Non-uniform Aged Modules Reconfiguration for Large Scale PV Array

Abstract—**In the past decades, a large number of photovoltaic (PV) plants have been built. Due to the minor physical differences between PV cells and the influence of environmental factors such as rains, temperature and humidity, the aging of a PV array is often distributed unevenly within each PV module. This non-uniform aging causes further decreased output power, which is often easily observed for large size PV arrays. Although the global maximum power point tracking (GMPPT) strategy can improve the output power, the GMPPT cannot exploit the maximal power generation potential from non-uniform aging PV arrays. In order to exploit further the power generation potential and extend the service time of non-uniform aging PV arrays, a novel PV array reconfiguration method is developed in this paper. The concept of cell-unit is applied to investigate the aging phenomenon of PV modules, and each PV module is assumed to be composed of 3 sub-modules, while these 3 sub-modules within any single PV module might have different aging conditions and thus different power output capacities. The challenge is how to rearrange the PV array under the cases where (i) each PV module has non-uniformly aged cell-units; (ii) there are a large number of PV modules; (iii) the voltage working range is restricted. To solve these problems, a nonlinear integer programming problem is formulated to maximize the power output under the constraints of non-uniformly aging and voltage restrictions. A small size 7×10 PV array is simulated to illustrate the proposed method. Furthermore, medium size 20×10 and large size 125×20 PV arrays are employed to verify the feasibility of the proposed method. A 1.5 kW 2×4 real PV array under non-uniform aging conditions is presented and experimentally tested to confirm the proposed rearrangement method.**

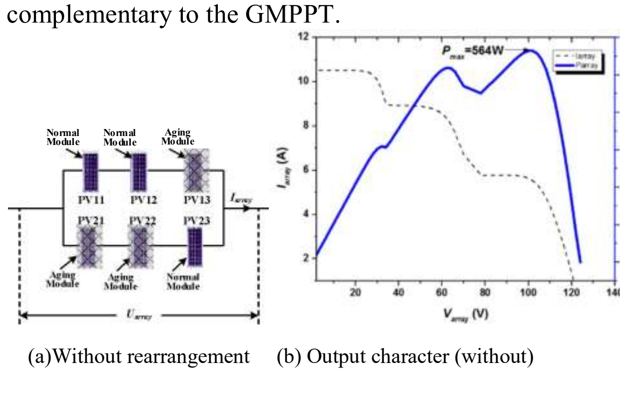
Index Terms—**Photovoltaic array, non-uniform aging, reconfiguration, cell-unit.**

I. INTRODUCTION

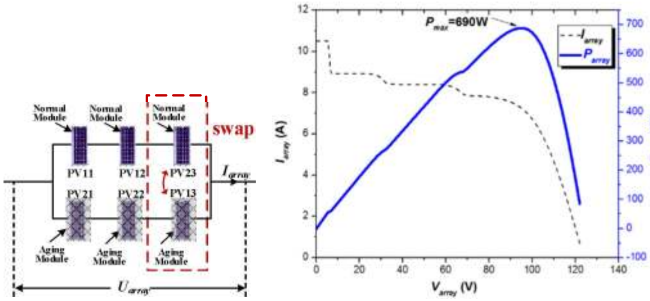
Solar energy is a popular solution for sustainable development that has received much attention across the globe over the last decades [1]-[6]. Currently, photovoltaic (PV) power devices are gaining in popularity in the global renewable energy market, primarily owing to the continuously reducing manufacturing costs of PV panels and technical progress in power conversions [7]-[8]. There is a great need to achieve high solar energy conversion efficiency and extended PV array service time due to considerations on capital and operational costs of PV plants.

During the operation of PV systems, PV arrays suffer from various forms of system faults, which include temporary obstructions such as shadow, dust and bird drop, and also permanent degradation like degraded performance or failure of PV cells or diodes. According to the research results from the National Renewable Energy Laboratory (NREL) [9, 10], the aging speed in the PV array is non-uniform, the PV module degradation satisfies Gaussian distribution, and the PV module degradation speed is 0.5% per year. Therefore, it is important to investigate PV power generation maximization technologies for aged PV arrays so that these PV plants can have extended life cycle with maximized power output.

In order to improve the PV power output efficiency, there are typically two solutions. The first one is to use global maximum power point tracking (GMPPT) strategy to pursue high energy conversion efficiency. Although GMPPT can improve the PV array output efficiency under fault conditions compared to traditional MPPT, there are still power generation capacities not being fully developed. In order to fully explore PV array generation capacity under fault or aging conditions, the second solution is proposed, which employs on-site PV array reconfiguration to improve PV array efficiency. The work in [11] developed a model-based reconfiguration algorithm to realize fault-tolerance operation. Similarly, reference [12] developed a switch matrix to reconfigure the PV array according to the influence of shadow. The work in [13] developed dynamic photovoltaic arrays (DPVAs) utilizing the "irradiance equalization" reconfiguration strategy to achieve over 10% improvement in efficiency. Reference [14] employed "Irradiance Equalization Index" and online computation to reconfigure the PV array by a 3×3 switch matrix. At the modular level, paper [15] developed a PV module reconfiguration control algorithm. Reference [16] developed an improved strategy which combines power channels and relays to combat the shadow influence. Fig. 1 is an example to illustrate the difference between the first solution (GMPPT) and the second solution (reconfiguration). From Fig.1(a), the global maximum power is 564W. By the GMPPT, the non-uniform aging PV array can generate 564W before reconfiguration. Fig.1 (b) presents the output characteristics after the reconfiguration, the global maximum power points is 690W, which represents a power generation improvement of 22.3% after reconfiguration. In order to achieve the maximum efficiency operation, both of the GMPPT strategy and reconfiguration strategy are needed to work together so that the PV array always generates the maximal possible power. Therefore, the reconfiguration aging array rearrangement is complementary to the GMPPT.



(a)Without rearrangement (b) Output character (without)



(c) With rearrangement (d) Output character (With)

Fig. 1 Maximum power generation with and without rearrangement

For on-site reconfiguration, in order to search the best reconfiguration, a fast mathematical searching mechanism needs to be developed to consider the fault condition of each PV module. Reference [17] proposed a classical optimization algorithm to reconfigure a reconfigurable total cross-tied (RTCT) array. Tested on a 6×4 PV array, a branch and bound algorithm was employed to minimize the cost, while the algorithm still needs much computational efforts. Tabular search method was developed in [18] and tested for a small scale PV array (24 PV modules), it is almost impossible to use this method for large PV arrays due to its computational complexity. For a 3×2 PV array, reference [14] reduced the searching space by fixing the number of modules per row, while paper [19] developed an exhaustive searching algorithm in a 3×2 PV array. In order to speed up the configuration selection process, paper [20] developed a sorting algorithm based on the best–worst paradigm and applied this method to a 3×3 array. The fuzzy logic algorithm was also proposed to search for the best reconfiguration [21]. The work in [22] presented the summary of the state-of-the-art online reconfiguration of PV arrays.

Although references [11-22] present various on-site reconfiguration methods, these studies either assume the uniformly distributed fault conditions, or rely on exhaustive searching techniques. Paper [23] proposed a fast online reconfiguration algorithm which can be applied to non-uniformly distributed fault/aging conditions, and it simplifies computational complexity by using approximated values of maximum power point current and voltage to screen the maximum power point. Its convergence for extremely large scale PV arrays (e.g. 125×20) is unclear when candidate maximum power point current/voltage is widely distributed. Reference [24] proposes a genetic algorithm to solve the rearrangement problem, however it does not provide a mathematically explicit formulation and thus restricts the application of other optimization algorithms. . Note that a real PV module consists of many cell-units, which is composed of PV cells and connected in parallel with a bypass diode to restrict hotspots in the PV module, as shown in Fig.2 (a). The corresponding PV array is also formed by many cell-units while all those cells are aggregated in the format of PV modules, as illustrated in Fig.2 (b). The fault conditions of those cell-units in a module may be different, and in most cases, these cell-units can be grouped into three sub-modules, each sub-module has roughly the same fault conditions. Although a few algorithms from [11-23] can solve the non-uniform fault/aging conditions, they are usually not effective to solve PV rearrangement problems with extremely large sizes and potentially widely distributed aging conditions. Therefore, it is necessary to formulate this rearrangement problem as an explicitly defined nonlinear integer programming problem so that any efficient optimization algorithm, either an existing one or some efficient one to be developed in the future, can be applied to find the maximum power. Computational challenges for the application of those exhaustive searching based algorithm to large size PV arrays (e.g. an array larger than 10×10) are explained below. When each module is divided into 3 sub-modules, a 10×10 PV array will have 10×30 sub-modules to be considered, which increases significantly computational complexity. Many existing reconfiguration algorithms need to search all possible combinations of rearranged PV modules, and the 3 sub-modules in each PV module should not be physically decomposed and moved to different PV strings. For a $p \times s$ PV array, the total number of possible reconfigurations is $\binom{ps}{s}\binom{(p-1)s}{s}\binom{(p-2)s}{s}\dots\binom{2s}{s}\binom{s}{s}/p!$, which increases very fast when p and s increase, and it equals 3 for $p = s = 2$, 280 for $p = s = 3$, 5.1947×10^{12} for $p = s = 5$, 6.4955×10^{85} for $p = s = 10$. For $p = 20$ and $s = 10$, Matlab can only estimate that this is a very big number greater than 1×10^{15} and cannot give its exact value; and for $p = 125$ and $s = 20$, Matlab cannot calculate and returns an infinite value. The above algorithms, particularly those branch and bound technique based methods, need to search over these possible number of reconfigurations. For smaller p and s, such as $p = s = 3$, it is still possible to search these combinations, for $p = s = 10$, it is very challenging to search 6.4955×10^{85} possible combinations. For larger values, such as $p = 20$ and $s = 10$, or $p = 125$ and $s = 20$, the storage of all these combinations in a computer become impossible, and those existing algorithms turn to be infeasible since they either require all those combinations to be stored in the computer, use exhaustive searching techniques, or evaluate functions at tremendously large number of possible combinations.

Therefore, there are three challenges for PV array reconfiguration:

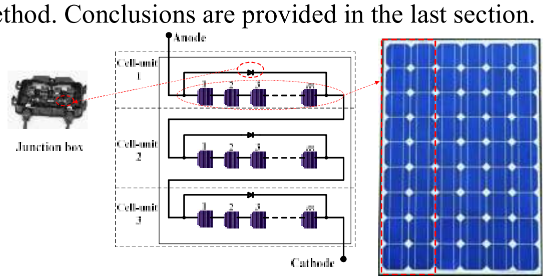
(1) to consider non-uniform aging of cell-units for large size PV arrays,

(2) to design efficient and fast reconfiguration algorithms for large size PV arrays;

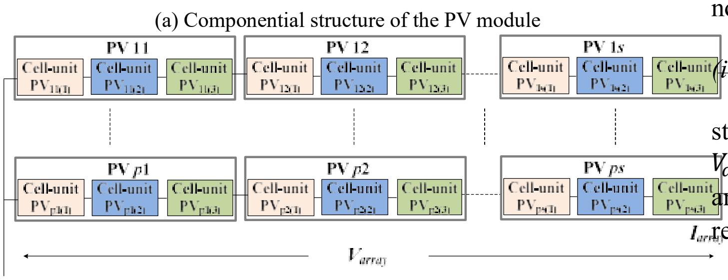
(3) to optimize the proposed algorithm considering the limits of PV array output voltage.

For large scale PV arrays, the non-uniform aging phenomenon increases computational challenges for reconfiguration algorithms. This paper aims to solve the above challenges by formulating them into a constrained nonlinear integer programming problem, which can be solved by any popular algorithms, such as any of the intelligent computing algorithms. Obviously, the maximum power can only be achieved by searching those $\binom{ps}{s}\binom{(p-1)s}{s}\binom{(p-2)s}{s}\dots\binom{2s}{s}\binom{s}{s}/p!$ combinations for a $p \times s$ PV array. A difficulty in designing such a searching algorithm is to represent all these combinations for large p and s so that all the combinations have equal opportunity to be searched and evaluated. A modern Fisher-Yates Shuffle method [25, 26] is adopted to randomly generate permutations for the sequence of natural numbers (1, 2, …, ps), then each of these obtained permutations is further mapped to a reconfiguration of the $p \times s$ PV array. The searching of the best possible combination to achieve maximum power output is transformed into the solution of a nonlinear constrained integer programming problem. Intelligent computing based algorithms can then be applied to solve this optimization problem. As an example, this paper uses genetic algorithm to solve the obtained optimization problem. This reconfiguration algorithm is tested for a 20×10 PV array and a 125×20 PV array using various randomly generated data, and it is observed that the maximum power output has been improved from 6% to more than 10% depending on the characteristics of the aging conditions.

The layout of the remaining sections is given below. Section II illustrates the aging models of the PV module. Section III formulates the reconfiguration problem into a nonlinear integer programming problem and provides the solution procedure by using the genetic algorithm. Section IV is the simulation results undertaken on the 7×10, 20×10 and 125×20 PV arrays. In Section V, a 2×4 PV array is built to verify the proposed method. Conclusions are provided in the last section.



(a) Componential structure of the PV module



(b) PV array

Fig. 2 PV array with considering cell-unit structure

II. Modeling of PV Modules with Aging Parameter

When a PV cell is aging, a direct indication is that its output power is lower than the nominal value. Due to the *p-n* junction characteristics of the PV cell, its open-circuit voltage only changes slightly when the short circuit current changes dramatically. According to references [27-28], the degradation of short circuit current is about 10%, while the degradation open-circuit voltage is 2% in average after one year, which means the short circuit has dominant influence. It is found that short circuit current has close relations with power losses [29, 30]. Therefore, in this paper, we use the short circuit current to represent the aging condition of PV cells; and use the same open circuit voltage to approximate different PV cells.

In order to introduce necessary notations and terminologies, the modeling of PV modules with non-uniform aging cell-units is recalled in this subsection, further details can be found in [31].

(i) PV module with non-uniformed aged cell-units

Consider a cell-unit with m series-connected PV cells, denote the output current by i_{cu} and the terminal output voltage by V_{cu}. Without loss of generality, assume that the magnitudes of the short-circuit currents of the m cells satisfy

$$I_{sc\,i_1} \le I_{sc\,i_2} \le \cdots \le I_{sc\,i_m} \qquad (1)$$

Let i_{cell} be the actual current passing the PV cells. When the current i_{cell} starts to increase from 0 to $I_{sc\,i_1}$, all the cells generate electricity. When i_{cell} exceeds $I_{sc\,i_1}$ but less than $I_{sc\,i_2}$, cell i_1 cannot generate electricity: it is either bypassed or turned into a resistor because of the so-called bucket effect, which means that the electricity generated by this cell-unit is limited by the minimum of the maximum short circuit currents of the cells which generate electricity. In other words,

$i_{cell} \le \min\{I_{SCik}$:$1 \le k \le m$, the cell with maximum short circuit current I_{SCik} is not bypassed }

(ii) PV strings with aged PV modules

Assume that a PV string consists of s PV modules, with the terminal voltage V_{string} and current i_{string}. Denote the terminal voltage, current and maximum current of the kth PV module by $V_{module,k}$, $i_{module,k}$, and $i_{module,k}^{max}$, respectively. Then the following relationship can be obtained.

$$i_{string} = i_{module,1} = i_{module,2} = \cdots = i_{module,s} \qquad (2)$$

$$V_{string} = V_{module,1} + V_{module,2} + \cdots + V_{module,s} \qquad (3)$$

Due to the bucket effect, the maximum current in the PV string is limited by the minimum $i_{module,k}^{max}$ of those un-bypassed modules. That is,

$i_{string} \le \min\{i_{module,k}^{max}$: $1 \le k \le s$, and the kth module is not bypassed}.

(iii) PV array with aged PV strings

Consider a PV array consisting of p parallel-connected PV strings; denote its terminal voltage and current by V_{array} and i_{array}, respectively. Assume the terminal voltage and current for the jth PV string are $V_{string,j}$ and $i_{string,j}$, respectively. Then:

$$i_{array} = i_{array,1} + i_{array,2} + \cdots + i_{array,p} \qquad (4)$$

$$V_{array} = V_{string,1} = V_{string,2} = \cdots = V_{string,p} \qquad (5)$$

The power output from the PV array is the sum of p strings, which is also limited by the bucket effect. If the cell-units within any PV module have the same degree of aging conditions, while the aging conditions between different PV modules can be different, then the maximum power generation from the PV array can be optimized through rearranging the positions of these PV modules, and the following results can be obtained.

Proposition [31]: For a given $p \times s$ PV array with uniformly aging conditions within each PV module but different aging conditions between different modules, assume the maximum short circuit currents of these ps modules are arranged from the highest to the lowest as follows:

$$\beta_1 \ge \beta_2 \ge \cdots \ge \beta_{ps}. \qquad (6)$$

Then the maximum power output from a simplified non-uniform aging PV array is $\max\{P_1^{\max}, P_2^{\max}, P_3^{\max}, \ldots, P_s^{\max}\}$, where

$$P_1^{\max} = (\beta_1 + \beta_2 + \beta_3 + \cdots + \beta_{(p-1)} + \beta_p)V_{module} \quad (7)$$

$$P_2^{\max} = 2(\beta_2 + \beta_4 + \beta_6 + \cdots + \beta_{2(p-1)} + \beta_{2p})V_{module} \quad (8)$$

$$\vdots$$

$$P_{s-1}^{\max} = (s-1)\big(\beta_{s-1} + \beta_{2(s-1)} + \beta_{3(s-1)} + \cdots + \beta_{(p-1)(s-1)} + \beta_{p(s-1)}\big)V_{module} \quad (9)$$

$$P_s^{\max} = s\big(\beta_s + \beta_{2s} + \beta_{3s} + \cdots + \beta_{(p-1)s} + \beta_{ps}\big)V_{module} \quad (10)$$

In the case where the PV cell-units within a same PV module have different maximum short circuit currents, the above Proposition does not hold any more. Detailed algorithmic solution for this general situation is provided in the following section.

III. Optimization Modeling for Large Array Rearrangement

For a general $p \times s$ PV array with unevenly distributed aging conditions for each PV module, assume that each module can be divided into 3 sub-modules and the aging condition of the cell-units on any sub-module is evenly distributed. For the ease of PV module reconnections, it is assumed that the 3 sub-modules within any PV module cannot be separated and connected in different PV arrays, while the 3 sub-modules within any PV module may not generate power simultaneously, i.e., some of the three may generate power while others within the three do not. The reconfiguration methodology of this general $p \times s$ PV array is proposed as follows.

Prior to any rearrangement of the ps PV modules, the original positions of these ps modules can be denoted by the sequence of integers $(1, 2, \ldots, ps)$. In this sequence, the first s component $(1, 2, .., s)$ represents positions of the s PV modules in the first string, the second s component $(s+1, s+2, \ldots, 2s)$ represents positions of modules in the second string, and similarly, the last s component $((p-1)s+1, (p-1)s+2, \ldots, ps)$ represent the last string. In this way, the positions of any PV module within the PV array is represented by an integer in the sequence $(1, 2, \ldots, ps)$. For example, the PV module lying in the first string and third column is represented by 3 in this sequence, and the PV module lying in the third string and 4th column is represented by the integer $2s + 4$. Therefore, the position of any PV module (i.e. locations determined by strings and columns) can be represented by the integers within the sequence $(1, 2, \ldots, ps)$, and for convenience, an integer from $(1, 2, \ldots, ps)$ is also used to represent the position of a module in the PV array. Following this convention, any possible PV module rearrangement can be represented by a permutation of $(1, 2, \ldots, ps)$. This is to say, for any permutation $x := (x_1, x_2, \ldots, x_{ps})$ of $(1, 2, \ldots, ps)$, it implies that the PV module originally in the k-th position of the sequence will go to position x_k, where $k = 1, 2, \ldots, ps$. The following is a simple example to explain the above notations. Consider the case $p = 2$ and $s = 3$. Then this PV array has 2 PV strings, each has 3 PV modules. The 3 modules in the first string are named as the 1st, 2nd, and 3rd module of the array, while the 3 modules of the second string are called 4th, 5th and 6th module. Consider any permutation $(x_1, x_2, \ldots, x_{ps})$ of $(1, 2, \ldots, 6)$, for instance, take the permutation (3, 4, 6, 2, 1, 5). Then this means that the rearranged PV array is obtained by the following way. The 1st module in the previous unarranged PV array goes to the 3rd PV module's place in the rearranged array, the 2nd module goes to the 4th place, the 3rd module goes to the 6th place, the 4th modules goes to the 2nd place, the 5th module goes to the 1st place and the 6th module goes to the 5th place. This one-to-one correspondence between the positions of PV modules and a permutation is illustrated by Fig. 3. Note that if a module still remains in the same PV string, then there is no need to actually move it. Therefore, this newly rearranged PV array is obtained simply through move the 1st and 2nd modules in the first string to the second string, while move the 4th and 6th modules in the second string to the first string. Note further that we can even rename the first and second strings to minimize the number of movements, therefore, the new rearranged PV array can also be obtained by simply swapping the 3rd module and the 5th module.

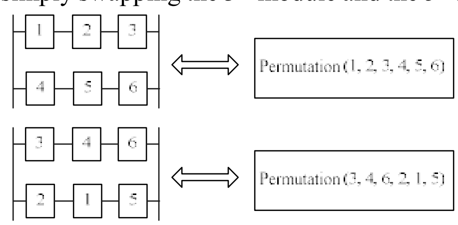


Fig. 3 One-to-one correspondence between PV module positions and permutations

Consider the PV array rearranged by the permutation $x = (x_1, x_2, \ldots, x_{ps})$. From the bucket effect, the maximum power generation from this rearranged PV array, denoted by $P_{max}(x)$, can be calculated by the following way:

$$P_{\max}(x) = \max\{P_{\max}^1, P_{\max}^2, \ldots, P_{\max}^{3s}\}, \quad (11)$$

where $P_{\max}^j$ is the maximum power generated by the PV array when there are only j sub-modules generate electricity in each PV string, $j = 1, 2, \ldots, 3s$. Assume that the maximum short circuit currents of all the $3s$ sub-modules in the i-th PV string are sorted from large to small as:

$$\delta_1^i \geq \delta_2^i \geq \delta_3^i \geq \cdots \geq \delta_{3s-1}^i \geq \delta_{3s}^i. \quad (12)$$

Then the maximum power $P_{\max}^j$ can be calculated as follows

$$P_{\max}^j = j\big(\delta_j^1 + \delta_j^2 + \cdots + \delta_j^{p-1} + \delta_j^p\big)U_{module}, j = 1, 2, \ldots, 3s. \quad (13)$$

For any general ps dimensional integer vector $x = (x_1, x_2, \ldots, x_{ps})$, the components $x_1, x_2, \ldots, x_{ps}$ may be repetitive even though these x_i were selected from the set of integers $\{1, 2, \ldots, ps\}$. Noting this fact, the original PV reconfiguration problem can be transformed into the following equivalent optimization problem.

$$\begin{aligned} &\max P_{max}(x) \\ \text{subject to:} \quad & x_i \in \{1, 2, \ldots, ps\}, i = 1, \ldots, ps; \quad (14) \\ & \prod_{\substack{1 \leq i, j \leq ps \\ i \neq j}} (x_i - x_j)^2 \geq 1 \end{aligned}$$

The constraints in the above optimization problem will prevent these integer variables taking same values so that a permutation can be properly generated. The above problem is a nonlinear constrained integer programming problem which is a typical NP hard problem. Therefore, there is not any very effective algorithm to find a global maximum solution, and popular intelligent computing tools are usually selected to solve the above problem in engineering practice. In this paper, Genetic Algorithm [32, 33] is applied as an example algorithm to solve the obtained nonlinear integer programming problem.

For large PV generation systems, the PV array is connected with the three phase inverter directly without DC-DC converters to boost voltage. The PV array output voltage should be higher than the peak voltage of power grid. Therefore, the restriction of working voltage area is needed in large PV generation systems. For a $p \times s$ PV array, with each string has $3s$ submodules, assume each submodule's maximum output voltage is 1 per unit (pu), then the maximum output voltage from the array is $3s$ pu. The restriction on working voltage area means a lower limit for the output voltage. Denote this lower limit by the notation $V_{\min}$ (pu). Since per unit is applied here, the limit $V_{\min}$ can be assumed to be an integer representing the number of submodules in a PV string which are generating electricity. Therefore, the actual output voltage must operate within the range $[V_{\min}, 3s]$. This voltage limitation can be easily included in the above reconfiguration optimization problem by revising the power calculation formula (13) into the following.

$$P_{\max}^{j} = \begin{cases} j(\delta_j^1 + \delta_j^2 + \cdots + \delta_j^{p-1} + \delta_j^p)U_{module}, \; j = V_{\min}, V_{\min}+1, V_{\min}+2, \ldots, 3s; \\ V_{\min}(\delta_{V_{\min}}^1 + \delta_{V_{\min}}^2 + \cdots + \delta_{V_{\min}}^{p-1} + \delta_{V_{\min}}^p)U_{module}, \; j = 1, 2, \ldots, V_{\min} - 1. \end{cases} \quad (15)$$

Therefore, for voltage limited cases, it only needs to solve optimization problem (14) under conditions of (11), (12) and (15). In fact, if $V_{\min}$ is taken to be 1, then this means there is not any real restrictions on the minimum output voltage, and the voltage unrestricted case can be understood as a special case of this voltage limited case. The following figure illustrates the general reconfiguration algorithm to calculate the maximum power output.

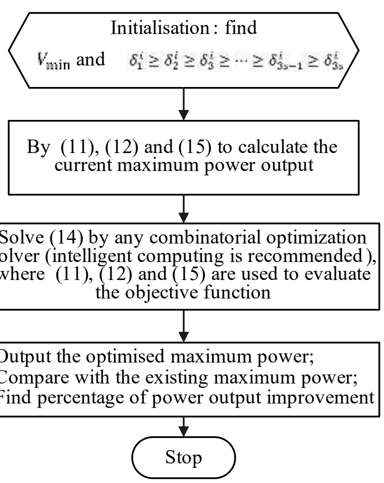


Fig. 4 PV array reconfiguration algorithm process flow

IV. Simulation

In this section, PV arrays of three sizes are considered, which are the 7×10 array, 20×10 array, and 125×20 array. The PV module parameters are presented in Table I.

A computer with Intel (R) Core (TM) i7-3540M CPU @ 3.00GHz, 8G RAM, is used to perform the calculation, and the computing time for a 7×10 array, a 20×10 array, or even a 125×20 array is just a few seconds, therefore, each of the examples is calculated 10 times and the best optimal solutions from the 10 calculations are identified. The average computing time for each round of calculation is listed in Tables V, VI, and VII. From the listed computing time, it is obvious that intelligent computing based algorithms can provide a feasible solution to the obtained combinatorial optimization problem efficiently.

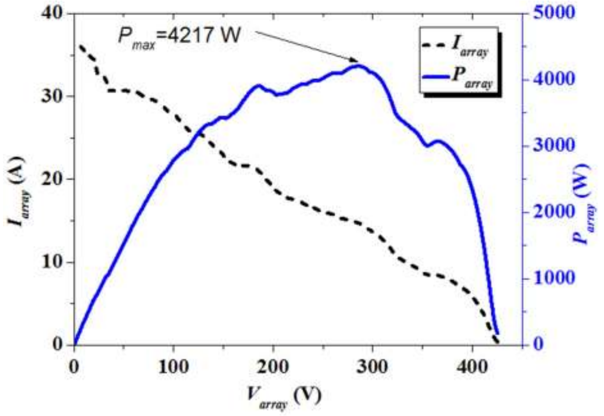
Table I Specifications of the PV Module

Parameter	Value
Open-circuit voltage	44.8 V
Short-circuit current	5.29 A
Power output	180 W
MPP current	5 A
MPP voltage	36 V
Current temperature coefficient	0.037%/K
Voltage temperature coefficient	−0.34%/K
Power temperature coefficient	−0.48%/K
Nominal operating cell temperature	46±2°C

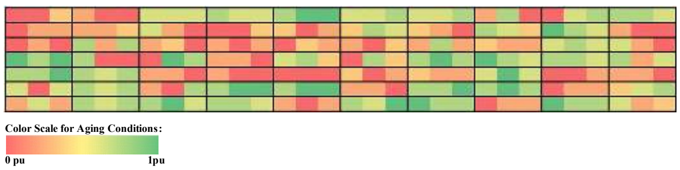
A. Case study undertaken on a 7×10 PV array

In a 7×10 PV array, there are 7 PV strings and 10 PV modules in each string. Each PV module consists of 3 cell-units, and each cell-unit is treated as a sub-module. The aging conditions for cells are not uniform, as shown in the color scale in Fig. 5(a). The maximum short-circuit current in a healthy cell-unit is set as 1 pu under the standard testing condition (STC), which refers to the 1,000 W/m² irradiance, AM 1.5 solar spectrum and 25°C module temperature. Without a rearrangement, the PV array has a typical output characteristic, as illustrated in Fig. 5(b). The maximum output power is 4217 W and PV array output voltage for the global MPP is 285 V. After the proposed array reconfiguration without setting a voltage limit (Fig. 5(c)), the maximum power is achieved at 4793 W and the PV array output voltage for the global MPP becomes 233 V, as shown in Fig. 5(d). The total output power is increased by 13.6% and the lower voltage limit is 275 V. When the minimal output voltage limit is set at 275 V for the reconfigured PV array, the new PV array arrangement is presented in Fig.5 (e). The corresponding maximum power is 4616 W and the voltage for global MPP is 279 V, as shown in Fig. 5(f). Compared with the original PV array, the rearranged PV power (with a voltage limit) increases by 9.5%, which is about 4% lower than the proposed array reconfiguration without a voltage limit. This is because that the voltage for the global MPP (233V) is outside of this voltage limit (>275V). The consequent output power with a voltage limit is lower than the case without a voltage limit.

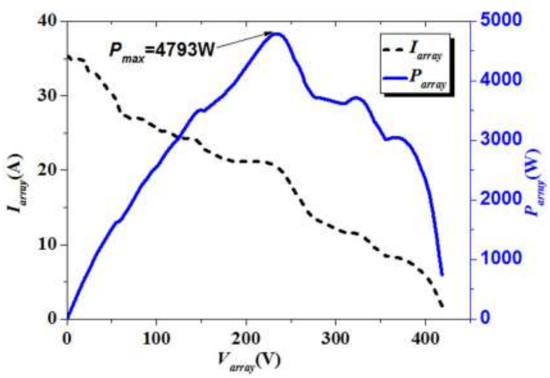
(a) The aging conditions of the array before the rearrangement



(b) The array output before the rearrangement

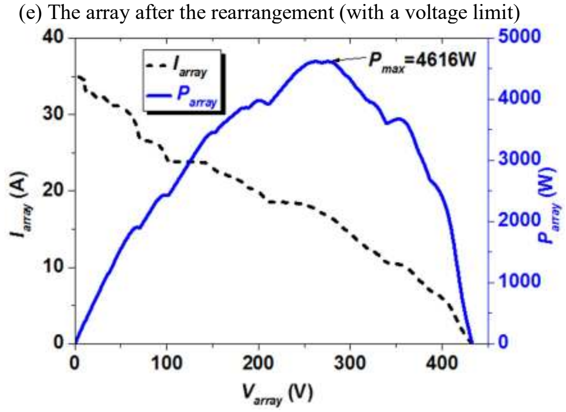


(c) The array after the rearrangement (without a voltage limit)



(d) The array output after the arrangement (without a voltage limit)

(e) The array after the rearrangement (with a voltage limit)



(f) The array output after the arrangement (with a voltage limit)

Fig. 5 The application of the proposed reconfiguration to the 7×10 array.

B. Case study on 20×10 PV arrays

Now consider a medium size 20×10 PV array with power output 36kW. If the aging of these $20 \times 30 = 600$ submodules are randomly and evenly distributed, then we can take the maximum short circuit current of each of the submodule as per unit values and assume they satisfy uniform distribution on the interval [0, 1]. Fig.6 (a) presents the aging conditions of the 20×10 array before the rearrangement, in which the maximum power is 155.8276 pu. Fig. 6 (b) shows the improved maximum power output after the rearrangement proposed in this paper, in which the maximum power is 169.7949 pu. By the proposed method, only 2 seconds are needed for a single round of calculation and the whole converter efficiency improves 8.96%. Table II provides the power improvement information for 20 randomly generated 20×10 PV arrays. The maximum short circuit currents of these 600 submodules are completely random, and the power improvement of the 20 random case studies through PV module rearrangement is between 6.33%-8.96%. The average computing time is 3.091 seconds for these scenarios.

(a) The aging conditions of the 20×10 array before the rearrangement

(b) The 20×10 array output after the arrangement (without a voltage limit)

Fig. 6 The application of the proposed reconfiguration to the 20×10 array.

TABLE II THE 20×10 ARRAY AFTER REARRANGEMENT

Test number:	Old max power (pu)	New max power (pu)	Power Improvement (Percentage)	Computing time (seconds)
1	160.6146	172.5058	7.40%	4.016
2	158.4578	168.9221	6.60%	2.038
3	148.0050	159.1169	7.51%	2.799
4	151.4564	164.2514	8.45%	2.564
5	152.8170	163.0034	6.67%	4.002
6	155.8276	169.7949	8.96%	3.508
7	149.4776	161.6073	8.11%	1.642
8	160.2544	170.3979	6.33%	3.219
9	166.4527	177.4925	6.63%	4.040
10	147.1880	159.2220	8.18%	4.370
11	149.2979	159.6420	6.93%	4.062
12	146.3742	158.2942	8.14%	2.160
13	153.5193	165.4725	7.79%	2.776
14	161.4991	172.9757	7.11%	2.041
15	162.4714	173.3151	6.67%	2.909
16	146.3742	158.2942	8.14%	2.116
17	160.6146	172.5058	7.40%	2.157
18	163.4191	174.9899	7.08%	4.285
19	158.4120	170.7848	7.81%	4.137
20	66.6965	180.8929	8.52%	2.977

C. Case study on125×20PV arrays

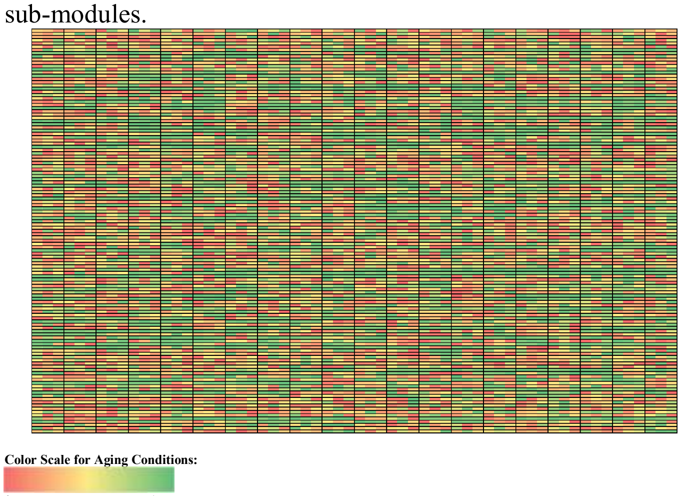
For large scale PV arrays, a 125×20 array is studied here. Table III provides the power improvement information for 15 randomly generated 125×20 PV arrays. It has been observed that the power improvement through re-arrangement is from

7.58% to 10.93%, and the corresponding average computing time for these tests is 3.925 seconds. Although the nonlinear integer programming problem (14) is NP hard, the genetic algorithm applied here still solves the 125×20 array problem very quickly, and the average computing time 3.925 (seconds) is only slightly higher than that of the case 20×10 arrays, which is 3.091 seconds.

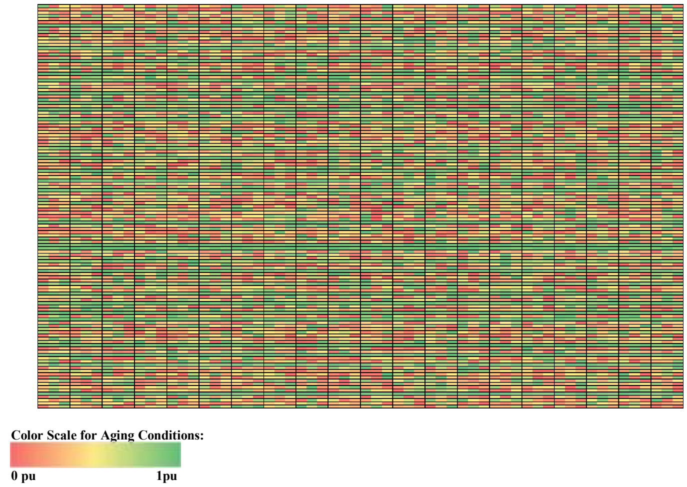
TABLE III REARRANGEMENT FOR RANDOMLY GENERATED 125×20 PV ARRAYS

Test Number:	Old max power (pu)	New max power (pu)	Power improvement (Percentage)	Computing time (seconds)
1	2386.8	2604.5	9.12%	3.297
2	2397.8	2613.9	9.01%	5.251
3	2390.9	2637.5	10.31%	3.498
4	2346.9	2566	9.33%	3.954
5	2403.7	2613.8	8.74%	4.589
6	2155.1	2318.5	7.58%	3.203
7	2368.9	2614.2	10.36%	4.859
8	2377.2	2616.8	10.08%	4.011
9	2360.3	2597.4	10.04%	5.391
10	2371.1	2630.3	10.93%	3.592
11	2397.3	2628.7	9.66%	3.443
12	2238.0	2418.2	8.05%	3.383
13	2191.2	2389.3	9.04%	3.361
14	2384.4	2611.5	9.53%	3.799
15	2352.4	2577.8	9.58%	3.239

The following Fig .7 shows the original PV array and the reconfigured PV array for the 10-th case study in the Table III, where different colors indicate different aging conditions of the sub-modules.



(a) The aging conditions of the 125×20 array before the rearrangement



(b) The 125×20 array output after the arrangement (without a voltage limit)

Fig. 7 The application of the proposed reconfiguration to the 125×20 array.

Now consider the impact of voltage limit by studying the 10th Case Study Case as an example. If there is not any minimum output voltage limit, i.e. 'unlimited' case in Table IV, then the range of output voltage is between 0pu to 60pu, and the maximum power improvement is 10.93%. With the application of different minimum output voltage limits from 40pu to 54pu, the power improvement ranges from 0.90% to 5.97%. If the minimum output voltage is greater than or equal to 55pu, then the power improvement is 0, which is caused by the too limited voltage range. The average computing time is 6.787 seconds, which is longer than the average computing time 3.925 seconds for unlimited output voltage range. This is mainly caused by the extra time needed for logic operations to identify if the output voltage is within the allowed range.

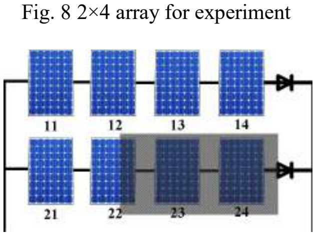
TABLE IV REARRANGEMENT OF A 125×20 PV ARRAYS UNDER OUTPUT VOLTAGE LIMITS

Case study minimum voltage limit (pu)	Original maximum power (pu)	Maximum power after rearrangement (pu)	Power improvement (percentage)	Computing time (s)
Unlimited	2371.1	2630.3	10.93%	3.925
40	2362.6	2503.7	5.97%	7.524
41	2348.9	2487.1	5.88%	8.160
42	2343.1	2470.3	5.43%	3.487
44	2315.8	2390.6	3.23%	6.231
45	2303.9	2362.0	2.52%	4.566
46	2275.4	2328.1	2.32%	8.043
47	2250.9	2299.1	2.14%	9.321
48	2205.5	2253.7	2.18%	8.870
49	2176.7	2205.9	1.34%	4.368
50	2143.6	2168.8	1.17%	4.560
51	2094.3	2129.4	1.67%	7.524
52	2055.7	2085.9	1.47%	9.216
53	1999.0	2017.7	0.94%	7.373
54	1959.4	1977.1	0.90%	5.771

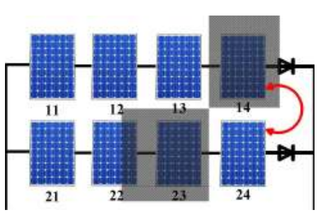
V. Experimental Tests

In this section two experiments are carried out to verify the proposed algorithm. Firstly, a 1.5kw 2×4 array is employed to verify the proposed method, see Fig.8. The PV module parameters are presented in Table. I. In the 2×4 array, the modules are under non-uniform aging conditions, in which a plastic film is used to cover the surface of modules to simulate aging conditions. Fig.9 (a) is the explanatory drawing of aging PV array, in which No.22 PV panel is operating under non-uniform aging condition, and one of the three cell-units is completely covered so that its maximum output power is only $\frac{2}{3}$ of the normal module's; while No.23 and No.24 PV panel are operating under uniform aging condition. Taking the maximum short circuit current and output voltage of a normal cell-unit as the per unit bases, the power output of a normal cell-unit is 1 pu, and the output voltage from the two strings should be the same. Therefore, the maximum power output of Fig.9 (a) is (3+3+3+3)*1=12pu. Now consider the rearrangement algorithm. It is easy to find that an optimized rearranged PV array will have both No.22 and No. 23 in one string, No.24 in another string, or No.22 is in one string while No.23 and No.24 are in another string. For the first case, the maximum power output is $(3+3+2)*2=16$ pu; for the second case, the maximum power output is $(3+3)*2=12$pu. Therefore, the best re-arrangement will be the case to put No.22 and No.23 in one string, while No.24 in another string, as shown in Fig.9 (b). The improvement of maximum power output is $\frac{16-1}{12}=33\%$. Experimental measurement is carried out to verify the rearrangement algorithm. Before rearrangement, the PV array output characteristics are presented in Fig.9 (c) and (d). In Fig.9 (c), there are two local maximum power points; the global maximum power is 442W. As presented in Fig.9 (d), there is no output current in the range of 80V~160V for the aged String 2. Fig.9 (e) and (f) are the PV array output characteristics after rearrangement. As shown in Fig. 9 (e), the maximum PV array output power is 532W. Compared to Fig.9 (c), the maximum power improvement is 20.4%. This experimental result is a little bit lower than the calculated theoretical result due to measurement errors and the minor differences between each module.

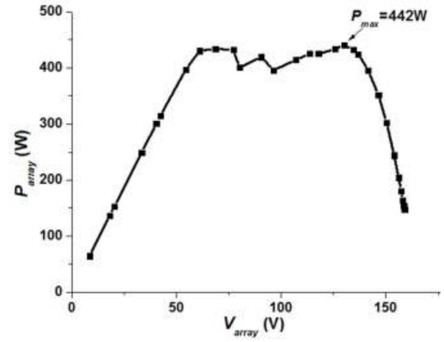
Fig. 8 2×4 array for experiment



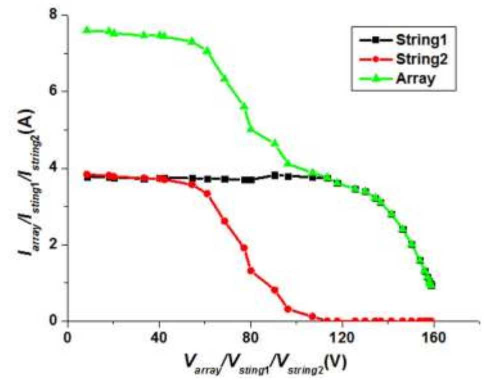
(a) Before rearrangement



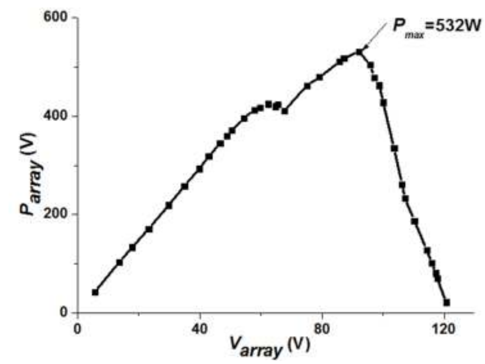
(b) After rearrangement



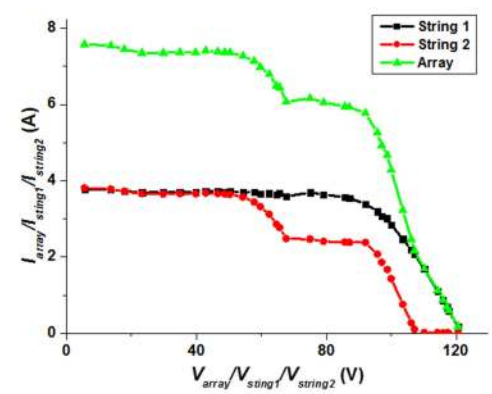
(c)Voltage-power output curves before arrangement



(d)Voltage-current output curves before arrangement



(e)Voltage-power output curves after arrangement



(f)Voltage-current output curves after arrangement

Fig.9 Experimental results before and after rearrangement

VI. CONCLUSION

Due to the impact of rain, temperature, humidity and other environmental factors during the long service period of PV arrays, non-uniform aging phenomena widely exists in PV generation plants. This paper proposes an optimization model to rearrange the non-uniform aging PV array to exploit the power generation improvement potential. The contributions of this paper are summarized below.

(i) According to the hardware structure of PV modules, the non-uniform aging cell-units in the PV modules are considered in this paper. A nonlinear integer programming problem is formulated to maximize the power generation by rearranging the non-uniformly aged PV modules.

(ii) The PV array working voltage limitations are considered in the above rearrangement algorithm.

(iii) PV arrays with sizes (7×10, 5.5kW), (20×10, 36kW), and (125×20, 450kW) and non-uniformly aged modules are tested to verify the proposed reconfiguration algorithm. A 2×4 array is also employed in the experiment to verify the proposed method.

Since this aging phenomenon happens only gradually, the developed rearrangement technique can be implemented offline during scheduled maintenances (e.g., once a few years or even longer). It can be combined together with other online maximum power point tracking and reconfiguration techniques for real time shadowing to improve the overall power generation efficiency.

REFERENCES

[1] P. L. Carotenuto, P. Manganiello, G. Petrone, and G. Spagnuolo, "Online recording a PV module fingerprint," *IEEE J. Photovolt.*, vol. 4, no. 2, 659-668, Mar. 2014.

[2] Y. A. Mahmoud, W. Xiao, H. H. Zeineldin, "A parameterization approach for enhancing PV model accuracy," *IEEE Trans. Ind. Electron.*, vol. 60, no.12, pp. 5708-5716, Dec, 2013.

[3] Y. Hu, W. Cao, J. Ma S. Finney, D. Li, "Identifying PV module mismatch faults by a thermography-based temperature distribution analysis," *IEEE Trans. Device and Materials Reliability,* vol. 14, no. 4, pp. 951-960, Dec. 2014.

[4] M. Z. S El-Dein, M. Kazerani, M. M. A. Salama, "Optimal photovoltaic array reconfiguration to reduce partial shading losses," *IEEE Trans. Sustainable Energy*, Vol. 4, Issue 1, pp. 145-153, Jan. 2013.

[5] M. Mattei, G. Notton, C. Cristofari, M. Muselli, P. Poggi, "Calculation of the polycrystalline PV module temperature using a simple method of energy balance," *Renewable Energy*, 31, pp.553-567, 2006.

[6] M. Boztepe, F. Guinjoan, G. Velasco-Quesada, S. Silvestre, A. Chouder, E. Karatepe, "Global MPPT scheme for photovoltaic string inverters based on restricted voltage window search algorithm," *IEEE Trans. Ind. Electron.*, vol. 61, no. 7, 3302-3312, Jul. 2014.

[7] M. Abdelhamid, R. Singh, M. Omar, "Review of microcrack detection techniques for silicon solar cells" *IEEE J. Photovolt.,* vol. 4, no. 1, 514 - 524, Jan. 2014.

[8] B. N. Alajmi, K. H. Ahmed, S. J. Finney, B. W. Williams, "A maximum power point tracking technique for partially shaded photovoltaic systems in microgrids," *IEEE Trans. Industrial Electronics*, vol. 60, no. 4, pp. 1596-1606, Apr. 2013.

[9] Dirk C. Jordan and Sarah R. Kurtz, "Photovoltaic Degradation Rates — An Analytical Review," *Progress in Photovoltaics: Research and Applications*. Vol. 21, Issue 1, pp. 12-29. 2013.

[10] D.C. Jordan, R.M. Smith, C.R. Osterwald, E. Gelak, and S.R. Kurtz, "Outdoor PV Degradation Comparison," *Presented at the 35th IEEE Photovoltaic Specialists Conference (PVSC '10)* , *Honolulu, Hawaii*, June 20-25, 2010

[11] H. Obane, K. Okajima, T. Oozeki, and T. Ishii, "PV system with reconnection to improve output under nonuniform illumination," *IEEE J. Photovolt.*, vol. 2, no. 1, pp. 341–347, Jul. 2012.

[12] D. Nguyen, B. Lehman. "An adaptive solar photovoltaic array using model-based reconfiguration algorithm," *IEEE Trans. Ind. Electron.*, vol. 55, no. 7, pp. 2644-2654, Jul. 2008.

[13] J. P. Storey, P. R. Wilson, and D. Bagnall, "Improved optimization strategy for irradiance equalization in dynamic photovoltaic arrays," *IEEE Trans. Power Electron*., vol. 28, no. 6, pp. 2946-2956, Jun. 2013.

[14] G. Velasco-Quesada, F. Guinjoan-Gispert, R. Pique-Lopez, M. Roman-Lumbreras, and A. Conesa-Roca, "Electrical PV array reconfiguration strategy for energy extraction improvement in grid-connected PV systems," *IEEE Trans. Ind. Electron*., vol. 56, no. 11, pp. 4319-4331, Nov. 2009.

[15] Y. Wang, X. Lin, Y. Kim, N. Chang, and M. Pedram, "Architecture and control algorithms for combating partial shading in photovoltaic systems," *IEEE Trans. Computer-Aided Design Integr. Circuits Syst.*, vol. 33, no. 6, pp. 917-929, Jun. 2014.

[16] S. Jonathan, R. W. Peter, and B. Darren, "The optimized-string dynamic photovoltaic array," *IEEE Trans. Power Electron*., vol. 29, no. 4, pp. 1768-1776, Apr. 2014.

[17] M. Z. S. El-Dein, M. Kazerani, and M. M. A. Salama, "Optimal photovoltaic array reconfiguration to reduce partial shading losses," *IEEE Trans. Sustain.Energy*, vol. 4, no. 1, pp. 145–153, Jan. 2013.

[18] E. Faldella, G. C. Cardinali, and P. U. Calzolari, "Architectural and design issues on optimal management of photovoltaic pumping systems," *IEEE Trans. Ind. Electron.*, vol. 38, no. 5, pp. 385–392, Oct. 1991.

[19] J. D. Bastidas-Rodriguez, C. A. Ramos-Paja, and A. J. Saavedra-Montes, "Reconfiguration analysis of photovoltaic arrays based on parameters estimation," *Simul. Modell. Pract. Theory*, vol. 35, pp. 50–68, Jun. 2013.

[20] M. Alahmad, M. A. Chaaban, S. kit Lau, J. Shi, and J. Neal, "An adaptive utility interactive photovoltaic system based on a flexible switch matrix to optimize performance in real-time," *Sol. Energy*, vol. 86, no. 3, pp. 951–963, Mar. 2012.

[21] Z. Cheng, Z. Pang, Y. Liu, and P. Xue, "An adaptive solar photovoltaic array reconfiguration method based on fuzzy control," in *Proc. 8th World Congr. Intelligent Control and Automation— WCICA*, pp. 176–181, Jul. 2010.

[22] G. Spagnuolo, G. Petrone, B. Lehman, C. A. Ramos Paja, Y. Zhao and M. L. Orozco Gutierrez, "Control of Photovoltaic Arrays: Dynamical Reconfiguration for Fighting Mismatched Conditions and Meeting Load Requests," *IEEE Industrial Electronics Magazine*, vol. 9, no. 1, pp. 62-76, Mar. 2015. [23] M. L. Orozco-Gutierrez, G. Spagnuolo, J. M. Ramirez-Scarpetta, G. Petrone and C. A. Ramos-Paja, "Optimized Configuration of Mismatched Photovoltaic Arrays," *IEEE Journal of Photovoltaics*, vol. 6, no. 5, pp. 1210-1220, Sept. 2016.

[24] P.L. Carotenuto, A. Della Cioppa, A. Marcelli, G. Spagnuolo, "An evolutionary approach to the dynamical reconfiguration of photovoltaic fields," *Neurocomputing,* vol. 170, pp. 393-405, 2015.

[25] DE Knuth (1998). "The Art of Computer Programming", Volume 2 (3rd ed.). Boston: Addison–Wesley.

[26] Fisher, R.A.; Yates, F. (1948). Statistical tables for biological, agricultural and medical research (3rd ed.). London: Oliver.

[27] Ababacar Ndiaye, Cheikh M. F. Kébé, Pape A. Ndiaye, Abdérafi Charkib, Abdessamad Kobi, Vincent Sambou. "A Novel Method for Investigating Photovoltaic Module Degradation," *Energy Procedia,* vol.36, pp.1222 – 1231, 2013.

[28] M.A. Munoz, M.C. Alonso-Garcia, Nieves Vela, F. Chenlo. "Early degradation of silicon PV modules and guaranty conditions," *Solar Energy*, vol. 85, pp. 2264–2274, 2011.

[29] Osterwald CR, Anderberg A, Rummel S, Ottoson L. "Degradation Analysis of Weathered Crystalline-Silicon PV Modules," *29th IEEE PV Specialists Conference*, New Orleans, Louisiana, USA, May 20-24, 2002.

[30] D. Jordan, S. Kurtz, "Photovoltaic module stability and reliability," Modelling, Measurement and Assessment, pp. 71–101, 2017.

[31] Y. Hu, J. Zhang, J. Wu, W. Cao, G. Y. Tian, "Efficiency Improvement of Non-Uniformly-Aged PV Arrays," *IEEE Transactions on Power Electronics*, accepted, DOI 10.1109/TPEL.2016.2544842.

[32] M. Mitchell, "An Introduction to Genetic Algorithms," The MIT Press, Cambridge, Massachusetts, 1996.

[33] H. Tamaki, H. Kita and S. Kobayashi, "Multi-objective optimization by

genetic algorithms: a review," *Proceedings of IEEE International Conference on Evolutionary Computation, Nagoya, Japan*, pp 517-522, 1996.