Determination of Module Rearrangement Techniques for Non-uniformly Aged PV Arrays with SP, TCT, BL and HC Configurations for Maximum Power Output

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***Abstract*—The power production of a PV array decreases due to some specific factors such as temperature, shading, soiling, non-uniform aging of PV modules etc. The non-uniform aging of PV modules in an array is a significant factor of power degradation. This increases current-voltage (*I-V*) mismatch among the array modules and causes power loss. There are different techniques of module rearrangements in an array to reduce mismatch power loss (MML) and thus increase the array output power. This paper investigates experimentally both the voltage based and current based module rearrangement techniques on a 4×6 aged PV array with series-parallel (SP), total-cross-tied (TCT), bridge-linked (BL) and honey-comb (HC) configurations. The results are compared with the conventional technique of randomly module arrangement in an array. The experimental results show that both current and voltage based module rearrangement techniques are performed better than randomly module arrangement technique with respect to output power for each SP, TCT, BL and HC configurations. Another comparison illustrates that the maximum output power is generated by HC configuration while the minimum is obtained by SP configuration.**

Keywords—mismatch power loss, module rearrangement, PV array configurations, photovoltaic system

I. INTRODUCTION

The utilization of photovoltaic energy has accepted remarkable recognition across the globe. In the past decades, a significant amount of research and developments occur in this field [1, 2]. Currently, PV technology is one of the widely used renewable energy (*RE*) technologies that are being used worldwide as a viable *RE* source. The drawbacks of PV technology are its low conversion efficiency, high operating cost and unreliability on long service time due to power degradation by the aging effect. The permanent degradation like a failure of PV cells can cause significant power loss in a PV system. The research results from the National Renewable Energy Laboratory (NREL) show that the aging speed of PV modules in an array is non-uniform, and the PV module degradation speed is 0.5% per year [3]. Hence, it is very effective to analyze the techniques of maximum power extraction from the aged PV array to increase its lifetime.

There are typically two solutions to produce the maximum output power from an aged PV array. The first solution is to use global maximum power point tracking (GMPPT) technique and the second solution is to use module rearrangement technique. Although GMPPT is better than traditional MPPT, can increase the PV array output power at non-uniform irradiation condition, but unable to fully explore the power from an aged PV array. The work in [4] developed a current based module rearrangement technique for non-uniformly aged modules, where a 1620 W 3×3 aged PV array is rearranged by using modules maximum power point current (Im) and the result shows that its output is increased 13.5% than randomly module arrangement technique. In order to extract the maximum power from an aged PV array, rearrangement technique is needed first after that to operate the array output always at the maximum power point (MPP) GMPPT is also required. Therefore, module rearrangement for aged PV array is complementary to the GMPPT. The work in [5] developed a new rearrangement technique where, the modules are arranged iteratively in a hierarchy pattern to minimize MML due to non-uniformly aged PV configurations (4×4, 10×10, 100×10) using MATLAB Simulation without any experimental investigations. In the literature, the voltage based module rearrangement technique for aged PV array is still not used.

On the other hand, for new PV array, module sorting (rearrangement) techniques had gained popularity among the researchers [6,7]. To extract the maximum output power by minimizing MML, photovoltaic maximum power parameters, such as maximum power point current, Im; short circuit current, Isc; maximum power point power, Pm; maximum power point voltage, Vm; and open circuit voltage, Voc. are typically used as PV module sorting parameters for the arrangement of newly installed PV array at uniform radiation condition [8]. In addition, different PV array configurations are available in literature such as SP, TCT, BL, HC are used to extract the maximum power of PV array at non-uniformly irradiance condition [9, 10]. Therefore, applying and investigating, Im and Vm based module rearrangement techniques for an aged PV array is one of the main objectives of this work. Moreover, comparing SP, BL, HC and TCT array configurations using a 4×6 aged PV array is another objective of this work.

The layout of the remaining sections is given below. Section II formulates the mathematical model of aged array output power calculation process and also describes the reason of power loss due to the I-V mismatch of PV modules in an array. Section III describes the methodology of an experimental procedure to measure the array output power using different rearrangement techniques. Section IV illustrates the results and discussion by comparative

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analysis with respect to PV array output power. In the last section conclusions are provided.

II. Mathematical Modeling of Aged PV Arry

In SP, BL, HC, and TCT PV configurations, series connected modules are work at the same amount of current in a string and parallel connected strings are work at the same amount of voltage at a time. As a rule, Kirchhoff voltage law (KVL) is applied for string voltage calculation and Kirchhoff current law (KCL) is for array current calculation. Therefore, according to KVL, the string voltage equals the summation of modules voltage in the string and according to KCL, the array current equals the summation of strings current in the array [11]. However, in a practical PV array, a central MPPT is used to get its GMPP. Therefore, all panels are led to work at their maximum power, Pmpp which are not completely same for all modules even from same power rating due to non-uniform aging effects which causes MML in the PV array. For example, if two modules are connected in series having non-identical Impp then they compromise to operate at lower Impp and similarly two parallel connected modules are having different Vmpp operate at lower Vmpp [12].

Now, consider a PV string be made up of L series-connected PV modules, with string voltage, and string current, The string voltage and current of the *Kth* PV module can be denoted by and respectively. With this notation, maximum string voltage and current can be expressed as follows.

$$V_{String}^{mpp} = \sum_{K=1}^{L} V_{Module,K}^{mpp} \tag{1}$$

$$I_{String}^{mpp} \le \min \left\{ I_{Module,K}^{mpp} : 1 \le K \le L \right\} \tag{2}$$

Again, consider a PV array has M number of parallel connected string; identify its terminal voltage and current for *Jth* PV string are $V_{String,J}^{mpp}$ and $I_{String,J}^{mpp}$ respectively. With this notation maximum array current and maximum array voltage can be expressed as;

$$I_{Array}^{mpp} = \sum_{J=1}^{M} I_{String,J}^{mpp} \tag{3}$$

$$V_{Array}^{mpp} \le \min \left\{ V_{String,J}^{mpp} : 1 \le J \le M \right\} \tag{4}$$

Now, consider an $L \times M$ PV array has L number of series connected modules in a string and M number of parallel connected string; identify its output terminal power and *Ith* PV module are and respectively. With this notation maximum array output power in the PV array can be expressed as;

$$P_{Array}^{mpp} = V_{Array}^{mpp} \times I_{Array}^{mpp} \tag{5}$$

In an aged PV array, the array power decreases because the array voltage is equal to the minimum voltage of the string connected in parallel and array string current is equal to the minimum current of the module connected in series. Therefore, array output power is always less than the summation of individual modules power in the array [13].

III. Methodology

In order to make a comparative analysis among three different module rearrangement techniques, in terms of array output power a 14.4 W aged PV array is used in this work. Where, the PV array contains 24 PV aged modules of 0.6 W are connected in a 4×6 array arrangement. These 24 PV modules are two years of aged and collected from a solar lantern manufacturing company. After that, these modules are tested by a PV module manufacturer company to get their datasets with electrical characteristics. Hence, these datasets are used to rearrange the PV modules according to the rearrangement techniques. Finally, the significance of PV array configurations (SP, TCT, BL, and HC) are investigated experimentally applying all these three rearrangement techniques for the 4×6 aged PV array and their output powers are compared accordingly. The step by step procedures is described in the following sections.

A. *Dataset of Aged PV Modules*

In this work, 24 polycrystalline PV modules of two years aged are tested by a PV manufacturer company. Where, the PV modules are tested at STC (25°C, 1000 W/m2, AM 1.5G) according to the IEC 60904-1 standard [14]. The tested data have been tabulated in Table 1; which contains the value of electrical characteristics of Voc, Isc, Pm, Vm and Im for each PV modules.

TABLE I. A Dataset of Two Years Aged 24 PV Modules

PV No	Electrical Characteristics of Two Years Aged PV Modules				
	Voc (V)	***Isc (A)***	***Vm (V)***	***Im (A)***	***Pm (W)***
1	2.92	0.08	2.394	0.073	0.175
2	2.8	0.14	2.296	0.128	0.294
3	2.81	0.23	2.304	0.211	0.486
4	2.85	0.25	2.337	0.230	0.538
5	2.89	0.25	2.369	0.230	0.545
6	2.75	0.27	2.255	0.248	0.559
7	2.78	0.27	2.279	0.248	0.565
. . .	. . .	. . .	. . .	. . .	. . .
23	2.97	0.28	2.435	0.257	0.626
24	3	0.28	2.46	0.257	0.632

B. *PV Array Configurations*

The well-known PV array configurations are SP, TCT, BL, and HC are mostly used for the new PV array arrangement purpose. In this work, these PV array configurations are used to analyze the rearrangement techniques for aged PV array with respect to output power. The connection diagram are shown in figure 1 (i), (ii), (iii) and (iv) of SP, TCT, BL, and HC PV array configurations respectively.

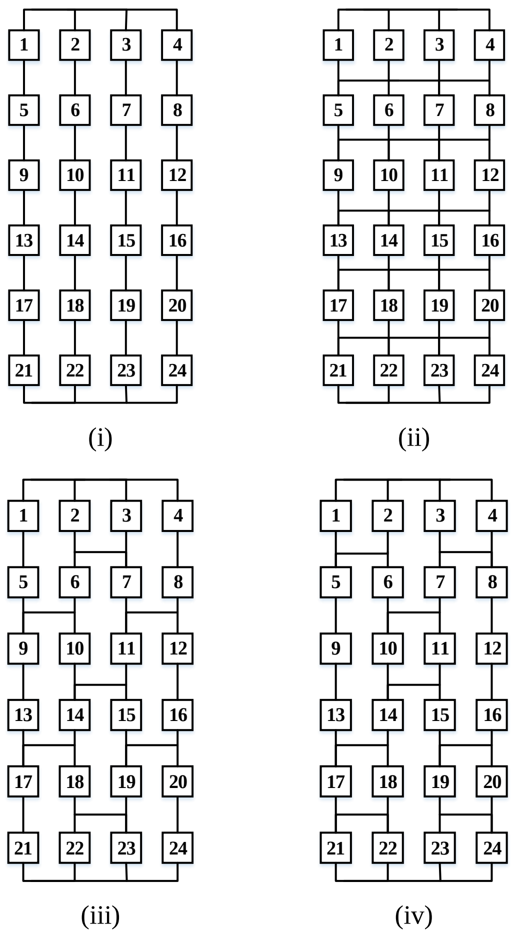

Fig. 1. Array configurations: (i) SP; (ii) TCT; (iii) BL; (iv) HC

C. PV Module Rearrangement Techniques

The work in [15, 16], developed the current based and voltage based module rearrangement techniques for different PV array configurations. In this work, aged PV array modules are rearranged by using three different techniques: i) Random method; ii) Im based method; iii) Vm based method. In order to explain the techniques, let consider, 24 PV modules are connected in a 4×6 (column × row) array and their positions are numbered by 1,2,3 to 24. Figure 2(a) shows the modules position are determined by a Random method which is actually a conventional technique of module arrangement usually used for newly installed PV array and remain unchanged until any serious damage or fault occurs in the array. Figure 2(b) shows the modules position determined by Im based method. In this method, all 24 modules are sorted in ascending order by their MPP current Im. Hence, the module in position 1 contains the lowest current and the module in position 24 contain the highest current. According to this technique, the current will increases from the first column to the fourth column, actually here increases the parallel brunch currents means array currents increases thus output power also increases.

Figure 2(c) shows the module positions are determined by Vm based method. In this method, the sorting of 24 modules has been done from lower values to higher values of Vm, as a result, module position1 contains the lowest value of Vm while module position 24 is the highest one. In this technique the parallel connected modules are operated almost in the same average voltages thus reduces mismatch voltage loss and output power increases accordingly.

1	2	3	4
5	10	11	12
6	13	14	15
7	16	17	18
8	19	20	21
9	22	23	24

(a)

1	12	13	24
2	11	14	23
3	10	15	22
4	9	16	21
5	8	17	20
6	7	18	19

(b)

1	19	7	13
24	6	18	12
2	20	8	14
23	5	17	11
3	21	9	15
22	4	16	10

(c)

Fig. 2. 4×6 PV array rearrangement techniques (a) Random method; (b) Im based method; (c) Vm based method

D. Experimental Procedure

In this section, the experimental procedure is described for the measurement of *I-V* and *P-V* characteristics of 4×6 aged PV array configurations. The experimental setup is shown in figure 3. The PV array modules are placed on an aluminum frame, with electrical isolation using double sided Sellotape and two halogen bulbs, 500W each, are mounted parallel to the PV modules using another aluminum frame. The measurement of light is done by a light meter LX-1102 and temperature are measured by using TA298. The input light intensity for the modules is fixed in 350 lux which is almost one third on the full sun irradiance (1000 Wm^{-2}) since the distance between the light source and modules remain constant. The laboratory room temperature is 25ºC has been maintained using an air conditioner. All practical data measurements of the PV array configurations are carried out according to the standard test conditions are described in [17].

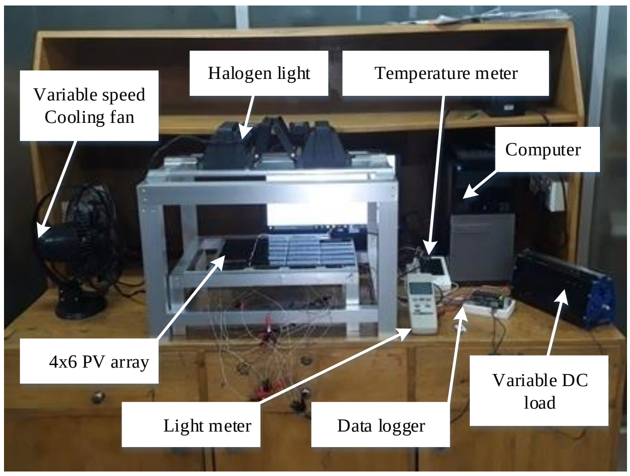

Fig. 3. Experimental setup to measure the output power of a 4×6 PV array for SP, TCT, BL and HC configurations.

A single test for *I-V* characteristics measurement of the PV array is carried out by less than a minute and real-time electrical data of output current and its corresponding voltage are recorded in a memory card of the data logger. During a single test, the PV module temperature has been increased maximum 1ºC and a variable speed cooling fan is used to reduce the temperature of the PV modules. After completion of each test five minutes interval is required to get the module temperature 25ºC using the cooling fan. In addition, a single test is repeated five times for each array configuration to get more accurate *I-V* curves. After a daylong experimental investigation, the output array power for all four array configurations has been tested and recorded using all three techniques.

IV. Results and Discussion

Table I shows that the 4x6 array electrical characteristics mean array voltage, array current, and, array power is obtained by using random module arrangement technique for four array configurations. The maximum output power, 5.214 W is generated by HC configuration and the minimum power 4.377 Wis generated by SP configuration. Though the array voltage is higher in SP configuration because of the lower array current its output power becomes lower. However, current is dominating the output power. Hence, in TCT, BL, and HC the array voltages are the same but the currents are different. The highest current is generating by HC. Therefore, the highest power is also obtained by HC configuration.

TABLE II. Array Outputs Obtained by Random Method

Array Configurations	**Array Outputs Obtained By Random Method**		
	Voltage (V)	***Current (A)***	***Power (W)***
SP	11.948	0.366	4.377
TCT	11.457	0.433	4.960
BL	11.457	0.448	5.130
HC	11.457	0.455	5.214

TABLE III. Array Outputs Obtained by Im Based Method

Array Configurations	**Array Outputs Obtained By Im Based Method**		
	Voltage (V)	***Current (A)***	***Power (W)***
SP	10.911	0.455	4.966
TCT	10.911	0.525	5.733
BL	10.911	0.533	5.814
HC	11.457	0.511	5.850

TABLE IV. Array Outputs Obtained by Vm Based Method

Array Configurations	**Array Outputs Obtained By Vm Based Method**		
	Voltage (V)	***Current (A)***	***Power (W)***
SP	10.366	0.437	4.526
TCT	10.366	0.522	5.408
BL	10.366	0.537	5.561
HC	10.911	0.503	5.561

The Im based module rearrangement technique is also applied in 4x6 arrays for SP, TCT, BL and HC configurations. The output results are presented in Table II. The maximum output power is 5.85W and the minimum power is 4.966 W obtained by HC and SP configurations respectively. For SP, TCT, and BL the output voltages are same but the currents are not, they are dominating the power outputs. Therefore, the higher power 5.814 W is obtained at BL configuration because of the higher output current. However, HC configuration is generating the highest output power for its higher output voltages.

Table III shows the output results, which are obtained by using Vm based module arrangement technique. It can be seen the lower output is 4.526 W obtained by SP array configurations and the higher output power 5.611 W obtained by both BL and HC configuration. The comparative analysis is illustrated in figure 4. The HC configuration is performed better than SP, TCT, and BL with respect to output power. Another significance of HC configuration is that its output voltage is higher both in Im and Vm based techniques. Finally, the current based technique is performed better than voltage based technique for all four array configurations.

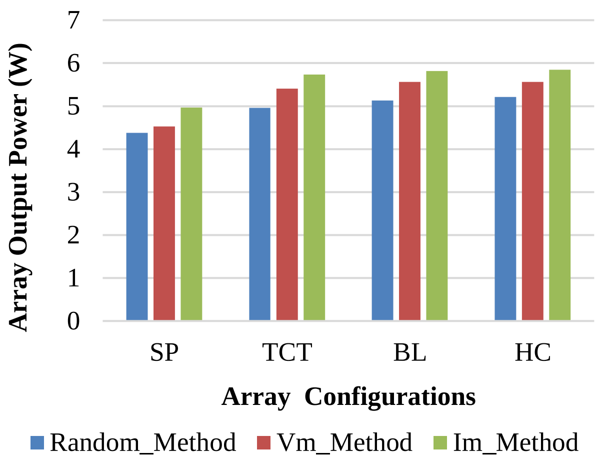

Fig. 4. Comparison of power outputs between SP, TCT, BL and HC configurations

V. Conclusion

In this work, a comparative analysis of aged PV module rearrangement techniques are analyzed for SP, TCT, BL and HC configurations to extract the maximum array output power. One of the main contributions of the paper illustrates that the Im based technique is performed better for all array configurations with respect to array output power. Additionally, it is observed that TCT, BL and HC configurations are outperformed than SP configuration. Besides, BL performed better than TCT configuration. Finally, HC configuration is recommended as the best configuration for the aged PV array.

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