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Improved Dynamic Reconfiguration Strategy for Power Maximization of TCT Interconnected PV Arrays under Partial Shading Conditions

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***Abstract*—In photovoltaic (PV) systems, partial shading is a major issue that may cause power losses, hot spots, and PV modules damage. Thus, PV array dynamic reconfiguration approaches based on irradiance equalization (IEq) between rows have been proposed to alleviate the shading effect thereby improving PV power production. However, the existing IEq-based reconfiguration techniques focus only on the minimization of row current error, without taking into consideration the voltage effect, which in turn, may result in power losses. In this regard, an improved reconfiguration strategy is proposed in the present paper to maximize the power production of a TCT interconnected PV array operating under partial shading conditions (PSCs). The proposed strategy aims to achieve a PV array reconfiguration that mitigates the droop voltage issue by considering irradiance levels in both rows and columns. An in-depth investigation of a typical PV module and TCT module is provided, demonstrating that there are cases where the partial shading does not affect the PV module current but the operating voltage. In addition, an analysis highlighting the limitations of the IEq technique regarding the droop voltage issue is presented. Furthermore, mathematical development is established for deriving the objective function of the proposed strategy. The efficiency of the proposed reconfiguration strategy is assessed through experimental tests carried out on a 20 MWp PV station in Ain El-Melh, Algeria. The obtained results reveal that the proposed method overcomes the weaknesses of the existing IEq strategy and ensures power production higher than the TCT and IEq configurations by 17.25% and 19.34%, respectively.**

***Index terms*—Power Maximization, PV array reconfiguration, partial shading, irradiance equalization (IEq).**

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Nomenclature

PV	Photovoltaic
IEq	Irradiance equalization
TCT	Total Cross Tied
PSC	Partial shading condition
MPP	Maximum Power Point
STC	Standard Test Conditions
NOCT	Nominal Operating Cell Temperature
EI	Equalization index
IMI	Level mismatch index
V_{PV}, I_{PV}	Output voltage and current of the PV module
V_m, I_m	Optimum voltage and current of the PV module
V_d	Diode forward voltage
V_{Ri}	Maximum voltage of the i^{th} row
G_{ij}	Irradiance of each module in row i and column j
G_{Ri}	Total irradiance of the i^{th} row
G_0	Standard irradiance
I_{Ri}	Maximum current of the i^{th} row
EI	Average irradiance difference found in each row
P_{PV}	Output power of the PV array
I_j & I_i	total irradiance of column j and row i
I_{sc}	Short-circuit current
V_{oc}	Open-circuit voltage

I. Introduction

Photovoltaic (PV) energy is intermittent energy. However, it is a promising solution as an alternative or additional to conventional electricity production sources, due to its advantages including; free and renewable solar energy production without the need for fuel, medium reliability requiring low maintenance, noiseless, clean, and environment friendly [1]. Despite the mentioned advantages, various factors may influence the PV output power, among them solar irradiance, temperature, shade, and dust. In the case of dust or shade, some parts of the array behave like an electrical load dissipating power and causing damage. Thus, the PV total output power may be reduced. The partial shading issue was widely discussed in the literature [2-4]. To deal with this issue, different PV array configurations were proposed to improve power production. Among them, the conventional configurations are categorized into four types; honey-comb (HC), bridge-linked (BL), serial-parallel (SP), and total cross-tied (TCT) [5]. The static TCT configuration is exposed as the most adequate strategy to reduce power losses of a shaded PV array [6-7]. Besides, to further increase the maximum power output and minimize the mismatch influence, scientists have proposed PV array reconfiguration methods based on PV module relocations according to the existing shading conditions.

The irradiation equalization strategy (IEq) is the main concept used to mitigate the losses due to partial shading [8-9]. In fact, this strategy is the overall platform for most of the research work carried out. The IEq strategy is based on the dispersion of shadows over the entire PV array interconnected initially in TCT configuration to avoid bypass diode activation and increase the output power. The reported research works were divided into two categories; dynamic reconfiguration and physical relocation of PV modules. The physical reconfiguration methods have two limits, the poor shading dispersion and wiring complexity that causes a voltage drop. Several techniques for physical reconfiguration were proposed by the authors in [10]. The physical location of the modules is modified based on SuDoKu [11], Futoshiki [12], non-symmetrical reconfiguration [13], magic square (MS) [14], Zig-Zag [15], dominance square (DS) [16], competence square (CS) [17], odd-even reconfiguration [18], SD-PAR [19], and Skyscraper [20] techniques to alleviate the effects of the partial shading over the entire PV array.

The dynamic or electrical reconfiguration techniques require more switches, sensors, and a complex control algorithm. However, this does not change the modules' physical location in the PV array, and shading mitigation is accomplished by dynamically adjusting the modules' electrical interconnections. The equalization index (EI) concept, which quantifies the degree of irradiance equalization, was proposed in [8]. Accordingly, the best arrangement is the one that keeps the EI as low as possible. Another alternative approach to this technique was presented in [21], which is applicable in cases where unequal numbers of modules per row are involved. However, with the increasing scale of PV arrays, the problem becomes much more complex, and the optimal solution cannot be reached in a timely manner. To this end, a growing number of research works have applied heuristic algorithms like [22], particle swarm optimization [23], grasshopper optimization [24], flow regime algorithm, social mimic optimization, and Reo algorithm [25], and modified Harris Hawks optimization [26], for PV array reconfiguration based-output power enhancement. These reconfiguration techniques use mathematical models for the equalization of PV modules' irradiance, which ensures the best possible irradiance balance for every row as much as possible. However, such techniques suffer from high computational burdens. Therefore, in order to get an optimal IEq arrangement, the authors in [27] have adopted an iterative and hierarchical sorting method. In addition, similar methods were discussed in [28] and [29], and recent methods like followed the regularized leader (FTRL) algorithm-based regression prediction model [30], and maximum-minimum tier equalization swapping (MMTES) algorithm [31], were proposed. These techniques apply the concept of shadow dispersion in the IEq concept for distributing the effects of shadow within the individual rows as equally as possible using specific rules. Given that there is practically no necessity to develop and resolve mathematical functions for irradiance equalization, these methods are comparatively simple. However, the mentioned methods have not been able to achieve an optimal radiation balance in the same cases of partial shading.

An additional approach, known as array adaptive reconfiguration (AAR), was introduced in [32], [33], and [34]. This method is made up of two parts, fixed and adaptive. The main principle of this method is to associate the highly enlightened modules of the adaptive part with the row that is the shadiest from the fixed part, to make the levels of irradiation in every row almost identical. This means that the adaptive part always follows the principle of IEq. Further, in [35], the authors have provided an advanced reconfiguration technique based on the balancing of physical quantities such as current and voltage. The influence of voltage on the energy output of the photovoltaic array was discussed and a method for reconfiguring modules in the presence of mismatch was proposed.

Generally speaking, almost all existing reconfiguration methods utilize the IEq principle and result in a fairly uniform dispersion of the shadow. However, when we investigate the basic idea of the IEq principle, it becomes clear that this principle focuses on improving the generated energy only. This improvement is based on the principle of line current minimization without considering the effect of the bypass diode. In fact, in practice, PV modules are occupied by more than one bypass diode, each diode ensuring the protection of one-third of the module. In the case of partial shading of the module, the current remains flowing through the bypass diodes. However, the voltage may drop according to the degree and the location of the shade. Thus, methods of reconfiguration which are based on the principle of IEq cannot be able to achieve the PV array optimal configuration under different PSCs. Therefore, power generation improvement cannot be guaranteed. In [7], a fixed configuration method has been outlined, which primarily examines the bypass diode effect on the PV array voltage. However, the proposed method in this study is typically based on the IEq strategy, and the authors have conducted simulation tests using PV modules with low power and equipped with one bypass diode.

In this regard, the present paper proposes an advanced strategy-based PV array reconfiguration. The main concept of this strategy is based on increasing simultaneously the maximum row current error and the minimum column voltage error. Applying such a strategy for PV reconfiguration can ensure the highest power production under PSCs compared to TCT and IEq configuration methods. The main contributions of the present work are:

- A new strategy-based PV array reconfiguration is proposed, which focuses on mitigating the droop voltage effect by considering irradiance levels in both rows and columns;
- The limitations of the TCT configuration and the IEq reconfiguration methods are highlighted by investigating the output characteristics of commercial PV modules, used in practice, under PSCs;
- The weakness of the IEq method is demonstrated regarding the droop voltage issue, which can be mitigated by interconnecting the PV modules in parallel to avoid the operation in the undesirable zone IV.
- Mathematical model development: we develop a comprehensive mathematical model to derive the objective function of our proposed strategy. This model takes into account the irradiance levels in both rows and

columns of the PV array, allowing for optimal reconfiguration to mitigate the voltage droop issue and maximize power output.

To assess the performance of the proposed strategy, an experimental comparative study between the proposed approach and TCT and IEq configuration methods regarding power production under PSCs is established.

The rest of this paper is structured as follows. Section II discusses the problem of the structure of the PV module as well as the TCT configuration under PSCs. In section III, the limitation of the IEq technique is provided. Section IV describes the proposed strategy. Sections V and VI provide the experimental results and main conclusions of the present paper.

II. ANALYSIS OF PV MODULE UNDER PARTIAL SHADING

In the present section, the partial shading effect on a PV module is investigated through theoretical analysis and experimental study. More particularly, it highlights the problem of the voltage droop addressed in this work in a typical PV module and a TCT-configured one.

A. *Typical PV module*

Generally, a series of individual solar cells are usually connected to obtain a higher voltage in the PV module. The string can work at the MPP and achieve maximum output power if the electrical characteristics of all the cells in the string's sub-module are identical. Fig. 1 shows the structure of a PV module consisting of three sub-modules, in which each sub-module includes 12-36 cells that are serial-connected. A bypass diode is placed over each sub-module to protect the PV module in the case of shading.

In the presence of partial shade on one or two parts of a PV module, the cells under shade become in reverse bias, Therefore, the bypass diode starts working in forwarding bias. The objective of using the bypass diode is to add another current flow path in order to support bypassing the current around the damaged PV sub-module.

Fig. 2 illustrates a PV string with one partially shaded module. In this module, the shaded cell is located on the lower part. The bypass diode concerned by this group of cells (20 cells) starts operating in forwarding bias (short circuit of the infected sub-module) thereby ensuring the current flow through the string. Once the bypass diode operates, it introduces an inevitable voltage drop meanwhile the same current is circulated in the whole string.

Accordingly, the output voltage and current of the shaded module can be derived as follows:

$$V_{PV} = \frac{2 \times V_m}{3} + V_d \quad (1)$$

$$I_m = I_{String} \quad (2)$$

where V_{pv} is the module's output voltage, V_m and I_m the operating voltage and current of the PV module, respectively, and V_d is the diode forward voltage.

Thus, as indicated in (1) and (2), the partial shading may affect only the module output voltage, not the current.

To further highlight the partial shading effect, an experimental test is carried out as shown in Fig. 3. In this test, a PV module type Yingli solar 250 Wp is considered with an operating voltage and current at standard test conditions (STC), i.e., 29.8 V, and 8.92 A. As seen, the shaded cell is located on the lower part of the PV module. The obtained P-V and I-V characteristics are presented in Fig. 4. As shown, the maximum delivered power, current, and voltage of the healthy PV module are 146 W, 5.53 A, and 26.3 V, while that of the shaded module are 97 W, 5.54 A, and 17.6 V, respectively. This means that the current is not affected by the shading, contrary to the PV voltage, which is dropped by 8.7 V. Therefore, it can be concluded that there are cases where partial shading affects only the PV module output voltage, not the current.

B. *TCT- configured PV module under partial shading*

As depicted in Fig. 5, the TCT configuration is obtained by associating, in parallel, all the PV modules on the same row of the different strings. This gives a PV array in the form of a matrix *M* of dimension (m×n); *m* rows and *n* columns; in which (m×n) modules are arranged. In this way, the currents in the different nodes and the voltage of the PV modules connected in parallel are equal, hence, there is no phenomenon of mismatch between PV modules. Each module is labeled with the index '*i*, *j*' where '*i*' indicates the row and '*j*' denotes the column in which the module is linked [29].

In the case of one bypass diode for each module and given that the PV module's optimum current is proportional to its irradiance and noting that the maximum current value in any row is related to the total amount of the radiance levels of the modules installed in the concerned row. Considering the irradiance of each module in row *i* and column *j*, G_{ij}, the total irradiance G_{Ri} of the i^{th} row can be expressed as follows:

$$G_{Ri} = \sum_{j=1}^{n} G_{ij} \quad ,i\_ = 1\ldots\ldots m \quad (3)$$

Besides, the maximal current (current limit) of the i^{th} row (I_{Ri}) can be obtained as follows:

$$I_{Ri} = \frac{G_{Ri}}{G_0} I_m \quad ,i- = 1\ldots\ldots m \quad (4)$$

where G_0 denotes the standard irradiance (1 kW/m²) and I_m is the optimum current of the PV module under standard irradiation conditions.

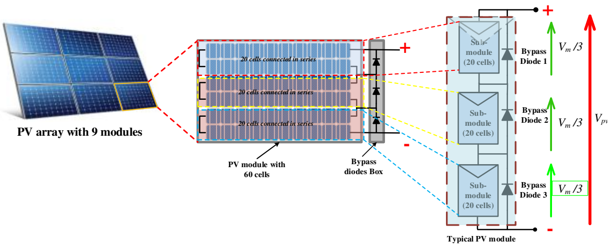


Fig. 1. PV module consisting of three sub-modules with bypass diodes. Each sub-module has a series connection of 20 PV cells.

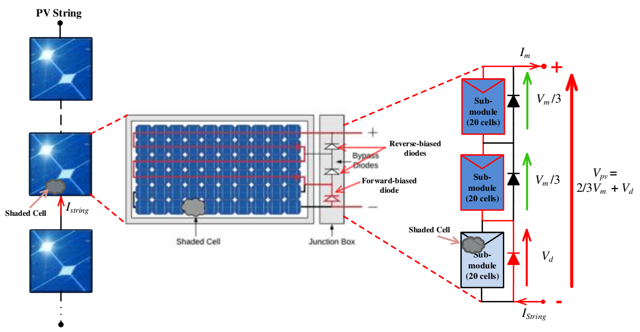


Fig. 2. PV module under partial shading serially connected.

When the partial shading phenomenon occurs, the current of the rows becomes different. Then, the rows that cannot reach optimum currents will be bypassed via the diode in order to protect them from damage. Thus, the output voltage drops to a lower voltage level, causing peaks in the PV array output characteristics.

In the case of three bypass diodes for each module, that means 3 sub-modules installed in each PV module. If the PV module is not fully shaded, as discussed previously, the total output current, I_{PV}, of the PV module is not influenced by the partial shading. However, the optimum voltage of the PV module may drop depending on the level and location of the shadow [36].

On the other hand, according to Fig. 5(b), the operating voltage for each PV row, V_{Ri}, can be obtained as follows:

$$V_{Ri} = \min\left(V_{ij}\right) \tag{5}$$

where V_{ij} is the operating voltage of the PV module in row i and column j. Therefore, the total output voltage of the PV array can be defined as follows:

$$V_{PV} = \sum_{i=1}^{m} V_{Ri} \tag{6}$$

As a result, the optimal output power P_{PV} of the PV array can be obtained by:

$$P_{PV} = V_{PV} \times I_{PV} \tag{7}$$

According to this equation, it can be noticed that the PV array output power may be degraded when the voltage drops.

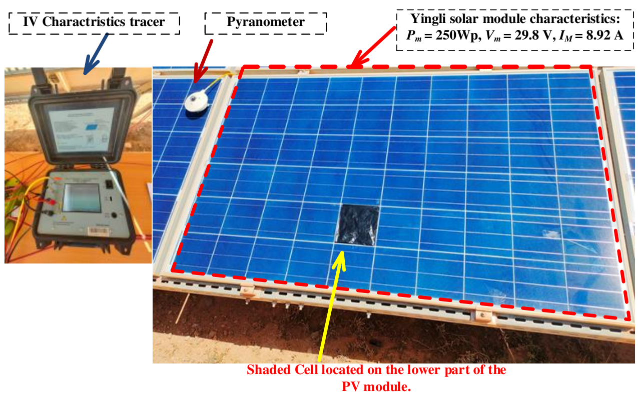
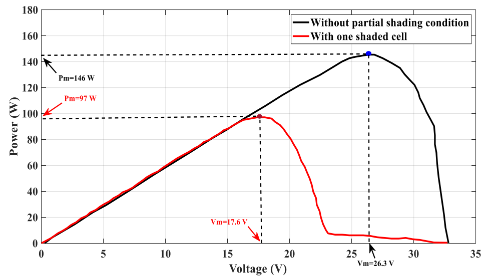
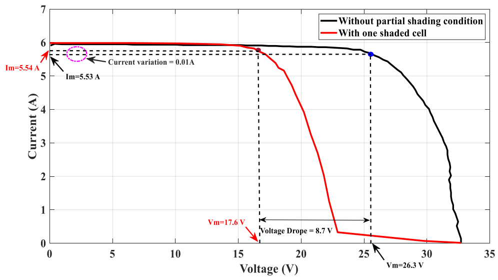


Fig. 3. Experimental test setup of a PV module under partial shade.



(a)



(b)

Fig. 4. Experimental PV module's characteristics under partial shading conditions; (a) P-V curve and (b) I-V curve.

III. Limitation of the Irradiance Equalization IEq

This section provides an overview of the irradiance equalization method and its limitations regarding the voltage droop issue.

A. *Mathematical models of IEq strategy*

The mitigation of the shade effect over the PV array is the main idea for the IEq principle. This is done by moving the modules with high illumination to the most shaded row in order to make the total illuminance of each row close to equal. Therefore, the row current difference minimization is indispensable. A wide number of IEq formulas have been proposed in the literature. For example, the authors in [8] have proposed a mathematical method called equalization index (EI). This method is based on an optimization algorithm that calculates the average irradiance difference found in each row by using the following expression:

$$EI = Max\left(G_{Ri}\right) - Min\left(G_{Ri}\right) \quad \forall i \tag{8}$$

where G_{Ri} denotes the average irradiance found in row i.

The optimization algorithm should choose the PV array configuration that minimizes the EI.

A similar mathematical method named level mismatch index (IMI) has been proposed in [21]. The row irradiance level was minimized based on the following expression:

$$IMI = 0.5\sum_{i=1}^{m}\sum_{l=1}^{m}\left(G_{Ri} - G_{Rl}\right)^2 \tag{9}$$

where G_{Ri} and G_{Rl} are the resulting levels of irradiance in rows i and l, respectively.

Similarly, the arrangement of the PV array was done according to the lower value of IMI.

B. *Limitations of the IEq reconfiguration method*

IEq-based-reconfiguration methods provide an effective way to enhance the PV output power connected in TCT under various PSCs. However, in the case of the industrial

PV modules with three bypass diodes or more, the IEq strategy may no longer be optimal and can even reduce the maximum output power of the rearranged PV array. To confirm the IEq weakness, an experimental test is conducted based on a PV array with (3×2) TCT interconnected modules.

Fig. 6(a) depicts the PV array configuration under a partial shading pattern (Before using IEq principal to shade dispersion). The initial shading pattern with a low level of irradiation (60 W/m²) is found in two PV modules (5 and 6) placed in the same row and two modules (2 and 4) with an irradiation level of 310 W/m².

Fig. 6(b) illustrates the new configuration of the PV array using the IEq principle. The shadows are dispersed throughout the PV array to avoid the current limit.
By considering (8), the level of difference between the row irradiance of both arrangements (initial configuration and IEq strategy configuration) can be given by:

$$EI\_a = \left(\frac{577+310}{2}\right) - \left(\frac{60+60}{2}\right) = 383.5 \qquad (10)$$

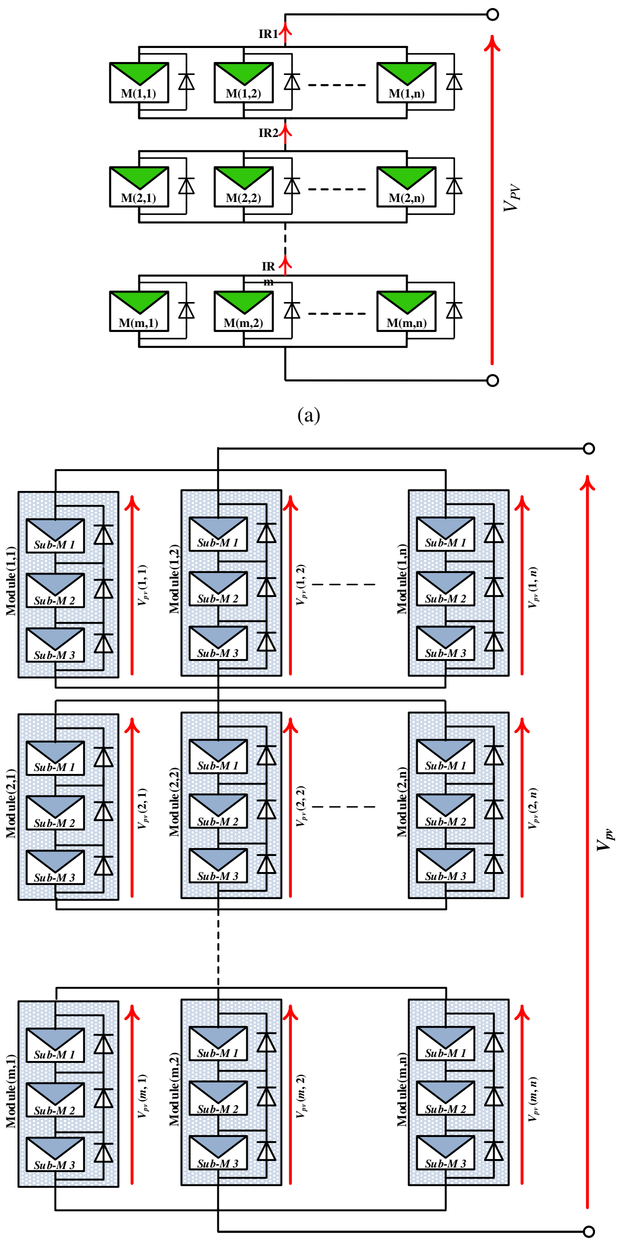
$$EI\_b = \left(\frac{310+310}{2}\right) - \left(\frac{577+60}{2}\right) = 18.5 \qquad (11)$$

with EI_b and EI_a indicating the equalization index of both patterns after and before reconfiguration.

According to (11), it is evident that the IEq-based reconfiguration method minimizes the difference in row irradiances resulting in a better shadow dispersion. However, from the P-V characteristic curve shown in Fig. 7, the maximum output power of the PV array that is reconfigured using the IEq strategy is reduced compared to the initial configuration. In addition, it can be seen that the optimal PV array voltage is decreased after the reconfiguration using the IEq strategy, while the operating current almost remains unchanged. This means that the total power is reduced due to the voltage drop.

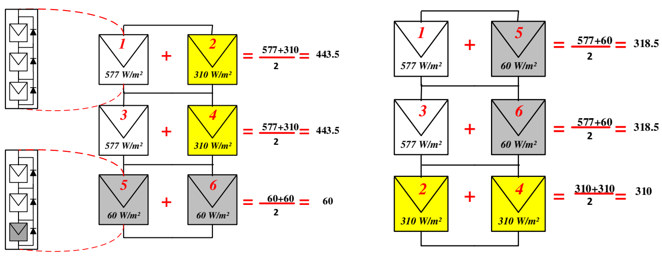
It is worth mentioning that for the PV array with initial configuration, the low-irradiance sub-modules of the modules under shade are bypassed and their optimal output voltage is reduced. However, the shaded modules are connected in the same row instead of dropping the voltage of the other rows. So, the remaining rows can deliver a higher output voltage. In contrast, by using the IEq strategy, the sub-modules' low irradiance affects the voltage of two rows, thereby reducing the PV array's maximum output power.

In conclusion, the IEq strategy minimizes only the row current error of the PV array. This cannot guarantee that the output power is maximized in the case of a PV array containing commercial modules with more than one bypass diode. As a consequence, the principle of IEq is not always the best solution to maximize the power output of a PV array.



(b)

Fig. 5. TCT interconnected PV array; (a) modules with one diode bypass and (b) modules with three bypass diodes.



(a) (b)

Fig. 6. PV array under shading; (a) initial configuration and (b) reconfiguration using IEq strategy.

IV. Proposed Strategy for PV Power Maximization

To avoid the total voltage droop of the PV array interconnected in TCT under PSCs, thereby maximizing the PV output power, an advanced reconfiguration strategy is proposed in this section. Such a strategy is more suitable for the case of PV modules equipped with more than one bypass diode and may not be suitable for other types of PV modules. The proposed strategy focuses on minimizing the average irradiance error between the PV columns meanwhile maximizing the average irradiance error among PV rows.

The block diagram of the proposed approach procedure is shown in Fig. 8. In addition, to further clarify the operation principle of the proposed strategy, a simple example is established. In this example, a PV array interconnected in TCT configuration consisting of 9 identical PV modules with three bypass diodes is adopted as shown in Fig. 9. This PV array is subjected to various irradiances indicated for each module in W/m². The proposed strategy can accomplish the task based on two steps. In the first step, the control algorithm relocates the modules to equalize the average of irradiances present at each column to 2100W/m² as given in Fig. 9(b). This is achieved by swapping modules 2 with 3, and 4 with 8.

In the second step, the row irradiance maximization is performed to avoid the voltage drop with a parallel connection. For this, the control algorithm swaps module 4 with 5, and module 2 with 9. Note that the row irradiance difference will be (3000 - 800 = 2200 w/m²) instead of (2100 - 2100 = 0 w/m²) found in the initial configuration.
To derive the mathematical expression of the objective function that should be optimized based on the proposed reconfiguration strategy, the following mathematical development is established.

Considering an array consisting of (n×m) PV modules, each module's irradiance is identified using conventional matrix notation. With a module located in row i and column j operating under an irradiance of I_{ij}, the total irradiance of column j and row i [8], can be defined as follows:

$$I_j = \sum_{i=1}^{m} I_{ij} \tag{12}$$

$$I_i = \sum_{j=1}^{n} I_{ij} \tag{13}$$

By evaluating all possible irradiance amounts of each column and row (I_j and I_i) for all possible combinations of module interconnections, (14) and (15) define the M index and N index, respectively. Moreover, the algorithm provides a combination that minimizes the M index and maximizes the N index. The derived objective function of the proposed strategy-based reconfiguration is written as follows:

$$M = \max(I_j) - \min(I_j) \quad \forall j \tag{14}$$

$$N = \max(I_i) - \min(I_i) \quad \forall i \tag{15}$$

$$Obj\_F = Minimzie(M) \times \text{Maximize}(\text{N}) \tag{16}$$

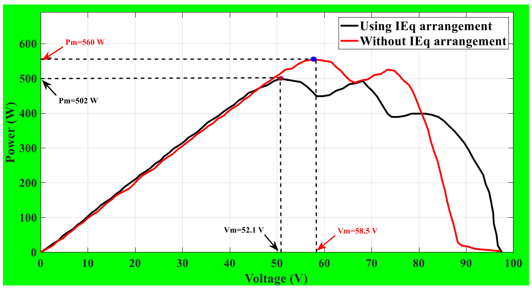


Fig. 7. P-V and I-V characteristics of the TCT and IEq arrangements.

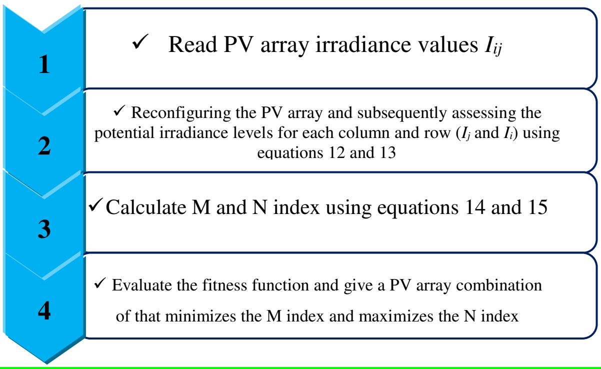
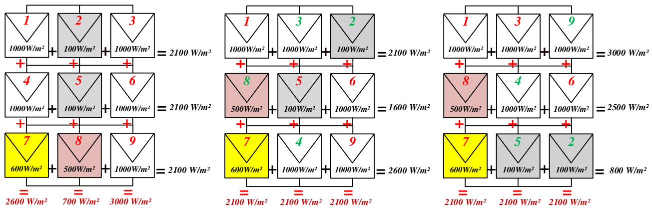


Fig. 8. General procedure for reconfiguring photovoltaic panels based on the proposed approach.



(a) (b) (c)

Fig. 9. Proposed strategy steps; (a) initial configuration, (b) step one, and (c) step two.

V. Experimental Results and Discussion

To evaluate the efficiency of the suggested reconfiguration strategy in comparison with the irradiance equalization (IEq)-based reconfiguration scheme, an experimental setup is built using commercial PV modules installed in a large-scale grid-connected PV station located in Ain El-Melh, Algeria. Fig. 10 displays the experimental testbed including the used components.

The artificial shading is made by covering the PV modules with black and yellow plastic sacks. In which, the black color may reflect around 90% and the yellow color around 49% of the in-plane irradiance. The data are obtained through an I-V characteristics tracer (type Kewell IVT-12-1000) and plotted using MATLAB software.
The testbed components are listed hereafter:

- Twelve PV modules Yingli-YL250P (250Wp) with the parameters listed in Table. I.
- I-V characteristics tracer type Kewell IVT-12-1000.
- In-plane irradiance sensor (Pyranometer type: KIPP&ZONEM).
- Cell temperature sensor (Pt1000)
- Switching matrix box.
- Banana plugs and Laptop.

Note that the most ideal IEq method is compared to the proposed strategy. Therefore, given that all published methods use the IEq concept and their mathematical functions are similar, the best IEq configuration can be achieved by any of these methods, ignoring the variants in the computing capacities of the algorithms.

Fig. 10. Experimental test setup with the used components.

TABLE I: MODULE SPECIFICATION (YINGLI SOLAR YL2545-29B)

PV module	Specifications
STC power rating	250 Wp ±5%
Number of cells	60
V_{mp}	29.8 V
I_{sc}	8.92 A
I_{mp}	8.39 A
V_{oc}	37.6 V
Power temperature coefficient α %/°C	-0.45
NOCT (°C)	1000V

The proposed strategy is assessed against two shading cases with different levels.

A. *Case 1: 1/3 shaded PV modules*

In this case, a PV array of 12 modules (6×2) is divided into three clusters as shown in Fig. 11. The exposure profiles of irradiances considered for this case are 416W/m², 203 W/m², and 40 W/m², respectively. Note that 1/3 of each PV module is partially shaded in the lower part (modules; 7, 10, 11, and 12).

Fig. 12(a) shows the initial shading pattern of the PV array under study with TCT Configuration. By considering the IEq concept, the resulting shading pattern configuration is given in Fig. 12(b), in which the row current difference is minimized as much as possible. After that, by applying the proposed reconfiguration approach, the obtained shading pattern is given in Fig. 12(c).

Besides, the voltage, current, and the corresponding total power produced by the PV array can be computed as follows:

- When applying the IEq method:

$$V_{PV} = 2\times V_m + 4\times\frac{2}{3}V_m = \frac{14}{3}V_m \qquad (17)$$

$$I_{IEq} = 2I_m \qquad (18)$$

$$P_{PV} = \frac{14}{3}V_m \times 2I_m = \frac{28}{3}I_m V_m \qquad (19)$$

- When applying the proposed strategy:

$$V_{PV} = 4\times V_m + 2\times\frac{2}{3}V_m = \frac{16}{3}V_m \qquad (20)$$

$$I_{PS} = 2I_m \qquad (21)$$

$$P_{PV} = \frac{16}{3}V_m \times 2I_m = \frac{32}{3}I_m V_m \qquad (22)$$

According to the above equations, it can be noticed that the voltage and power delivered by the PV array when applying the IEq are lower than the ones of the proposed strategy by $2/3V_m$ and $4/3V_m$, respectively. While the produced currents based on both methods are similar ($2I_m$). This means that when applying the conventional IEq, the shaded sub-module in each infected module is bypassed causing a voltage drop, hence, power losses. While, if the suggested reconfiguration strategy is functioning at the maximum power point (MPP), the partially bypassed modules (a sub-module has been bypassed) are grouped into similar rows to avoid the voltage drop of the healthy modules.

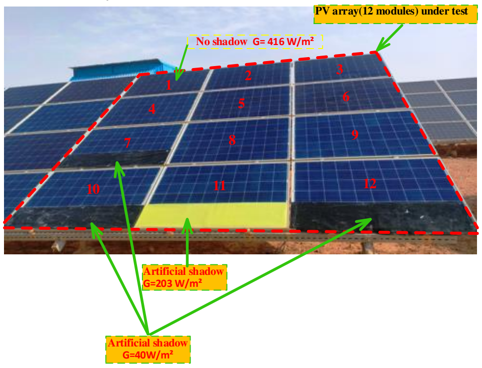


Fig. 11. Layout of the PV array under partial shading pattern for case 1.

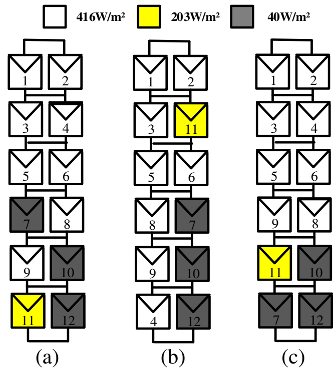


Fig. 12. Partial shading pattern for case 1; (a) standard TCT configuration, (b) IEq-based arrangement pattern, and (c) Proposed strategy pattern.

The obtained P-V characteristics of the PV array using the proposed reconfiguration strategy compared to the IEq and TCT arrangements are shown in Fig. 13. From this figure, it can be seen that the produced power by the PV array at the MPP using the proposed strategy is 1004 W, which is higher by 12.05% than the standard TCT array power (883 W) and 12.94% higher than the IEq method power (874 W). In addition, it can be noted that the TCT reconfiguration has an output power higher than the IEq strategy. This confirms the weakness of the IEq approach against partial shading of the PV modules with 3 bypass diodes installed in the plant.

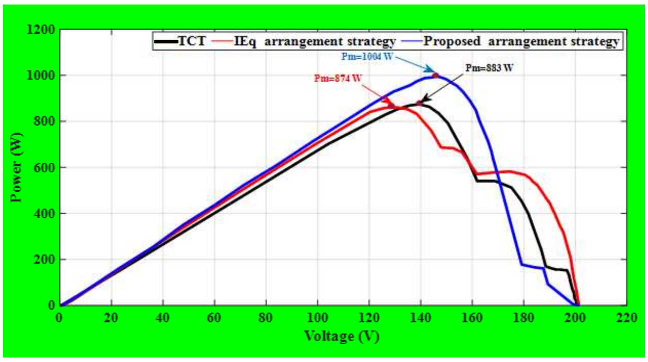


Fig. 13. P-V experimental curves for case 1 of; (a) TCT, (b) IEq, and (c) proposed strategy-based PV reconfigurations.

B. *Case 2: 1/2 shaded PV modules*

Here, a half shadow of the PV modules is considered. The shading profiles considered for this case are 513 W/m², 255 W/m², 107 W/m², and 53 W/m² as shown in Fig. 14. Notice that 1/3 of each PV module is partially shaded in the lower part (modules; 3, 5, 8, 10, and 12).

Fig. 15(a) shows the initial shading pattern, Fig. 15(b) depicts the reconfigured scheme by using the IEq method, and the resulting scheme after applying the proposed strategy is illustrated in Fig. 15(c). In addition, the corresponding obtained P-V curves for TCT, IEq, and the proposed strategy are presented in Fig. 16. It can be noticed that the maximum output power when applying the proposed algorithm is 1153 W, while the MPPs for the TCT and the IEq configurations are 954 W and 930 W, respectively. This means that the suggested reconfiguration strategy generates higher power than the other TCT and IEq approach configurations, by 17.25% and 19.34%, respectively.

As a result, the adopted reconfiguration can significantly increase the PV array's maximum output power while avoiding voltage losses. A significant power increase of more than 19% compared to the standard TCT configuration is observed in the case where a large number of modules are shaded. However, the IEq-based reconfiguration scheme fails to optimize the PV array, resulting in a power loss compared to the TCT configuration.

Fig. 14. Layout of the PV array under partial shading pattern for case 2.

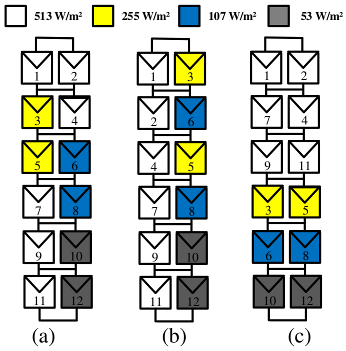


Fig. 15. Partial shading pattern for case 2; (a) standard TCT configuration, (b) IEq-based arrangement pattern, and (c) Proposed strategy pattern.

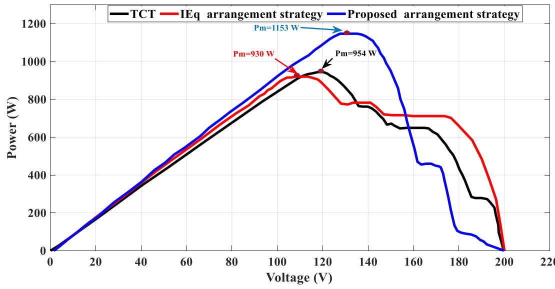


Fig. 16. P-V experimental curves for case 2 of; (a) TCT, (b) IEq, and (c) proposed strategy-based-PV reconfigurations.

Furthermore, through extensive experimental investigation, it is verified that for diverse shading patterns, the maximum power obtained by using the suggested technique is always higher than the one provided by the IEq-based strategy.

VI. CONCLUSION

In this paper, an advanced reconfiguration strategy was proposed for enhancing the total output power production of a TCT interconnected PV array under PSC. While the existing IEq-based strategies have focused on improving the PV output power by considering obtaining the lowest value of the minimum rows' irradiance, the suggested strategy has strived to minimize, also, the minimum columns' irradiance. The PV array optimal reconfiguration was obtained by using a developed mathematical model. A theoretical demonstration has provided and demonstrated that the proposed strategy was able to surmount the irradiation equalization (IEq) method limitations and enhance the PV array power production. In addition, the performance of the adopted approach was experimentally investigated. The results prove that the PV total maximum power of the suggested method was remarkably higher compared to the TCT and IEq-based configuration techniques. More particularly, in the case of half-shaded PV modules, the produced power based on the proposed strategy was obtained to be 17.25% and 19.34% higher than the TCT and IEq configurations, respectively. Our future works will address the implementation of the proposed PV reconfiguration approach based on optimization algorithms.

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