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Experimental Investigation of PV Array Interconnection Topologies at Nonuniform Aging Condition for Power Maximization

Ahmed Al Mansur, Mohammad Asif ul Haq, Md. Hasan Maruf, ASM Shihavuddin, Md. Ruhul Amin and Kazi Khairul Islam

***Abstract*—In vast Photovoltaic (PV) power plant the output power production decreases significantly due to the fact of non-uniform aging of PV modules. The non-uniform aging of PV modules increases current-voltage (I-V) mismatch among the array modules and causes mismatch power loss (MPL). There are different interconnection topologies of the PV module in an array to minimize MPL and thus maximize the array output power. This paper investigates four different interconnection topologies experimentally on a 4×4 nonuniformly aged PV array. Three different patterns of PV module rearrangement are used to investigate the performance of each interconnection topology in terms of array output power and MPL. The experimental results show that the proposed interconnection topology is yields about 3.28% (average) higher output power than that of the most commonly used series-parallel array topology.**

***Index Terms*—Non-uniform aging, interconnection scheme, photovoltaic modules, power losses.**

I. Introduction

THE exploration PV power systems (PVPs) has obtained outstanding recognition across the world in terms of their optimal deployment and maximum utilization of solar radiation. A significant amount of research activities and developments occur in this field, in the last decades [1]. At present, PVPs technology is one of the extensively used renewable energy technologies that are being used worldwide as a viable renewable energy source with variable capacities depending on the deployment scenarios. In the operation of photovoltaic power plants, PV modules in the array suffer from various types of faults due to shading, soiling, snail trail, PV cell damage, and power reduction for nonuniform aging [2]. The aging process of solar panels in an array is non-uniform, and the speed of aging is on an average 0.8% per year [3]. Therefore, it is very imperative to study different methods applied for maximum power production from a photovoltaic array at nonuniformly aging condition.

The most popular solution is to utilize the global max power point tracking (GMPPT) technique to produce maximum energy from a shaded PV module. Although GMPPT is an improved method of conventional max power point tracking (MPPT) [4] that can increase the PV array power generation at non-uniform irradiation condition, it is unable to fully extract the power during the non-uniformly aging condition. Hence, the module rearrangement technique is required first to extract the maximum output power during the non-uniform aging condition of PV array modules, after that GMPP is also compulsory to operate the array at the peak power point.

The work in [5], the output power of a non-uniformly aged PV array is investigated by the max power point current based module reorganization method (*Im*) and compared with the random rearrangement technique (*Ra*). The result shows that the output is increased by 13.5% by *Im* based method than *Ra* based module arrangement technique. The work in [6], a genetic algorithm (*GA*) based module rearrangement technique is introduced to extract peak power from PV arrays at aging condition by reducing MPL. A relative analysis of different rearrangement techniques of non-uniformly aged PV modules is performed experimentally to reduce the MPL and rise the output power, however, module interconnection topologies are not investigated [7]. The work in [8], module rearrangement techniques are investigated at nonuniform aged PV arrays with different sizes, such as 3 × 4, 5 × 8 and 7 × 8 arrays. Here simulation-based comparison of different rearrangement

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techniques is made using series-parallel array connection only, no hybrid connections are investigated. In [9], gene evaluation based new technique of module rearmament is investigated using 5×5 and 7×20 series-parallel PV arrays configurations. The simulation result shows that the rearrangement techniques are independent of array size and dimensions. However, hybrid interconnection topologies are not tested at nonuniform aging conditions of PV array modules. In [10], maximum power extraction from aged PV array is performed using a new method of module arrangement using current collector optimizer without hybrid connections. The work in [11], an adaptive genetic algorithm-based module rearrangement technique is investigated for nonuniformly aged PV arrays with series-parallel connections, but no other interconnection topologies are considered.

On the other hand, module interconnection topologies had gained popularity among the researchers, to maximize output power during non-uniform irradiance conditions, not for nonuniform aging [12-20]. The work in [21], five different PV array configurations such as series-parallel (SP), total cross tie (TCT), ladder diagram (LD), honey comb (HC) and bridge link (BL) are investigated to extract maximum output power for different non-uniformly irradiance conditions not considering the aging condition.

Therefore, applying and investigating, four different module configurations (SP, TCT, LD, and SP-LD) for the PV array modules at aging condition is the objective of this work. Moreover, a comparative analysis is performed among conventional array configurations (SP, TCT, and LD) and the proposed hybrid array configuration (SP-LD) for MPL and output power using a 4×4 PV array modules at nonuniform aging condition.

II. Methodology

In this work the performance of the three conventional and a newly proposed interconnection topologies is investigated with respect to PV array power using a 160W array at aging condition. Here the PV array modules (10W each) are configured in a 4×4 dimension. The PV panels are four years of age and are tested by a PV module manufacturer company to get their electrical characteristics and power degradation. Three patterns of module arrangements are proposed in this work based on these experimentally collected datasets. The performance investigation of the interconnection topologies (SP, TCT, LD, and SP-LD) are made with respect to the output power. Besides, all the configurations are tested experimentally using the three patterns of module rearrangement using the 4×4 PV array. The overall process of the work is described below.

A. *Aged PV Array Output Power*

In order to investigate the performance of the nonuniformly aged PV array output power calculation is required. According to the literature, an aged PV module generates lower power than its rated power. The average degradation rate of open circuit voltage and short circuit current are 2% and 10%, respectively [5]. Hence, the power degradation in an aged module has a close relationship with the short circuit current. In [6], the non-uniformly aged modules are compared using maximum short circuit current, considering the same open circuit voltage; where the power degradation of an old PV module due to its non-uniformly aged cells is explained by using the bucket effect. In this paper, it is considered that in an array, all the PV modules are non-uniformly aged and are not bypassed by diodes. The array output power, P_{Array}^{max} with a $(\alpha\times\beta)$ dimension can be calculated using the following equation.

$$P_{array}^{max} = \sum_{Q=1}^{\beta} min\ \{ P_{Q,Z}^{max} : 1 \le Z \le \alpha, \text{ and the } (Q,Z)th \text{ module is non by passed}\} \quad (1)$$

Where, $P_{Q,Z}^{max}$ is denoted as the maximum output power from the non-bypassed module at position (*Q, Z*) (*Z-th* module in the *Q-th* string) of the PV array.

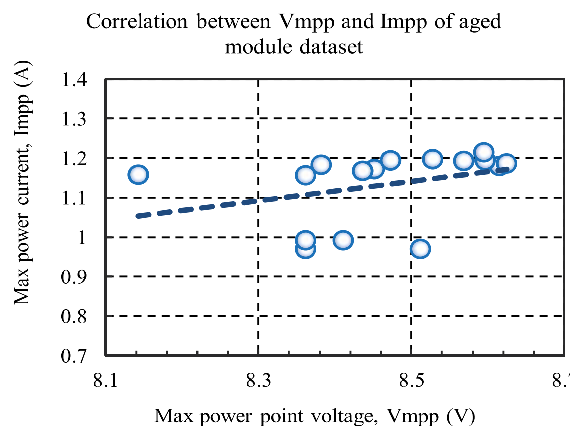

Fig. 1. Dataset of aged PV modules in the 4×4 array.

B. *Nonuniformly Aged PV Array Modules*

As an important step of this work, sixteen (16) solar panels are tested by a solar panel manufacturer company, Electro Solar Ltd. The solar panels are tested according to the IEC 60904-1 standard [22], considering the standard test condition at 1000W/m^2. Figure 1 shows the tested dataset of 16 PV modules at aging condition. The tested data have been presented in Fig. 1. Where the deviation of voltage and current from the trendline shows the degradation of solar panel characteristics due to aging. The tested data are summarized in Table 1. The parameters, *Voc, Isc,* *Pmpp, Vmpp,* and *Impp* for a single solar module and the 4×4 PV array has been tabulated. Here, a single module power is 10.16W, and the 4×4 PV aged array power is 153.35W.

TABLE I
SPECIFICATIONS OF PV PANEL AND 4×4 PV ARRAY

Electrical Specification	PV Panel	PV Array
Open circuit voltage, *Voc (V)*	10.02	39.36
Short circuit current, *Isc (A)*	1.28	4.92
Max power current, *Impp (A)*	1.17	4.52
Max power voltage, *Vmpp (V)*	8.61	33.85
Max power at MPP, *Pmpp (W)*	**10.16**	**153.35**

C. *PV Array Interconnection Topologies*

The most popular interconnection topologies of solar array modules, such as SP, TCT, and LD are used in this work. Besides, the performance of a new interconnection topology, SP-LD is compared with the conversional SP, TCT, and LD configurations considering array power. The connection diagram of the modules in an array for SP, TCT, LD, and SP-LD topologies are shown in Fig. 2 (a), (b), (c) and (d) respectively.

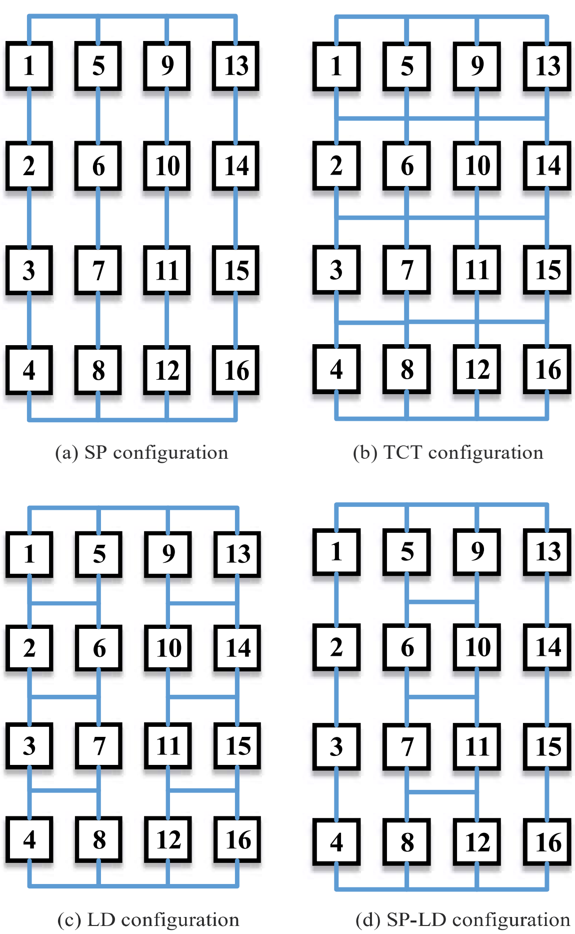

Fig. 2. PV modules interconnection topologies for 4×4 array.

D. *Module Rearrangement Pattern (MRP)*

In this work, four different interconnection topologies are tested using three different module rearrangement patterns (MRP). Fig. 3 shows the position of the aged PV modules, which are rearranged in three patterns MRP-I, MRP-II and MRP-III respectively. Where the aged PV modules are leveled from 1 to 24 in ascending order of their aging. PV panels no 1, 2, 3, and 4 are mostly degraded in power due to nonuniform aging effects. In this work, three MRP are selected based on the position of these four mostly aged PV modules. Hence, the effect of the most aged module position on the array output power has been added another dimension of comparative analysis of the module interconnection topologies.

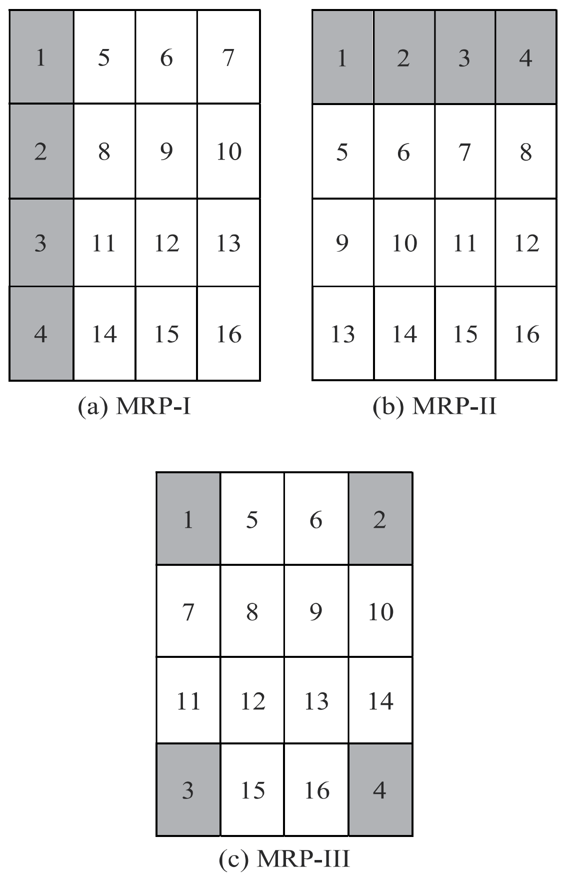

Fig. 3. Three different module rearrangement patterns (a) MRP-I, (b) MRP-II, and (c) MRP-III for a 4×4 PV array.

Therefore, three MRP are applied on the convention (SP, TCT, LD) and the proposed SP-LD interconnection schemes to evaluate their performance. The figure of merit of these three patterns is investigated with respect to mismatch losses and array maximum power output.

E. *Experimental Procedure*

The experimental procedure is explained in this subsection. Fig.4. shows the experimental setup of a 160W aged PV array. The array system is made by using 16 poly-crystalline solar panels. The power rating of each panel is 10 W. The moludes are positioned on the structures with a fixed tilt angle of 23.5°. The array is constructed in a 4×4 dimension. The solar panels are south faced and places on a rooftop, where the latitude is 23°43'N, and longitude is 90°25'E.

Here, the output electrical characteristics of the 160W array are extracted using a PV system analyzer (PVSA), model name PROVA-1011. The PVSA consists of a light sensor and a temperature sensor. Which are integrated with the measuring device, PROVA-1011 by Bluetooth communication to accomplish the measurement. PROVA-1011 can measure and store the output characteristics of the PV array in real meteorological conditions during the middle of a sunny day and clear sky. Modules rearrangement process takes 10 minutes while a single test by PROVA-1011 takes about a minute, maintaining standard test conditions at outdoor. According to IEC 60904-1 standards, during the *I-V* curve measurement at outdoor, the irradiance should be at least 800 W/m^2 [23,24]. Hence, the experimental data are recorded within the irradiance ranges (800 to 950) W/m^2. In [6], the artificial aging effect of the PV module is created by covering the top surface of the module using EVA paper. In this work, EVA papers are also used to cover the surface of the most aged four PV modules to simulate the increased aging condition.

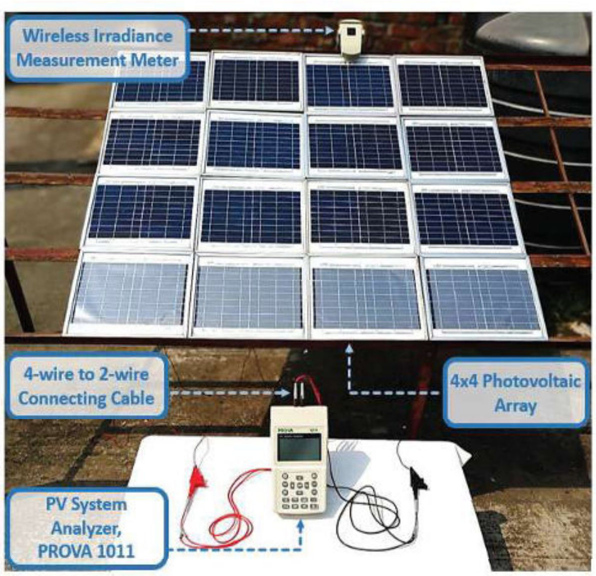

Fig. 4. Experimental setup of a 4×4 PV array for testing different interconnection topologies at the non-uniform aging condition.

III. Results and Discussion

The tested array output powers are analyzed here. Which is obtained by three conventional interconnection schemes and one novel configuration for three different MRP. Table II shows the results of array output power for four interconnection schemes (SP, TCT, LD, and SP-LD) using three-module patterns (MRP-I, MRP-III, and MRP-III). For MRP-I the lowest power is 145.16W, generated by LD configuration, whereas the highest power (149.88 W) is obtained by the proposed SP-LD interconnection. For MRP-II SP and TCT configurations are generated 130.47W and 128.47W respectively. Though the powers are higher than that for LD but lower than the proposed SP-LD configurations. On the other hand, for MRP-III, the output power is increased for LD than for SP and TCT but still, the proposed one is yielded higher outputs than all three conventional configurations. The percentage of recoverable energy (%RE) is calculated using the following equation.

$$\%RE = \frac{P_{SP-LD}^{array} - P_{SP}^{array}}{P_{SP}^{array}} \times 100 \quad (1)$$

Where P_{SP-LD}^{array} and P_{SP}^{array} are denoted as the maximum output power obtained by SP-LD and SP configurations respectively using a particular MRP. Fig.5 illustrates that the %RE by SP-LD interconnection for three rearrangement patterns of aged PV modules. The highest %RE (4.89%) is attained for MRP-III, while the lowest %RE (1.83%) is obtained for MRP-I. The average %RE is also calculated and its value is 3.28%.

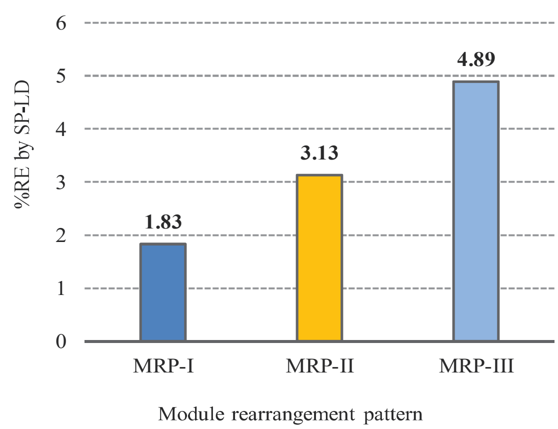

Fig. 5. Recoverable energy obtained by SP-LD interconnection topology for 4×4 array at three rearrangement patterns.

The percentage of mismatch power loss (MPL%) is calculated as follows.

$$MPL\% = \frac{\sum_{n=1}^{16} P_{module}^{mpp} - P_{array}^{mpp}}{\sum_{n=1}^{16} P_{module}^{mpp}} \times 100 \quad (2)$$

Where the summation of all (1 to 16) aged modules maximum output power is denoted by, $\sum_{n=1}^{16} P_{module}^{mpp}$ and the array output power is mentioned by, P_{array}^{mpp} at any particular interconnection topology and MRP. Table III summarized the mismatch losses for four configurations. For MRP-I the lowest MPL is 2.262% obtained by SP-LD interconnection. For MRP-II the highest loss is 18.447% occurred by LD configuration, whereas the lowest by SP-LD interconnection. For MRP-III, the maximum MPL is 8.79% occurred by SP configuration, however, the minimum MPL is 4.329% obtained by SP-LD interconnection topology.

TABLE II
OUTPUT POWER OBTAINED FROM 4×4 PV ARRAY

PV Array Interconnections	Array output power (watt)		
	MRP-I	MRP-II	MRP-III
SP	147.19	130.47	139.87
TCT	146.81	128.47	139.91
LD	145.16	125.06	143.94
SP-LD	**149.88**	**134.55**	**146.71**

TABLE III
MPL OBTAINED FROM 4×4 PV ARRAY

PV Array Interconnections	Mismatch power loss (%)		
	MRP-I	MRP-II	MRP-III
SP	4.016	14.920	8.790
TCT	4.264	16.224	8.764
LD	5.340	18.447	6.136
SP-LD	**2.262**	**12.259**	**4.329**

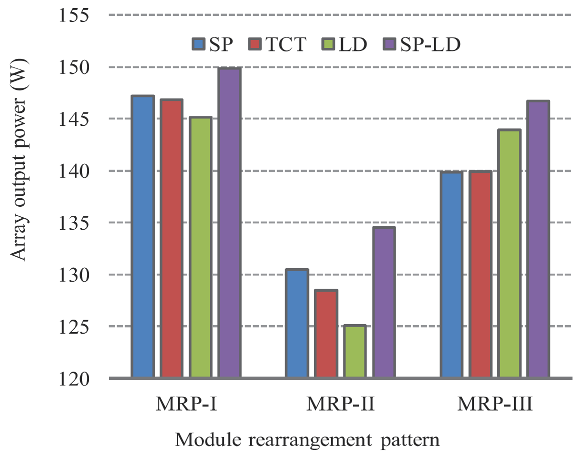

Fig. 6. Output power obtained by four different interconnection topologies for 4×4 array at three rearrangement patterns of aged photovoltaic modules.

Fig. 6 illustrates the output power obtained by four different interconnection topologies (SP, TCT, LD, and SP-LD) for 4×4 array at three cases (MRP-I, MRP-II, and MRP-III) of nonuniformly aged PV modules. For each case, the proposed novel hybrid SP-LD interconnection is performed better than conventional configurations for output power. Another observation is that the overall output power generation is decreased at MRP-II for all interconnection topologies, while maximum power is generated during MRP-I. On the other hand, Fig. 7 shows the lowest MPL is obtained by MRP-I. Hence, for nonuniformly aged solar array modules MRP-I is recommended as the best rearrangement process. Finally, the proposed SP-LD interconnection topology is outperformed for output power maximization and mismatch loss minimization.

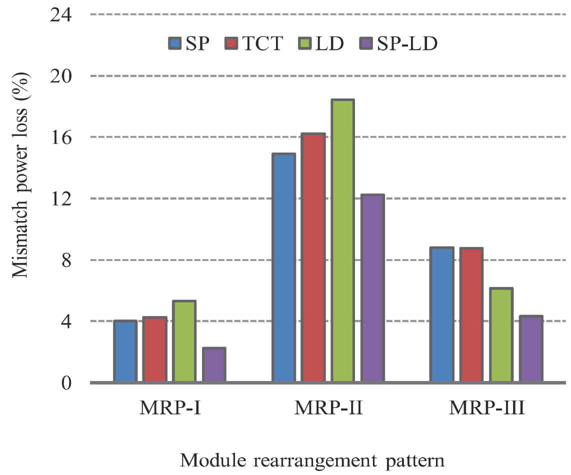

Fig. 7. Mismatch power loss obtained by four different interconnection topologies for 4×4 array at three rearrangement patterns of nonuniformly aged photovoltaic modules.

IV. CONCLUSION

Three most popular PV array interconnection schemes (SP, TCT, and LD) and a new hybrid interconnection topology (SP-LD) are experimentally tested using a 160W PV array the non-uniformly aging condition of PV modules. The proposed new configuration yields 3.28% (average) higher output power than the most commonly used SP array configuration. The positional effect of mostly aged solar panels in the 4×4 array is also investigated. The experimental results show that the output power increases significantly for all interconnection topologies when the mostly aged modules are connected in the series string connection at MRP-I. Hence, MRP-I is recommended for arranging the non-uniformly aged module in the 4×4 array. Moreover, a minimum MPL of 2.26% is achieved by the proposed SP-LD interconnection for MRP-I.

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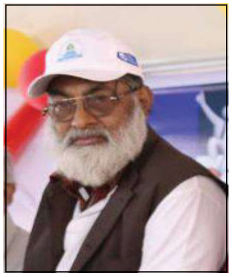

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