



Evaluations of Practical Engineering Application of Photovoltaic Reconfiguration Technology

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INTRODUCTION

One of the main issues of the application of photovoltaic (PV) system in practice is the mismatch between PV modules caused by partial shading (PS) (Iqbal et al., 2021; Zhao et al., 2021). The consequence of this phenomenon is that the energy generated by PV array is not fully utilized, which damages PV modules, shortens the service lifetime, and leads to economic losses. To mitigate this impact, PV reconfiguration technologies are recommended to disperse shadows uniformly, which are divided into static array reconfiguration and dynamic array reconfiguration (Yang et al., 2021a). In contrast to static array reconfiguration method, dynamic reconfiguration brings targeted change to the electrical connection between the PV modules according to the present irradiation on the PV array, which is more flexible and efficient. The above-mentioned method is implemented through a set of electrical switches embedded between the PV modules (Faiza and Cherif, 2021). However, the practical application of a reconfiguration technique will face many challenges. First of all, the current research papers lack expatiation about hardware realization of the PV array reconfiguration method. Second, after realizing the above-mentioned hardware requirements, it is worth thinking how to balance the economic benefits brought by reconfiguration and the potential risks brought by equipment reliability. This paper gives a clarification of the above-mentioned issues and brings some views on different PV reconfiguration technologies.

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STATIC RECONFIGURATION

Static reconfiguration approach changes the physical location of modules by some specific patterns to disperse the shading effect on the PV array, and there is no need for switches or other redesigned hardware. Hence, static reconfiguration is of lower complexity, easy to configure, and more manageable from the operation perspective. Providing an optimal scheme of module interconnections for PV array is the key in order to achieve the highest energy gain. The Sudoku reconfiguration approach designed for total cross-tied (TCT)-connected PV array rearranges the modules according to the Su Do Ku puzzle pattern (Rani et al., 2013). A particular work (Dhanalakshmi and Rajasekar, 2018a) proposed another puzzle-based reconfiguration scheme named the dominant square reconfiguration approach. Similarly, literature (Dhanalakshmi and Rajasekar, 2018b) introduced a competence square reconfiguration method to execute the physical relocation of PV modules. A more recent study proposed a method to increase output power by rearranging the PV modules based on the Magic Square puzzle (Reddy and Yammani, 2020). Researchers also developed a zigzag scheme for rearranging the modules (Vijayalekshmy et al., 2017). It is worth noting that the zigzag technique is available for a PV array with different numbers of rows and columns, which enhances the expansibility of the proposed method. The drawbacks of these methods are additional line losses due to the increased wire length

and ineffective dispersion due to the redundant constraints of the reconfiguration scheme. Therefore, an optimal Sudoku arrangement is developed to solve these problems (Potnuru et al., 2015). Considering wiring complexity and line loss, the extra wire length required depends on the relative position of the module with respect to the modules above and below in the same column, which minimizes the wiring loss. In addition, to improve the engineering practicability, the authors proposed a strategy for the optimal Sudoku technique applied in large-scale PV stations, *i.e.*, view a large-scale PV array as a system that consists of micro-arrays. The large-scale array and micro-arrays are all reconfigured by the optimal Sudoku method. However, all methods mentioned above can only be applied to a TCT-connected PV array. Complex wiring requirements also limit the application of static reconfiguration technology. Therefore, to implement static reconfiguration to large-scale PV power stations is a brand new and challenging task.

DYNAMIC RECONFIGURATION

Dynamic reconfiguration technologies use switching matrix to change the electrical interconnections of PV modules. The adaptive electrical array reconfiguration of PV modules is the earliest technology to use switching matrix in PV reconfiguration (Nguyen and Lehman, 2008). According to model-based control algorithm, the adaptive part and the fixed part of a PV array is connected by an alterable switching matrix (Karakose et al., 2016). The shadows are dispersed through connecting the less shaded rows of the adaptive part with the more shaded rows of the fixed part. Thus, row current can be equalized. This method is of low complexity, but the power loss mitigation is relatively small, and there is the need for a huge amount of switches, which leads to an increase in cost. The adaptive array reconfiguration approach divides the PV array into two sub-arrays. The adaptive sub-array is reconfigured by micro-control units to equalize the irradiance distribution (Liu et al., 2010). This method has a relatively high complexity and therefore is appropriate for a PV system in individual buildings or small geographic areas.

Meta-heuristic algorithm-based PV reconfiguration strategy is a very active area of research in recent years because of its flexibility, and there is no need of a precise system model (Yang et al., 2020a; Yang et al., 2020b; Dasu et al., 2021; Sakthivel and Sathya, 2021; Wang et al., 2021). So far, genetic algorithm (Deshkar et al., 2015), gravitational search algorithm (Hasanien et al., 2016), particle swarm algorithm (Babu et al., 2018), modified Harris hawks algorithm (Yousri et al., 2020a), marine predators algorithm (Yousri et al., 2020b), grey wolf optimization algorithm (Balraj and Stonier, 2020), butterfly optimization algorithm (Fathy, 2020), artificial ecosystem-based optimization (Yousri et al., 2020c), democratic political algorithm (Yang et al., 2021b), and other several meta-heuristic algorithms are applied in PV reconfiguration research. It should be noted that these strategies are all designed for TCT structure, the principle of which is changing the electrical interconnection of modules in the same column so as to equalize the row current. Some works (Deshkar et al., 2015; Babu et al., 2018; Balraj and

Stonier, 2020; Fathy, 2020; Yousri et al., 2020a; Yousri et al., 2020b; Yousri et al., 2020c) used row current as one of the evaluation criteria of the reconfiguration scheme, which reflects the principle of reconfiguration intuitively. Hasanien et al. (2016) designed the irradiance level mismatch index to analyze the irradiance level mismatch on the row level, which provides a new research idea of reconfiguration. Specifically, one work (Babu et al., 2018) took total income per year into account, which is worth using as a reference. Other works (Balraj and Stonier, 2020; Fathy, 2020; Yousri et al., 2020a; Yousri et al., 2020b; Yousri et al., 2020c; Yang et al., 2021b) used fill factor as an evaluation criterion of the reconfiguration results. It is debatable because fill factor is usually used to evaluate the performance of PV cells (Min et al., 2020). To verify the performance of algorithms, there is a need to introduce some parameters, such as the execution time used (Hasanien et al., 2016; Babu et al., 2018; Yousri et al., 2020a; Yousri et al., 2020b; Yousri et al., 2020c; Yang et al., 2021b) and the standard deviation (Babu et al., 2018; Yang et al., 2021b). The details of the evaluation criteria used by prior research are shown in **Table 1**. The array sizes applied in literatures are different, mostly arrays with the same number of rows and columns, such as 9×9 and 16×16 . Others are non-square arrays with varied sizes, such as 6×4 and 6×20 . It should be appropriate for researchers to apply non-square arrays to expand the applicability of the method studied in PV reconfiguration.

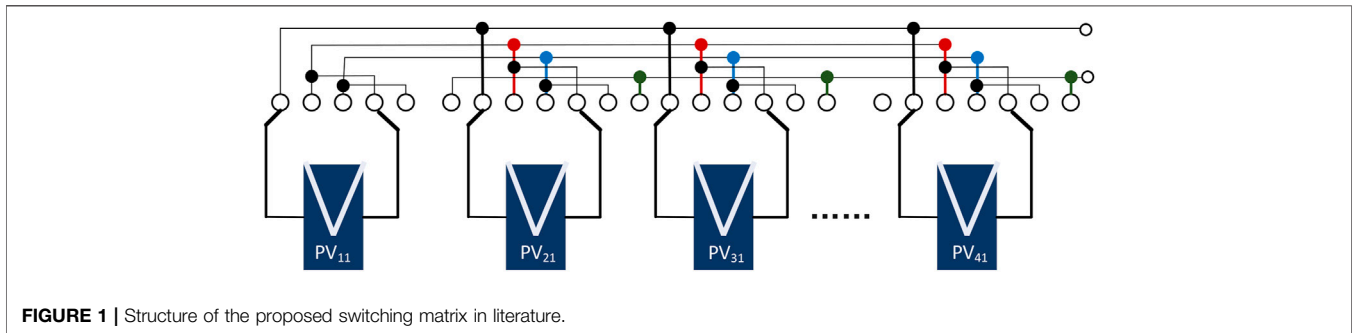
The investigated cases in Deshkar et al. (2015) and Yousri et al. (2020a) applied four shading patterns, *i.e.*, short and wide, long and wide, short and narrow, and long and narrow. One work (Hasanien et al., 2016) applied single-row PS, double-row PS, and quarter-array PS; these are three types of shadows. There are other shadow types like uneven row, uneven column, diagonal, outer, center, and random shadow (Yang et al., 2021b). Hence, it is necessary to develop a benchmark to support researchers in conducting a more reasonable study (Chen et al., 2018; Yang et al., 2019; Yao et al., 2019; Liu et al., 2020; Zhou et al., 2020; Huang et al., 2021; Xiong et al., 2021; Zhang K. et al., 2021). Moreover, simulations should be implemented in a standard test condition, which is $1,000 \text{ W/m}^2$ and 25°C .

TCT topology is the mainly used topology in existing research about PV reconfiguration, and the rest used series-parallel (SP) topology as the hardware structure of the PV array. In practice, SP topology is the sole structure of PV power station (Shams et al., 2021). It is worth noting that TCT topology-based PV reconfiguration improves the energy efficiency and the reliability of the PV system, but due to the increased wiring loss, high system complexity as well as high operational and maintenance cost, the SP topology has a higher efficiency than TCT. Under this circumstance, it is more appropriate to shift the research emphasis from TCT to SP. Significantly, reconfiguration solutions in large-scale PV stations should be developed to fit the actual engineering needs.

One of the most important parts to realize in reconfiguration technology is the hardware design of PV reconfiguration technology. It is worth learning from works (Yousri et al., 2020a; Yousri et al., 2020b) that proposed a switching matrix consisting of single-pole, multiple throw switches, which greatly

TABLE 1 | Summary of the evaluation criteria used in prior research papers on photovoltaic reconfiguration studies.

Method	Year	Evaluation criteria
Genetic algorithm (Deshkar et al., 2015)	2015	Row current, power enhancement
Gravitational search algorithm (Hasanien et al., 2016)	2016	Irradiance level mismatch index, performance ratio (PR), power enhancement, execution time
Particle swarm algorithm (Babu et al., 2018)	2018	Row current, execution time, total income per year, standard deviation (SD)
Modified Harris hawks algorithm (Yousri et al., 2020a)	2020	Row current, mismatch loss, fill factor (FF), percentage power loss, power enhancement, execution time
Marine predators algorithm (Yousri et al., 2020b)	2020	Row current, mismatch loss, FF, percentage power loss, power enhancement, execution time
Grey wolf optimization algorithm (Balraj and Stonier, 2020)	2020	Global shade dispersion index, total irradiance value of each row, power enhancement
Butterfly optimization algorithm (Fathy, 2020)	2020	Row current, mismatch loss, FF, power enhancement, PR
Artificial ecosystem-based optimization (Yousri et al., 2020c)	2020	Row current, power enhancement, mismatch loss, execution time, FF
Democratic political algorithm (Yang et al., 2021b)	2021	Power enhancement, mismatch loss, execution time, FF, SD

**FIGURE 1** | Structure of the proposed switching matrix in literature.

reduced the number of switches compared to TCT (see **Figure 1**). The required number of switches of a 4×6 PV array in this method is 48, but for a TCT-interconnected array of the same size, the number of switches is 258, which is calculated by the following equation:

$$Num_S = P \times (P + 1) - 2 + 2 \times Q(P \times Q - P) \quad (1)$$

where P is the number of rows, and Q is the number of columns.

Zhang et al. (2021) designed a varying PS to simulate shadows of moving clouds in 10 min, which means that the switching matrix should be switched in minutes. This will bring dependability issues due to various conditions like switch fault or increased expenses. Thus, it is worth considering how to balance the benefits and potential risks of optimal array reconfiguration. Moreover, researchers should focus on experiments instead of simulations, which has a far-reaching significance for applying reconfiguration into practical engineering.

Finally, due to the inherent defect of randomness in meta-heuristic algorithms, the quality of an optimal solution varies with the number of iterations and the number of populations (Yang et al., 2015; Zhang et al., 2015; Zhang et al., 2016; Yang et al., 2020c). The weight parameters assigned to algorithms should also be carefully chosen. For a PV array of different sizes, algorithm parameters need to be set purposefully to weigh the computational burden of the algorithm and the solution quality. In addition, previous methods found it difficult to solve a large-scale PV system optimization because the computing time is increased with system scale, which becomes

an urgent problem to be solved in the application of PV reconfiguration.

DISCUSSION AND CONCLUSION

PV reconfiguration technology is an effective strategy to extract the power of a PV system under partial shading condition, but it is still in its research and development phase. The efficiency and engineering practicability of this technique are major challenges, detailed as follows:

- Despite its cheap cost, static reconfiguration faces complex wiring difficulties and ineffective shadow dispersion. Setting reasonable constraints can avoid the invalid rearrangements of PV modules. Furthermore, the next step of researchers is to investigate some strategies to apply static reconfiguration into a large-scale PV station.
- The research keystone of dynamic reconfiguration is strategies for SP-connected PV array. Besides this, a benchmark of studied cases including PV array sizes and shading patterns can be formulated to verify the correctness of the studied results.
- Another important aspect of this technique is the hardware design of the dynamic reconfiguration. The switching frequency of the switching matrix is a critical research issue. Moreover, the material, price, and applicability of the switch used in the proposed technique should be considered carefully.

- (d) To cover the shortcomings of prior studies of meta-heuristic algorithm-based reconfiguration approaches, there is an urgent need to develop an effective and efficient control algorithm to apply a reconfiguration technique to meet the needs of a practical engineering project.

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AUTHOR CONTRIBUTIONS

RS contributed to writing the original draft and editing. BY contributed to conceptualization. YH contributed to visualization and the discussion of the topic.

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