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Optimum Power Extraction from Non-Uniform Aged PV Array Using Current Collector Optimizer Topology

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Harsh outdoor operating circumstances of photovoltaic (PV) array leads to non-uniform aging phenomenon among PV panels which in turn reduces the life span of the PV modules and the energy efficiency of the whole array. Under non-uniform aging conditions for series-parallel (SP) connected PV modules, the characteristics of the entire PV array are deformed resulting in multiple peaks where one of them is the global peak. The appearance of such multiple peaks can mislead traditional maximum power point tracking (MPPT) techniques to get trapped at local peaks, which leads to misleading power losses. This paper proposes a current collector optimizer (CCO) topology to extract maximum power from a non-uniform aged PV array. By using CCO topology, the PV array characteristics have a unique maximum power point (MPP) which easy to follow by a simple MPPT algorithm. Consequently, the proposed topology does not suffer from misleading power losses. Besides, the CCO topology requires offline rearrangement of aged modules to obtain the optimal maximum power. A comparative study is conducted to demonstrate the efficacy of the proposed topology. Ultimately, the paper presents an offline algorithm for rearranging erratic aged CCO modules to extract the optimum power from large-scale PV arrays.

K e y w o r d s : *photovoltaic system; current collector optimizer (CCO); non-uniform aging; PV array characteristics; mismatch power losses; offline rearrangement; reconfiguration techniques.*

I. Introduction

Over previous decades, an extensive amount of photovoltaic power plants have been installed worldwide [1], [2]. Under outdoor operating circumstances of PV plants, the PV arrays are subjected to several faults and harsh climate conditions such as dust, snow, rains, humidity, and temperature as well as potential risks from bird-dropping, partial shading, hotspot, or corrosion which affect the life span of PV panels and reduce their efficiency [3]—[5]. In general, the aging is often distributed unequally among modules of a PV array which leads to mismatch problem [1], [2]. Indeed, non-uniform aging causes mismatching among PV modules, while mismatching leads to faster aging, which is a prevalent issue in PV systems [6], [7].

For a non-uniform aging array, the mismatch power losses can be divided into three categories. The first category of power losses is due to a current mismatch between series-connected PV modules in a single string. In this case, bypass diodes are connected in parallel across each series module to protect PV panels from the hotspot effect. Under this situation, it is not possible to capture the maximum power from all series PV modules as they have different maximum power point (MPP) currents [3], [4], [8].

The second category is the power losses due to a voltage mismatch between parallel-connected PV modules or strings, which causes circulating currents between parallel branches. To overcome the presence of circulating currents, blocking diodes are connected in series to each PV string or parallel module. However, there is also power losses in these blocking diodes and mismatch still exists between parallel branches. Therefore, it cannot harvest the maximum power from all parallel branches because of their dissimilar MPP voltages [3], [4], [8].

The last category is misleading power losses due to false tracking of global maximum power point (GMPP), where the electrical characteristics of PV array exhibit multiple peaks in which one of them is the global peak. Although these misleading losses can be mitigated by using advanced maximum power point tracking (MPPT) algorithms, the MPP tracker cannot exploit the maximum power generated from non-uniform aged PV arrays, where a portion of power is lost in blocking diodes and bypass diode loops [8], [9].

From an investment perspective, superseding the aged modules by new ones is not an economical solution. In addition, PV modules of the same brand and ratings are not typically symmetrical due to fabrication tolerances or material imperfections, which also causing mismatch power losses [1], [2], [6], [10].

The most typical solutions to improve the efficiency of the non-uniform aging modules are AC-module inverters, which utilize micro-converters for each individual PV module to adopt distributed MPPT. The prime downsides of AC-module inverters are high expenditure and increased system intricacy since the number of micro-converters is proportional to that of PV modules [11], [12].

Another effective solution to enhance the power extracted from the non-uniformly aging array is reconfiguring PV modules as in references [1], [2], [6], [13]–[17]. However, reconfiguration minimizes the mismatch power losses but does not eliminate them. Furthermore, reconfiguration techniques suffer from misleading power losses, as the characteristics of PV array manifest multiple MPPs and need to adopt an advanced MPPT algorithm to track the GMPP [8], [11].

In references [11], [18], the authors proposed a newly centralized inverter topology based on a novel photovoltaic current collector optimizer (CCO) to improve the power yield from PV array and avoid the misleading power losses under partial shading or mismatch conditions. In this paper, the performance of the PV array with CCOs is evaluated in order to extract the maximum power under non-uniformly aging conditions of PV modules.

II. Current Collector Optimizer (CCO) topology

Figure 1 shows a schematic diagram of the proposed CCO topology. As can be seen, every eight modules or substrings are grouped to CCO as a single stack and then these stacks may be connected in series-parallel configuration to the grid via an inverter. Figure 2 illustrates the circuit diagram of the CCO. This circuit is a modified circuit that is used to harvest the current generated from MHD-generator electrodes', that have different voltages [19]. The main idea of the CCO is to find a way to harvest the currents from PV modules or substrings at approximately MPP voltages under non-uniform aging conditions.

As depicted in figure 2, all PV generators negative terminals' are gathered to a common negative line while each positive terminal is connected to thyristor-bridge and then all bridges are collected in a common positive line. The H-bridges are interconnected with each other through eight capacitors and transformers. The bridge thyristors' are triggered as in ordinary H-bridge. Thus, the upper and lower capacitors between adjacent PV generators alternatively change their polarities every half cycle. Forced commutation of thyristors is carried out during discharge of coupling condensers. Figure 3 shows the voltage waveforms across upper capacitors and the corresponding current and voltage waveforms of the SCRs during steady-state operation of the CCO (Note: the voltage waveforms across lower capacitors are out-of-phase with upper ones).

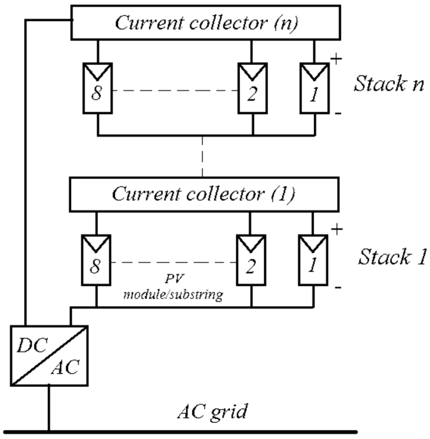

Figure 1. A schematic diagram of the CCO topology

The coupling transformers are symmetrically linked to each other concerning the power production section center. Their function is to compensate the voltage difference among parallel PV modules; under mismatch condition, to a current consolidation point v_{stack}. During steady-state conditions, the total power of a single stack CCO is defined by the sum of all PV generator current and the average voltage of the PV modules, further details about operation of CCO can be found in [11], [18].

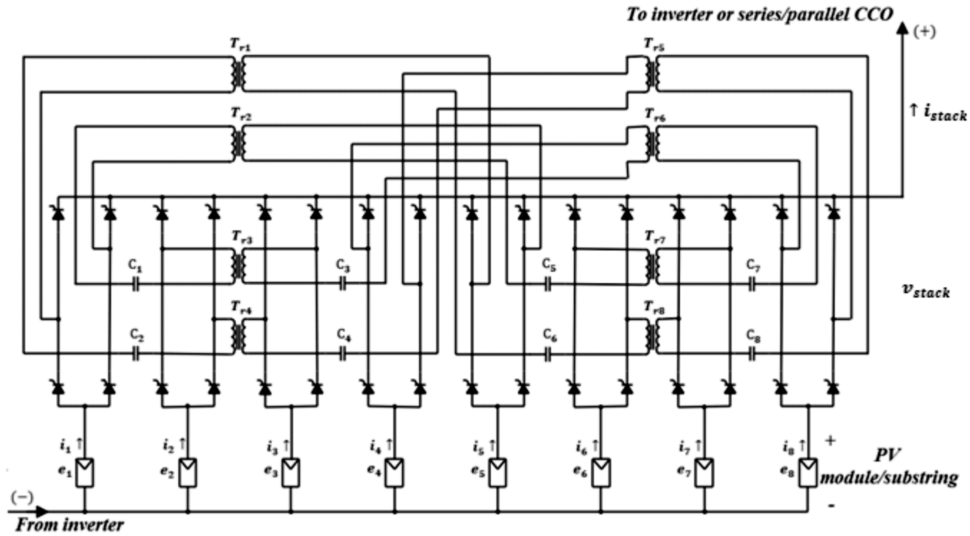

Figure 2. The circuit diagram of the CCO

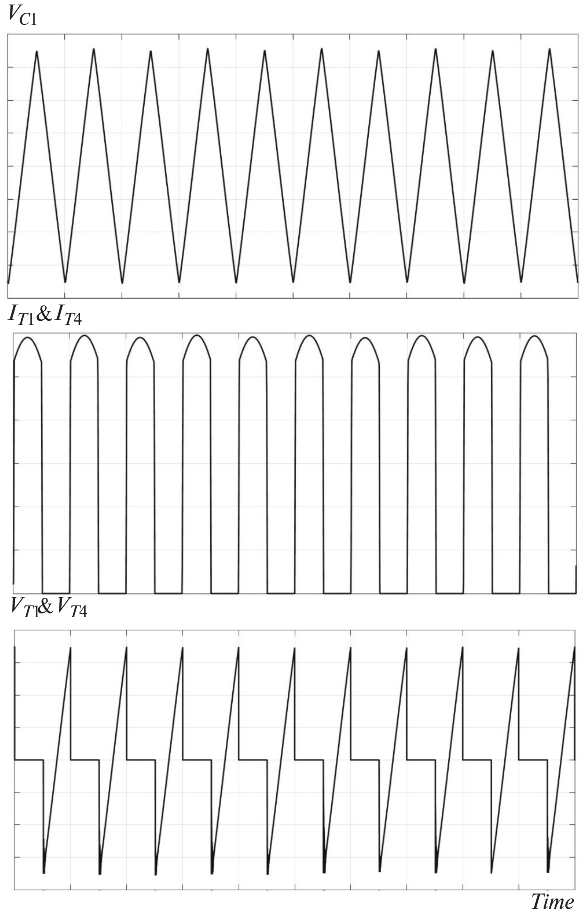

Figure 3. The voltage across upper condensers and the corresponding current and voltage waveforms of the SCRs

$$v_{stack} = \frac{1}{8}\sum_{n=1}^{8} K_{oc_p} e_p; \tag{1}$$

$$i_{stack} = \sum_{n=1}^{8} K_{sc_p} i_p; \tag{2}$$

$$P_{stack} = v_{stack} i_{stack}. \tag{3}$$

Where v_{stack} is the stack voltage, i_{stack} is the stack current, P_{stack} is the stack power, are the currents generated by PV modules, and e_p are the voltage across PV modules. While K_{oc_p} and K_{sc_p} are the aging coefficients for the open-circuit voltage and short-circuit current.

III. Performance of Non-Uniform Aged PV Array

Once a PV cell is exposed to aging, the electrical parameters of the PV module are changed from their nominal values. Because of the p-n junction properties of the PV cell, the short-circuit current has a substantial degradation level compared to a small one for open-circuit voltage when PV module undergoes outdoor aging experiments [20]. In other words, the degradation rate of the maximum power of the aged PV module is close to the rate of change of short-circuit current.

In this section, a case study is performed on MATLAB/Simulink to compare the performance of CCO topology and central SP array topology under non-uniform aging conditions of PV modules. For simplicity, assuming that all PV cells in the PV module are subject to uniform aging to represent the entire PV module by a single short-circuit current and a single open-circuit voltage. For all simulations, the whole PV array is operating under standard test condition (STC) in order to eliminate the mismatch power losses due to partial shading.

Consider a small size SP photovoltaic array with bypass diodes composed of 40 aged modules. The PV array consists of 8 parallel strings each comprised of 5 series modules. The PV module is represented by one diode model as described in reference [21]. For simulation purposes, a commercial PV module, i.e. Suntech Power PLUTO250-wdb, has been picked. The most significant specifications of this module are given in table 1.

***Table 1**. Module Parameters*

Parameter	Value
Output power at MPP	250 W
Voltage at MPP	30.8 V
Current at MPP	8.12 A
Open circuit voltage	37.1 V
Short circuit current	8.75 A

Assuming that the short-circuit current is used to evaluate the aging status of the PV module, while the open-circuit voltage is kept constant for different aging conditions (i.e. the maximum power of the PV panel is impacted only by the change in the short-circuit current). Supposing the open-circuit voltage and short-circuit current equal to 1 per unit (p.u) for a healthy module under STC. Therefore, the open-circuit voltage is set to 1 p.u for each module, while the short-circuit current is changed as a result of the aging process. Figure4 illustrates the effect of change of short-circuit current on the I-V characteristics of the

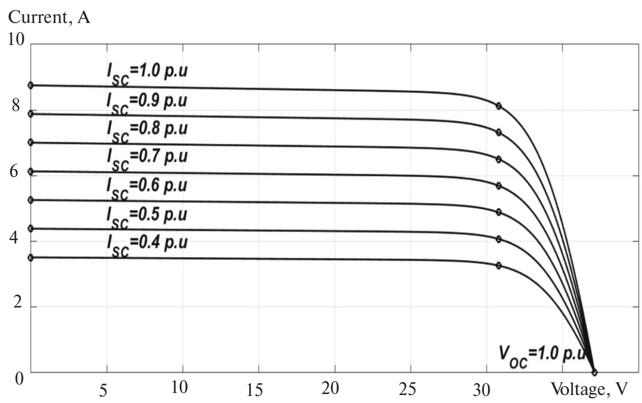

Figure 4. The module I-V characteristics for different short-circuit current aging factors at STC

PV module. For each aging situation, the five-parameters of PV single exponential model are adjusted so that the change of short-circuit current and open-circuit voltage are proportional to the change of the MPP current and MPP voltage, respectively.

As shown in table 2, the digits in the PV array stand for the different aging factors of the PV modules that are proportional to the short-circuit currents. It should be noted that the expected maximum power that can be obtained from the array is equivalent to only 26 modules (i.e. the maximum power equals 6.5 kW instead of 10 kW for the 40 healthy modules), which is the sum of all the aging coefficients of the short-circuit current.

Table 2.

Distribution of the short-circuit current aging factors along the array

	Column (string)							
	0.9	0.7	0.7	0.6	0.6	0.5	0.5	0.8
	0.8	0.8	0.6	0.5	0.7	0.7	0.4	0.6
Row (module)	0.5	0.4	0.4	0.6	0.8	0.6	0.5	0.8
	0.7	0.6	0.7	0.7	0.9	0.9	0.8	0.7
	0.9	0.8	0.6	0.8	0.5	0.5	0.4	0.5

The I-V and P-V characteristics of the entire SP array topology are shown in figure 5 by the dotted lines. As can be seen from curves, the electrical characteristics are deformed and multiple MPPs are observed. The voltage and current coordinates for the global MPP (GMPP1) are (163.05 V, 31.11 A) with maximum output power equals 5072 W. That means the mismatch power loss of the non-uniform aged PV array equals 1428 W, which is a significant power loss approximately 22% of the expected output power. Moreover, if the MPP tracker fails to track the global MPP, a misleading power loss is added to the aforementioned mismatch losses.

In fact, due to a current mismatch among series PV modules under this situation, each PV string current is limited by a minimum current of the un-bypassed module of those strings. Reconfiguration methods can be used to improve the performance of the non-uniform aged PV array by relocating the PV modules so that the rate of change of current in each string is small. Although reconfiguration techniques can mitigate these mismatch power losses, they do not totally eliminate them in case of SP array topology.

Now consider the (5Ч8) non-uniform aged PV array is stacked through 5 series-connected CCOs. To demonstrate the feasibility and the effectiveness of the proposed topology, its performance is re-evaluated under the same assumptions. The I-V and P-V characteristics of the CCO topology during the simulation run are shown in figure 5 by dashed lines.

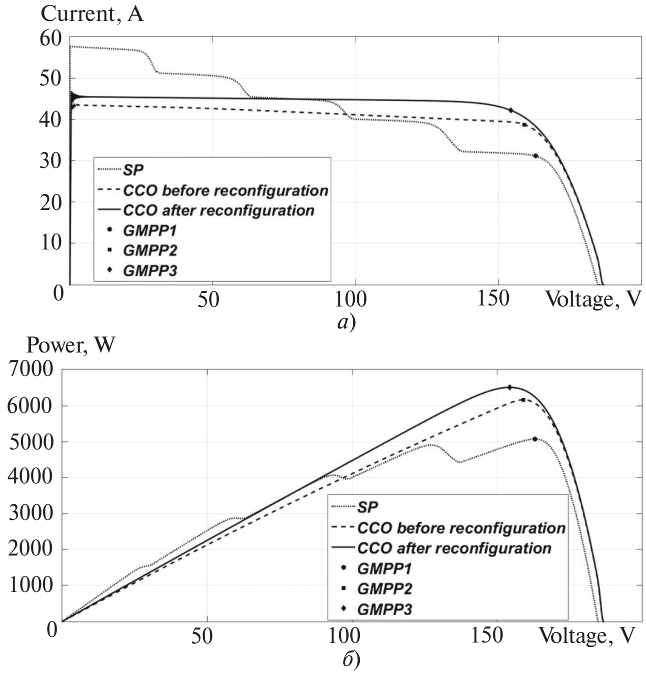

Figure 5. The characteristics of the PV array for both topologies: (*a*) the I-V curves and (*b*) the P-V curves

As can be seen, the PV array curves have a unique MPP which easy to follow by a simple MPP tracking algorithm. The global MPP (GMPP2) is located at coordinates of (159.13 V, 38.74 A) and the maximum output power is 6165 W. This means the maximum output power is increased by 1093 W compared to SP array with bypass diodes topology (i.e. the power loss reduced to only 5% of the total expected output power). However, there is a power loss equals 335 W due to a current mismatch between series-connected CCOs.

Table 3

Illustration of the rearrangement process of the aged PV panels

Before Rearrangement								K_G
0.9	0.7	0.7	0.6	0.6	0.5	**0.5**	0.8	5.3 pu
0.8	0.8	0.6	0.5	0.7	0.7	**0.4**	0.6	5.1 pu
0.5	0.4	0.4	0.6	0.8	**0.6**	**0.5**	0.8	4.6 pu
0.7	0.6	0.7	0.7	0.9	**0.9**	**0.8**	**0.7**	6.0 pu
0.9	0.8	0.6	0.8	0.5	0.5	0.4	**0.5**	5.0 pu
After Rearrangement								K_G
0.9	0.7	0.7	0.6	0.6	0.5	**0.4**	0.8	5.2 pu
0.8	0.8	0.6	0.5	0.7	0.7	**0.5**	0.6	5.2 pu
0.5	0.4	0.4	0.6	0.8	**0.9**	**0.8**	0.8	5.2 pu
0.7	0.6	0.7	0.7	0.9	**0.6**	**0.5**	**0.5**	5.2 pu
0.9	0.8	0.6	0.8	0.5	0.5	0.4	**0.7**	5.2 pu

This current mismatch can be treated by relocating the PV modules such that all CCOs get the same sum of current aging coefficients ($K_G = \sum_{p=1}^{8} K_{sc_p}$). A set of optimal solutions can be acquired, one of which is illustrated in table 3. As shown below, the is identical for all optimizers, so the optimal maximum output power is obtained. Figure 5 shows the corresponding I-V and P-V characteristic curves after rearrangement of PV panels by solid lines. The new global MPP (GMPP3) coordinates become (153.98 V, 42.17 A) with a maximum output power of 6493 W, which is approximately the total expected maximum output power from the aged PV array.

IV. Reconfiguration algorithm for CCO topology

This section presents a simple reconfiguration algorithm for extracting optimum power from CCO topology and eliminating mismatch power losses for large-scale non-uniformly aged PV plants. This reconfiguration strategy requires information about the per unit value of K_{sc} of each PV module which is proportional to the short-circuit current. The idea of the proposed algorithm is to keep swapping PV modules from one CCO to another until all CCOs have the same K_G. At this point, the optimal solution is obtained as there is no current mismatch between optimizers. The flowchart of the proposed CCO topology reconfiguration strategy is as shown in figure 6. The algorithm can be described throughout the following five steps.

Step 1: Calculate the optimal value of K_G for all CCOs as given in (4)

$$K_G^* = \frac{1}{n}\sum_{n=1}^{N} K_G. \quad (4)$$

Where n is the number of utilized CCOs.

Step 2: Select the two PV modules to be replaced in order to obtain a better equalization of K_G.

a) Calculate K_G for each CCO from 1 to N and arrange them in descending order (for $n=\overline{1,N}$).

b) Identify the two CCOs with the highest and lowest value of K_G.

c) Swap all PV modules one by one in the two identified CCOs that have the highest and lowest value of K_G.

Step 3: Minimize the difference between K_G of the two selected CCOs.

a) At each swap, the new value K_G for both CCOs will be calculated and the swap will only be approved if the CCO with the lowest K_G does not exceed the optimal value (K_G^*).

Step 4: Repeat the process to minimize the differences between the K_G for all CCOs.

a) If a swap is approved, repeat step 2 and step 3 until the CCO with the lowest value of K_G is reached to the optimal value K_G^*.

b) Otherwise, go to the next CCO with the second-highest (then third-highest, fourth-highest, etc.) value of K_G until no swap can be approved.

Step 5: Check if all CCOs have the optimal value (K_G^*).

a) If the number of the CCOs (N), that have K_G^* is less than the total number of CCOs (n), go to step 3(b).

b) Otherwise, optimum CCO topology configuration is achieved.

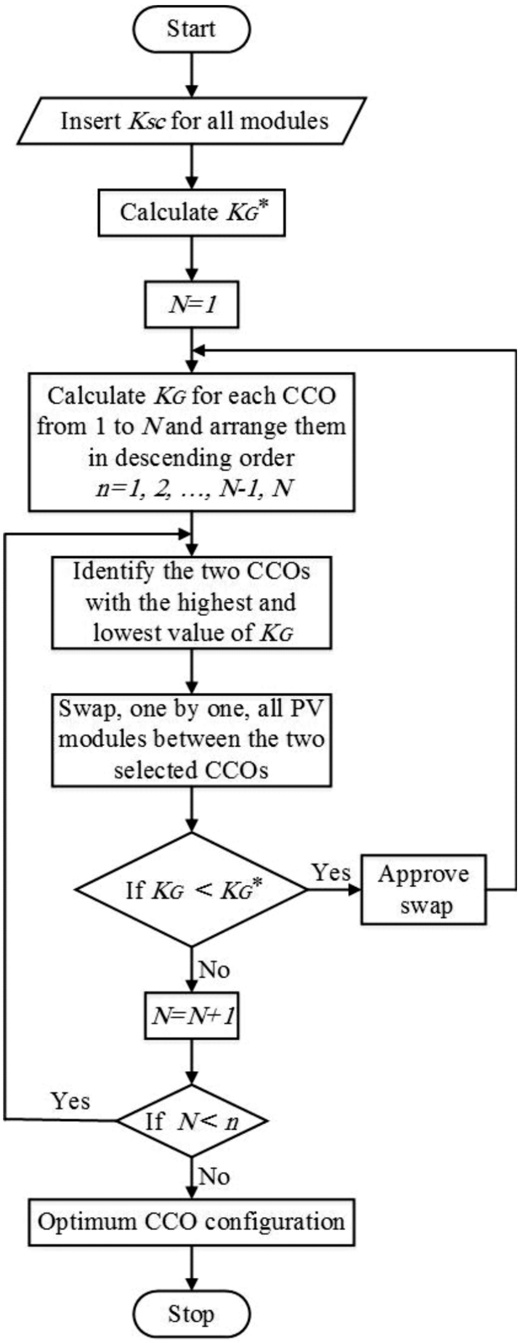

Figure 6. The reconfiguration strategy flowchart

V. Conclusion

This paper proposed a CCO topology to extract maximum power from a non-uniform aged PV array without replacing the aged panels by new ones. Computer simulations on Matlab/Simulink have been carried out in order to confirm the performance of the proposed topology. According to simulations results, the power extracted from non-uniformly aged PV array based on CCO topology is significantly increased compared to conventional SP array topology with bypass diodes. With CCO topology, the percentage of power saving compared to SP array topology before rearrangement of PV panels is 16.82% and after rearrangement is increased to 21.86% (i.e. about 99.9% of expected power is extracted). Finally, the paper proposed a simple reconfiguration algorithm to extract optimum power from non-uniformly aged modules for large-scale CCO topology applications. This reconfiguration strategy requires inexpensive instruments to periodically perform short-circuit current inspections of PV modules during maintenance. Thus, the proposed algorithm can substantially improve energy efficiency as well as profitability for any PV system scale.

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Оптимальное извлечение энергии из неоднородно стареющего фотоэлектрического массива с использованием сумматора тока

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Сложные условия эксплуатации фотоэлектрической матрицы на открытом воздухе приводят к неравномерному старению фотоэлектрических панелей, что сокращает срок службы фотоэлектрических модулей и энергетическую эффективность всей матрицы. При неравномерных условиях старения для последовательно соединенных фотоэлектрических модулей характеристики всей фотоэлектрической матрицы изменяются, что приводит к появлению многих пиков на кривой оптимального отбора мощности, лишь один из которых соответствует глобальному оптимуму. Появление дополнительных пиков вызывает ошибки в работе традиционных и широко используемых методов отслеживания точки максимальной мощности, что приводит к дополнительным потерям мощности. Эта статья предлагает использование сумматора тока для извлечения максимальной мощности из неоднородного фотоэлектрического массива. При использовании сумматора тока характеристики массива фотоэлектрических матриц приобретают уникальную форму, благодаря которой максимальная мощность определяется однозначно, даже если следовать простому алгоритму ее определения. Следовательно, предложенное решение позволяет избежать потерь мощности. Проведено сравнительное исследование для демонстрации эффективности предложенного решения. В конечном итоге, в статье представлен автономный алгоритм перестановки устаревших модулей для извлечения оптимальной мощности из крупномасштабных фотоэлектрических массивов.

Ключевые слова: *фотоэлектрическая система, сумматор тока, неравномерное старение, характеристики фотоэлектрической матрицы, потери мощности, перестановка модулей, методы реконфигурации*

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