Therefore, mitigation of partial shading has attracted the attention of many research-

ers. A good strategy to minimize PV power loss under PS is by implementing different PV array configuration and reconfiguration techniques. Many different types of configurations of PV arrays have been suggested over the years in this regard. The present paper has comprehensively reviewed the performance of different types of PV configurations such as S, P, SP, BL, HC, TCT, hybrid configurations and reconfigured, present in the literature, under PSCs. The different methodology used by the researchers in comparing the performance of different configurations under PSCs have also been highlighted in the present work. TCT configuration have been shown as the configuration whose performance is least affected under most of the partial shading conditions. However, TCT has the greatest number of cross ties which increases its redundancy. The performance of basic TCT configuration can be further enhanced by using reconfiguration methods. However, reconfiguration technique increases complexity and cost of PV system. This can reduce the practical significance of these configurations as the PV industry constantly strive to increase the power output and reduce cost at the same time.
This article has reviewed, discussed, and presented the pros and cons of various PV array configurations and reconfiguration techniques. This article would provide a guideline to the researchers in choosing a particular configuration or reconfiguration technique and to further improve the performance of PV array under PSCs.

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