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Enhancing the Performance of Aged Photovoltaic Arrays through Offline Reconfiguration: A Study on the Effects of Non-Uniform Aging

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Abstract - *There are several non-uniform effects on photovoltaic (PV) modules related to aging in a PV array. These subsequently bring about non-uniform operating parameters with individual PV modules, causing a variance in the PV array performance. The current study undertakes study to establish and positively affect the efficacy of a non-uniform aged 4 × 6 PV array, with a commercially available MSX60 photovoltaic module at 1000 W/m² (monocrystalline). This paper proposes a gene evolution algorithm (GEA) for offline reconfiguration that can provide more significant output power compared to non-uniformly aged PV arrays through repositioning instead of replacing aged PV modules, which will help lower maintenance expenses. This reconfiguration requires data input from the PV module's electrical properties in order to select ideal reconfiguration setups. The outcomes show that greater output power can be facilitated through a non-uniformly aged PV array and used on many different PV array sizes.*

Keywords: Solar photovoltaic; rearrangement; non-uniform aging; reconfiguration; Gene Evaluation Algorithm.

1. Introduction

An Energy resources and demand are essential for the advancement and sustainability of growing economies. Fossil fuels serve as the primary energy source for the global economy; yet, these resources are limited and depleting swiftly, resulting in detrimental effects on the broader ecology. Global energy consumption has surged by 3000% in the 21st century, highlighting the growing scarcity of renewable supplies. As energy demands escalate, the adverse environmental repercussions are concurrently intensifying. Greenhouse gases are emitted into the atmosphere via fossil fuels, exacerbating perilous climate change. Consequently, there is an urgent necessity to identify a renewable energy source that is non-polluting to satisfy contemporary global demands. The solar energy can be harnessed through several methods, including photovoltaic (PV) technology, which converts solar energy into electricity. Photovoltaic panels convert sunshine into electricity, and solar energy is increasingly gaining appeal and applicability as a sustainable alternative to conventional energy production methods. The performance of photovoltaic devices is significantly influenced by shade levels.

The electrical properties of the chosen PV modules in the array were verified to be equal. These modules exhibit distinct alterations under inhomogeneous insolation, leading to mismatch losses in a photovoltaic system and contributing to photovoltaic aging. To optimize efficiency and energy yield, the design of a photovoltaic system must evaluate performance in various climatic circumstances, including shading, dust accumulation, avian excrement, and structural defects. The aging process affects the energy output and electrical efficiency of a photovoltaic system; if the impact is significant, the system will fail to reach its optimal payback threshold [1]. Due to climatic conditions, the I-V curves deviate from their conventional form, resulting in a substantial decrease in PV array output power [2, 3]. Aging due to external

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causes is a substantial issue in extensive solar photovoltaic arrays. The influence of external factors on the power output of a solar PV system has been extensively examined in previous research [4, 5].

Likewise, power production losses due to aging have garnered much research attention [6, 7]. Environmental factors may reveal numerous local maximum power points (MPPs). The effective monitoring of global maximum power point (MPP) is hindered by local MPP, resulting in suboptimal performance, the formation of hot patches, and accelerated degradation of cells and modules [8, 9]. To provide optimal performance and minimize mismatch losses in a PV system under aging conditions, many connecting topologies for PV modules have been proposed [10, 11]. A multitude of simulation experiments for diverse interconnection configurations of photovoltaic modules were conducted to analyse the electrical behaviour of PV modules [12, 13]. Additionally, researchers have analysed basic interconnection methods, including series and parallel configurations (SP), and their effects on bypass diodes [14, 15]. The power loss in series-connected photovoltaic modules due to mismatching can be alleviated by employing anti-parallel bypass diodes [16]. Moreover, the parallel arrangement had a more pronounced effect under mismatching conditions [17]. An adequate power conditioning system and an appropriate DC-DC converter are essential for managing high current output at low voltage levels in parallel connectivity configurations [18]. Previous literature has demonstrated many connectivity systems, including series-parallel (SP), Total-cross-tied (TCT), Bridge-linked (BL), and Honeycomb configuration (HC), as illustrated in Figure 1. An ideal Sudoku structure was described in the references, which exhibited the drawback of a complex arrangement due to a significant increase in wiring. Piccoli [6]. proposed an alternative methodology that would optimize the utilization of building-integrated photovoltaic (BIPV) systems. A virtual reality environment was employed to analyse the PV modules and adjacent barriers; nevertheless, it did not provide further understanding of the real-time issues associated with different PV array configurations [19].

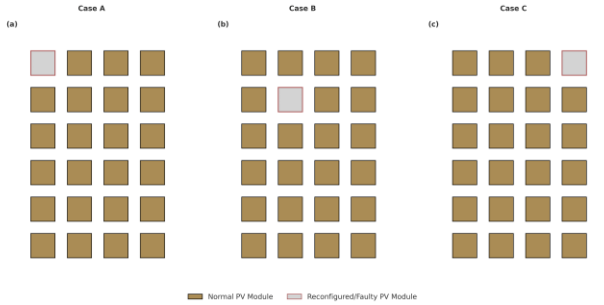

Figure 1: Twenty-five photovoltaic panels are interconnected in (a) series; (b) total current; (c) bypass arrangements.

The study proposed an offline rearrangement method to enhance the energy efficiency of aging photovoltaic (PV) systems by analyzing probable rearrangements of PV modules in accordance with the maximum power point (MPP) [20].

Additionally, employed the Munkres algorithm to assess the ideal configuration for balancing and mitigating the aging process of the switches inside the switching matrix. Issues related to the reorganization of photovoltaic array modules of varying sizes were demonstrated to be efficiently addressed through alternative ways. Conversely, these are exceedingly complex from a computational perspective and require significant time, as it is necessary to explore every potential restructuring alternative [21].

This work aims to propose a method for repositioning aging photovoltaic modules to mitigate the detrimental influence on the photovoltaic system, utilizing indoor experimentation. This will enhance the output capacity of a photovoltaic array, and for the present study requirements, the algorithm can swiftly identify the ideal reconfiguration.

2. Approach

2. 1. Genetic Algorithm (GA) Process for PV Optimization.

Employing GEA enables the identification of the configuration that yields the maximum power from potential connection patterns, while minimizing PV module substitutions. This algorithm's advantages encompass its capacity to do an arbitrary local search to a certain degree. Simultaneously, mutation techniques can expedite convergence to an optimal solution as iterations approach a superior outcome within a certain timeframe. Moreover, precocity is diminished by the presence of several practical solutions. In GEA applications, each configuration must be represented as a numerical row, functioning as a chromosome, while the power output of each configuration is evaluated by a fitness function. Pre-prepared chromosomes constitute the inputs for the fitness function, which the GEA subsequently use to determine the chromosomes picked as parents for the subsequent generation [22]. Consequently, intermittent activation and deactivation of the GEA-calculated PV array module is required, coupled with minimal substitutes.

2. 2. Genetic Algorithm (GA) Process for PV Optimization.

The power output of the PV array is governed by the following equation:

$$PV = \frac{pv_w}{\sum_{j-1}^{n_{pv}} S_{n(j)} v_{oc}} \tag{1}$$

$$j = 1,2,\ldots,n \times m \tag{2}$$

where:

- Sn represents the short-circuit current per module,
- Voc is the open-circuit voltage,
- PV denotes the total power output, and
- npv is the number of modules within the system.

The GEA optimization dynamically restructures the PV array by modifying the connections between modules, aiming to achieve an optimal PV value. Consequently, GEA aims to optimize the PV value, as illustrated in figure 2. To elucidate section (VII) in Table 1. The remaining slots are established according to the relative placements of the parental models. For instance, the chromosome may be represented as the sequence {1, 2, 3, ..., 46}.

2. 3. Structural Representation of 4×6 PV Array.

In a system where PV modules are arranged in a 4×6 PV array, the configuration is represented as follows:

$$n \times m = \begin{bmatrix} PV_{11} & PV_{12} & PV_{13} & PV_{14} & PV_{15} & PV_{16} \\ PV_{21} & PV_{22} & PV_{23} & PV_{24} & PV_{25} & PV_{26} \\ PV_{31} & PV_{32} & PV_{33} & PV_{34} & PV_{35} & PV_{36} \\ PV_{41} & PV_{42} & PV_{43} & PV_{44} & PV_{45} & PV_{46} \end{bmatrix} \tag{3}$$

Each PV element ($PVij$) represents a module in the system, and its placement is optimized through the GA-based reconfiguration.

2. 4. Adapting Genetic Crossover for a 4×6 PV Array.

To represent each chromosome as a 4×6 PV Array, apply crossover and mutation row or column-wise.

Parent One:

$$P_1 = \begin{bmatrix} 8 & 6 & 3 & 5 & 4 & 1 \\ 7 & 2 & 9 & 10 & 11 & 12 \\ 13 & 14 & 15 & 16 & 17 & 18 \\ 19 & 20 & 21 & 22 & 23 & 24 \end{bmatrix} \tag{4}$$

Parent Two:

$$P_2 = \begin{bmatrix} 1 & 7 & 8 & 2 & 5 & 6 \\ 4 & 3 & 9 & 10 & 11 & 12 \\ 13 & 14 & 15 & 16 & 17 & 18 \\ 19 & 20 & 21 & 22 & 23 & 24 \end{bmatrix} \tag{5}$$

2. 5. Crossover applying to the 4×6 PV Array.

Where the randomly selected offspring from parent one and two, Single-Point Crossover (Row-wise) when choosing a random crossover row between row 2 and row 3, and it will swap the lower part:

Offspring One:

$$C_1 = \begin{bmatrix} 8 & 6 & 3 & 5 & 4 & 1 \\ 7 & 2 & 9 & 10 & 11 & 12 \\ \mathbf{13} & \mathbf{14} & \mathbf{15} & \mathbf{16} & \mathbf{17} & \mathbf{18} \\ \mathbf{19} & \mathbf{20} & \mathbf{21} & \mathbf{22} & \mathbf{23} & \mathbf{24} \end{bmatrix} \tag{6}$$

And offspring two from parent two is:

$$C_2 = \begin{bmatrix} 1 & 7 & 8 & 2 & 5 & 6 \\ 4 & 3 & 9 & 10 & 11 & 12 \\ \mathbf{13} & \mathbf{14} & \mathbf{15} & \mathbf{16} & \mathbf{17} & \mathbf{18} \\ \mathbf{19} & \mathbf{20} & \mathbf{21} & \mathbf{22} & \mathbf{23} & \mathbf{24} \end{bmatrix} \tag{7}$$

2. 6. Mutation in a 4×6 PV Array.

Subsequently, access the group from the second mutation point of parent one in equations (4) and (5), and this can be done by swapping PV module positions: Mutation: Swap (8 ↔ 1) in Offspring One

$$C'_1 = \begin{bmatrix} \mathbf{1} & 6 & 3 & 5 & 4 & 8 \\ 7 & 2 & 9 & 10 & 11 & 12 \\ 13 & 14 & 15 & 16 & 17 & 18 \\ 19 & 20 & 21 & 22 & 23 & 24 \end{bmatrix} \quad (8)$$

The GEA converged in 8 iterations, achieving a final fitness value of 302, representing the total sum of the PV panel identifiers in the optimized 4×6 matrix configuration. In Figure 2 value is sufficient to achieve the optimal reconfiguration for exhibiting heterogeneous ageing.

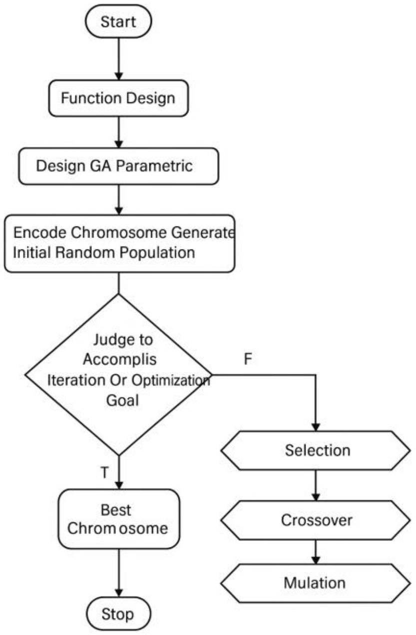

Figure 2: Displayed the GEA procedure of PV array reconfiguration.

3. Results and Discussion

To validate the proposed reconfiguration algorithm, simulations were performed on a 4 × 6 PV array using a PV array model developed in MATLAB. The maximum power outputs for both the baseline configuration and the reconfigured arrangement were obtained to evaluate the performance improvement. Table 1 shows the per-unit values of the PV modules before reconfiguration, while Table 2 presents the array after reconfiguration. As shown, the modules are redistributed in a way that groups weaker modules more effectively, thereby reducing mismatch losses at the string level.

Table 1. Photovoltaic array **Before** reconfiguration.

0.9 p.u.	0.8 p.u.	0.9 p.u.	0.7 p.u.	0.7 p.u.	0.8 p.u.
0.9 p.u.	0.9 p.u.	0.8 p.u.	0.9 p.u.	0.8 p.u.	0.6 p.u.
0.7 p.u.	0.7 p.u.	0.9 p.u.	0.9 p.u.	0.9 p.u.	0.7 p.u.
0.8 p.u.	0.5 p.u.	0.9 p.u.	0.8 p.u.	0.5 p.u.	0.9 p.u.

Table 2. Photovoltaic array **After** reconfiguration.

0.9 p.u.	0.8 p.u.	0.9 p.u.	0.7 p.u.	0.7 p.u.	0.8 p.u.
0.9 p.u.	0.9 p.u.	0.8 p.u.	0.9 p.u.	0.8 p.u.	0.7 p.u.
0.7 p.u.	0.6 p.u.	0.9 p.u.	0.9 p.u.	0.9 p.u.	0.7 p.u.
0.8 p.u.	0.5 p.u.	0.9 p.u.	0.8 p.u.	0.5 p.u.	0.9 p.u.

Table 3. The parameters of the 4 x 6 PV array before to and after arrangement.

Parameters	**Before**	**After**	**Power Improvement**	**Computing Time (s)**
Current $_{\text{GMPP}}$	2.59 A	2.63 A	-	-
Voltage $_{\text{GMPP}}$	48 V	48 V	1.93 %	10.37
Power $_{\text{GMPP}}$	124.4 W	126.8 W	-	-

According to the numerical evaluation shown in Table 3, the voltage at the GMPP stayed constant at 48 V, but the array current increased from 2.59 A to 2.63 A. This resulted in a relative gain of 1.93% as the output power increased from 124.4 W to 126.8 W. The computation duration of the algorithm to reach this result was about 10.37 seconds.

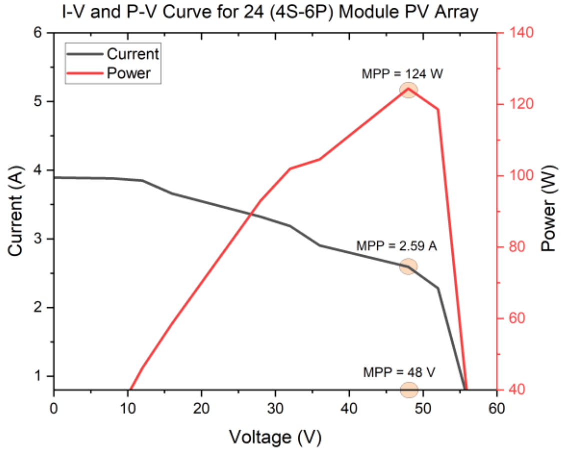

Figure 3: The 4 x 6 photovoltaic array presents power output figure before arrangements.

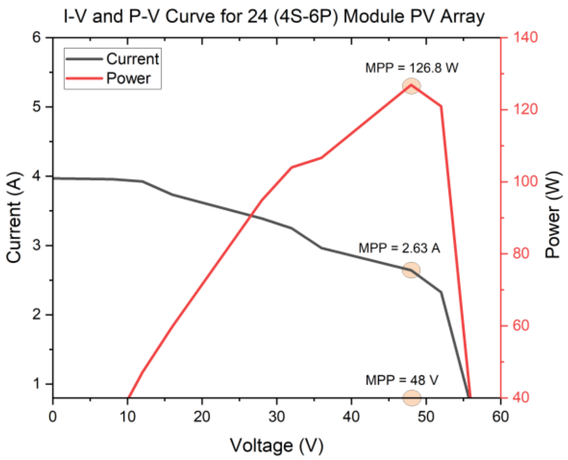

Figure 4: The 4 x 6 photovoltaic array presents power output figure after arrangements.

The findings suggest that the proposed algorithm applies to various sizes of PV arrays in a random manner. The results demonstrate that the algorithm enhanced maximum power output in this case. Furthermore, the algorithm mitigated the influence of the bypass diodes by reorganising the arrangement of individual PV modules inside each string, according to their respective ageing factors. This reduced the effect of mismatch losses across PV modules in any designated string, while voltage limitations were not addressed. This has been addressed in other literature. The suggested algorithm employs a hierarchical and iterative sorting method for photovoltaic modules. The P-V curves, illustrated in Figures 3 and 4, indicate that the impact of PV module mismatch diminished before and after the arrangement.

This demonstrates that the maximum power before 124.4 W and the maximum power after 126.8 W show a significant improvement, indicating that rearranging the PV array is a critical method for reducing operational costs and improving system efficiency.

Overall, these findings underscore that PV array reconfiguration—when guided by a structured algorithm—can serve as a practical and low-cost method for improving energy yield. Even small improvements on the order of 2% can accumulate to significant energy and economic benefits over the operational lifetime of large-scale PV systems.

5. Conclusion

Overall, these findings underscore that PV array reconfiguration when guided by a structured algorithm can serve as a practical and low-cost method for improving energy yield. Even small improvements on the order of 2% can accumulate to significant energy and economic benefits over the operational lifetime of large-scale PV systems.

The results demonstrated that the algorithm effectively reduced the impact of mismatch among PV modules through a process known as 'reconfiguration'. After this reconfiguration, the array current at the global maximum power point increased from 2.59 A to 2.63 A, while the voltage remained constant at 48 V. Consequently, the power output improved from 124.4 W to 126.8 W, corresponding to a relative gain of 1.93%. Although modest, this improvement aligns well with gains reported in recent literature and confirms the ability of reconfiguration strategies to enhance array efficiency without requiring additional hardware.

The findings highlight that even minor improvements can translate into significant long-term benefits, particularly in large-scale PV installations where cumulative energy yield improvements reduce operational costs. Furthermore, the study emphasises that reconfiguration can serve as a low-cost, algorithm-driven method to mitigate the influence of 'bypass diodes', which are components in a PV system that allow current to bypass a shaded or faulty module, and uneven module aging.

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