Solar Energy 188 (2019) 1306–1319

Contents lists available at ScienceDirect

Solar Energy

journal homepage: www.elsevier.com/locate/solener

A hierarchical architecture for increasing efficiency of large photovoltaic plants under non-homogeneous solar irradiation

Thanh Ngo Ngoc[a,b], Eleonora Riva Sanseverino[c], Ninh Nguyen Quang[d], Pietro Romano[c], Fabio Viola[c,*], Binh Doan Van[d], Hoang Nguyen Huy[a], Thang Tran Trong[a], Quang Nguyen Phung[e]

[a] Electric Power University, HaNoi, Viet Nam
[b] Graduate University of Science and Technology, Vietnam Academy of Science and Technology, Viet Nam
[c] Department of Engineering, University of Palermo, Palermo, Italy
[d] Institute of Energy Science, Vietnam Academy of Science and Technology, Viet Nam
[e] Hanoi University of Science and Technology, HaNoi, Viet Nam

ARTICLE INFO

Keywords:
Mismatch
Photovoltaic modules
Optimization
Reconfiguration

ABSTRACT

Under non-homogeneous solar irradiation, photovoltaic (PV) panels receive different solar irradiance, resulting in a decrease in efficiency of the PV generation system. There are a few technical options to fix this issue that goes under the name of mismatch. One of these is the reconfiguration of the PV generation system, namely changing the connections of the PV panels from the initial configuration to the optimal one. Such technique has been widely considered for small systems, due to the excessive number of required switches. In this paper, the authors propose a new method for increasing the efficiency of large PV systems under non-homogeneous solar irradiation using Series-Parallel (SP) topology.

In the first part of the paper, the authors propose a method containing two key points: a switching matrix to change the connection of PV panels based on SP topology and the proof that the SP-based reconfiguration method can increase the efficiency of the photovoltaic system up to 50%.

In the second part, the authors propose the extension of the method proposed in the first part to improve the efficiency of large solar generation systems by means of a two-levels architecture to minimize the cost of fabrication of the switching matrix.

1. Introduction

Currently, solar energy plays a very important role in global energy development. It is the green source with largest potential in renewable energy. Besides, direct conversion of solar radiation into electricity, without emission of greenhouse gases, through solar panels may bring the power generation closer to the loads, providing electricity in remote areas where the main power grid cannot reach. However, the investment cost for the solar panels is still high, although decreasing, and the performance is still low, leading to strong research on solar energy technology, to reduce costs and help the solar energy to compete with other renewable energy sources in the future (International Energy Agency, 2013; Lynn, 2011).

In recent times, a large part of the published works (Veerachary et al., 2002; Kouchaki et al., 2013; Balato et al., 2016; Yi-Hua et al., 2014; Zhaoa et al., 2015; Po-Cheng et al., 2015; Zhang et al., 2015; Salimi, 2018; Cheddadi et al., 2018; Abdel-Salam et al., 2018) are aimed at the identification of Maximum Power Point Tracking (MPPT) algorithms.

However, during operation, the solar panels may work with different performance levels, in particular, due to non uniform irradiation, when they are partly covered by shadow of clouds, trees, buildings. In addition, it is possible due to the aging and failure of the solar panels, after a long period of use, that the applied MPPT technology is inefficient, reducing the performance of the entire solar energy system (Femia et al., 2012; McCormick and Suehrcke, 2018). The non homogeneous working conditions of solar panels indeed cause the appearance of multiple optima in the P-V curve and the so-called *hotspot phenomenon* on the photovoltaic cells that are shaded, causing direct harm to the photovoltaic panel (Woytea et al., 2003; El-Dein et al., 2012).

In recent years, many studies have dealt with this issue and have proposed, as a possible solution, the reconfiguration of the PV generator topology (La Manna et al., 2014; Akrami and Pourhossein, 2018; Yadav

* Corresponding author.
E-mail address: fabio.viola@unipa.it (F. Viola).

https://doi.org/10.1016/j.solener.2019.07.033
Received 11 October 2018; Received in revised form 15 January 2019; Accepted 8 July 2019

Nomenclature

EI	Equalization Index
N	number of panels
i	row index
I-V	current-voltage
j	column index
m	number of rows
MPP	maximum power point
MPPT	maximum power point tracker
n_i	number of modules that are parallel connected of the row i
G	total irradiance
P-V	power-voltage
G_i	total irradiance of the row i
G_{ij}	irradiance value of module located on row i and column j
PS	partial shading
PV	photovoltaic
TCT	total-cross-tied
MAA	Munkres' Assignment Algorithm
DP	dynamic programming
SC	Smartchoice

and Mukherjee, 2018; Matam et al., 2018; Horoufiany and Ghandehari, 2018); on the same topic, the authors also proposed other methods (Riva Sanseverino et al., 2015; Ngo et al., 2016, 2017). In essence, the reconfiguration of the PV system consists in changing the connections of the solar panels to achieve an optimum configuration, thus providing the maximum systems' generated power. Currently, the reconfiguration is applied for 2 main connection topologies of PV systems: Series-Parallel (SP) and Total-Cross-Tied (TCT) configurations. In (Riva Sanseverino et al., 2015; Ngo et al., 2016, 2017), the authors proposed a reconfiguration method for improving the efficiency of the solar energy system under Total-Cross-Tied (TCT) connection. In this article, the authors propose a reconfiguration method for large PV systems based on a hierarchical approach. The basic topology at the two levels is different.

SP at the lower level and TCT at the higher level. The underlying idea is that the SP topology is currently the most adopted for existing solar PV generation systems.

Moreover, it may happen that the lower level topology (small perturbations in irradiation) may not change significantly while the upper level topology is the TCT.

Another important contribution of this paper is the proposal of a new switching matrix for reconfiguration PV system using SP topology. Based on that, an optimum configuration selection method is considered. The latter has been implemented in Matlab Simulink both for SP and TCT configurations. Then, to test the efficiency of SP topology under reconfiguration, an experiment was carried out on a small 1 kW peak solar energy system.

Finally, the authors propose a method for applying the reconfiguration strategy over larger solar PV systems hosting many PV panels. By Matlab simulation, it is proved that a medium size PV system (60 PV panels), using a hierarchical reconfiguration combining TCT and SP topologies, increases its output power for more than 50% as compared to the same system not using reconfiguration.

Paper is divided in the following sections: paragraph 2 recalls the more popular reconfiguration strategies; Section 3 proposes a novel reconfiguration topology; paragraph 4 describes the experimental setup for reconfiguration algorithm; Section 5 deals with the application of reconfiguration strategy for a large PV system; finally Section 6 concludes the paper.

2. Reconfiguration strategies

It is well known that reconfiguration is a measure devoted to mitigate the mismatch effect and maximize the output power of small photovoltaic plants under non-homogeneous working conditions. Therefore, reconfiguration means changing the connections of the solar panels adaptively by a dynamic switching matrix. Although many convenient interconnection topologies have been developed, so far, the most exploited solutions rely on TCT (Fig. 1a) and SP (Fig. 1b) module interconnections. A broad state of the art on the subject is reported in (La Manna et al., 2014).

2.1. Reconfiguration for TCT topology

In (Riva Sanseverino et al., 2015; Ngo et al., 2016, 2017), the authors proposed a reconfiguration method for improving the efficiency of PV systems using Total-Cross-Tied (TCT) topology, based on the irradiance equalization criterion. Irradiance equalization is achieved by changing the connections of the solar panels adaptively by a dynamic switching matrix so that total solar radiation on parallel circuits is the most equalized. Efficiency of this method is shown in Fig. 2. After reconfiguration, efficiency of the system increases by 14.1% and transfer from the initial configuration to the optimal one needs only 3 switching operations.

2.2. Reconfiguration for SP topology

In the SP topology, the solar PV panels are connected in series, the strings of series connected panels are then connected in parallel according to the SP connection, see Fig. 1b. Most solar energy systems use SP connection circuits, for the purpose of serial voltage boosting. Strings are then connected in parallel with the purpose of increasing the current, ensuring the DC output is feasible for either DC/DC or DC/AC conversion. However, during operation, in a serial circuit, when a solar panel is partially or entirely shaded, low operating efficiency becomes a *Hotspot*, thus consuming the power generated by higher performance solar panels (Hermann et al., 1997). Bypass diodes, mounted in each group of cells, are designed to avoid this phenomenon cutting off the power generated by the solar panel. Reconfiguration by means of SP topology aims to build strings of series-connected modules with similar irradiance levels and then connecting all these strings in parallel. In this way, well-irradiated solar panels will not be limited in current by a low irradiance panel of the same string (La Manna et al., 2014; Patnaik et al., 2011).

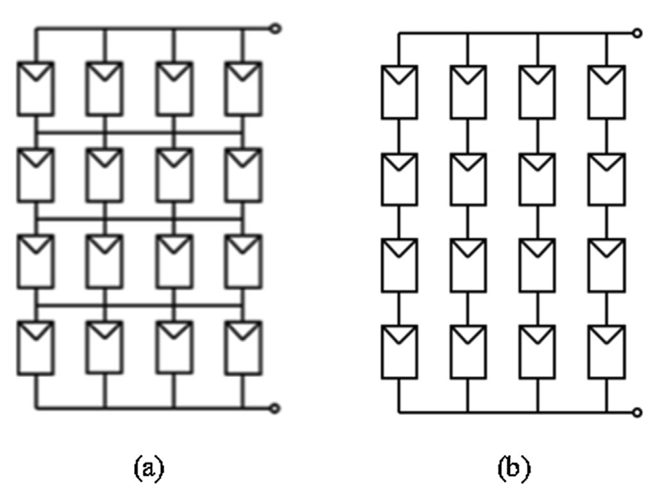
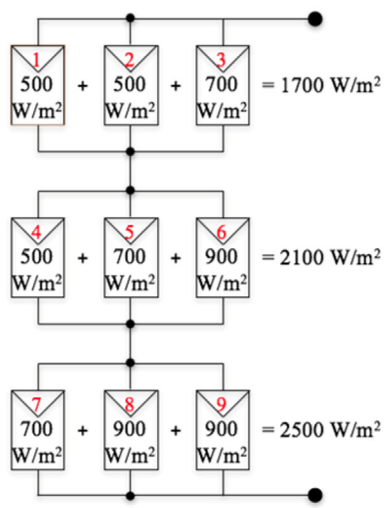
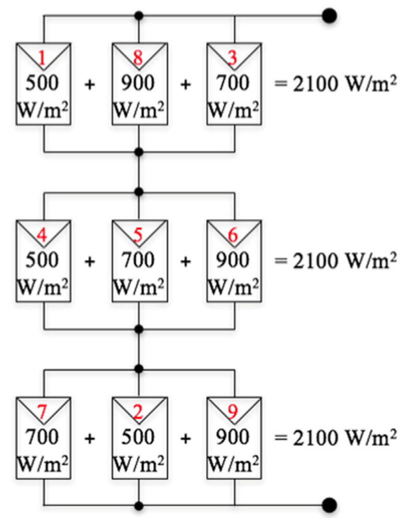


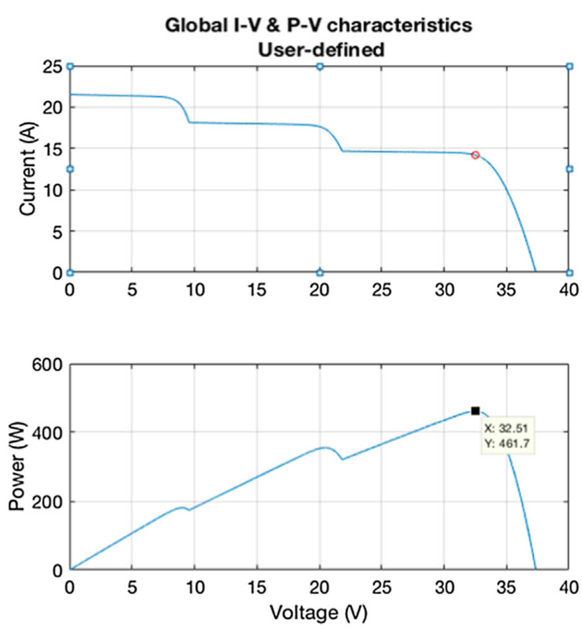
Fig. 1. Connection topologies of the PV array (a) Total-cross-tied topology (b) Series-Parallel.



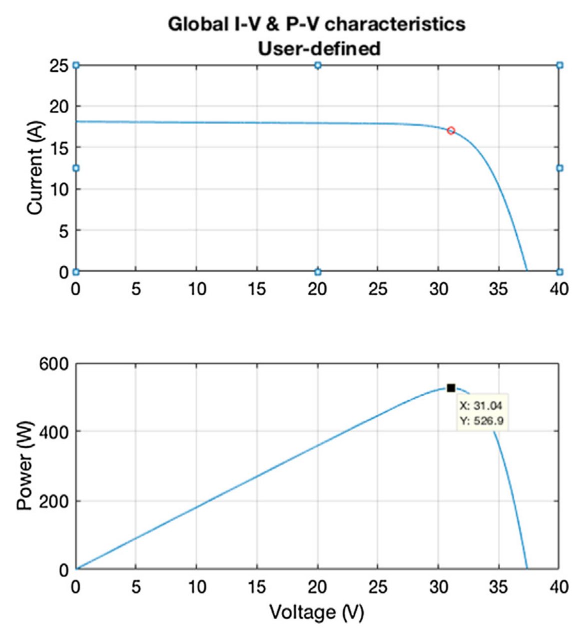
(a) TCT connection circuit before reconfiguration



(c) TCT connection circuit after reconfiguration



(b) I-V and P-V characteristic before reconfiguration (P_{MPPT} = 461.7W)



(d) I-V and P-V characteristic after reconfiguration (P_{MPPT} = 526.9W)

Fig. 2. PV system (a) and I-V P-V characteristic (b) before reconfiguration; PV system (c) and I-V P-V characteristic (d) after reconfiguration.

A Matlab simulation was run with the same case in Section 2.1, connected in SP topology, shown in Fig. 3, choosing PV panels Schüco International KG MPE 240 PS 04. The rating of each panel is reported in Table 1. At rated temperature 25 °C, the I-V and P-V characteristics of the PV system in Fig. 3a and b are shown in Fig. 3c and d. Before reconfiguration P_{MPPT} = 456 (Fig. 3c) and after reconfiguration (Fig. 3d) P_{MPPT} = 526.9 W, increasing the efficiency of 15.54%.

As it can be observed, the TCT configuration provides in general improved results in terms of output power, as compared to SP. In this paper, the two topologies were used starting from a centralized architecture of a large PV field, trying to minimize the cabling and avoid the change of the central inverter.

In order to make a more extensive comparisons more shading patterns have been considered and the following Table 2 shows the results.

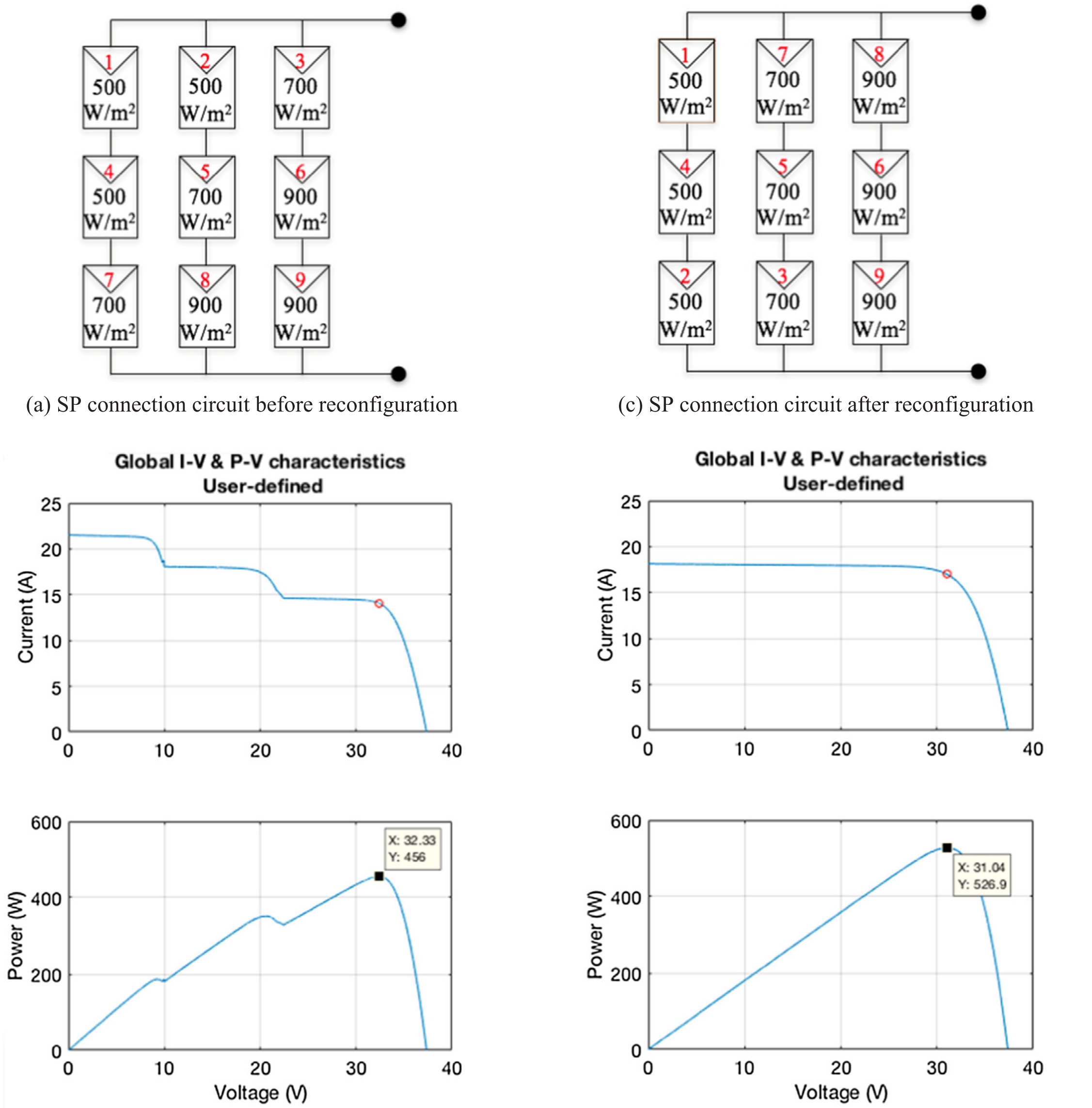
3. Proposed method for optimal photovoltaic array reconfiguration using SP topology

3.1. Switching matrix

For this particular application, the switching matrix is designed to include circuit breakers so that with proper opening and closing operation, it is possible to change the connection position of the solar panels in the SP connection circuit.

The proposed switching matrix is designed, see Fig. 4, so that each PV panel needs 3 switches on each row, hence with the switching matrix, the configuration of the PV system can be changed completely. The number of switches is N × 3 × M where N is the number of PV panels, M is maximum number of series connected PV panels.

The switching matrix in Fig. 4 is different as compared to other switching matrices proposed in the literature. In Patnaik et al. (2011) the authors proposed switching matrix which can sort the system's



(a) SP connection circuit before reconfiguration

(c) SP connection circuit after reconfiguration

(b) I-V and P-V characteristic before reconfiguration (P_{MPPT} = 456W)

(d) I-V and P-V characteristic after reconfiguration (P_{MPPT} = 526.9W)

Fig. 3. PV system (a) and I-V P-V characteristic (b) before reconfiguration; PV system (c) and I-V P-V characteristic (d) after reconfiguration.

Table 1
Electrical characteristics of Schüco international KG MPE 240 PS 04.

V_{MPP}	I_{MPP}	P_{MPP}	V_{OC}	I_{SC}
30.4 V	7.91 A	240 W	37 V	8.61 A

strings into two categories: the main PV string (MPV), which forms complete strings with the proper number of modules, and the sub-PV string, which forms a partial string that consists of the remaining PV modules that do not meet the required number to form an MPV. In operation, shaded PV modules are connect to DC/DC inverter in string; other PV modules do not change position. If there are no partial strings and hence the DC/DC bus and converter is not utilized. Not able change connection for fully configuration.

Each solar panel may connect to the serial circuits (Fig. 1b) with different switch sets, each set with 3 switches, positive pole switch (red), negative pole switch (blue), and line switch (yellow).

To create the SP configuration, and in particular the serial circuit, the positive pole switch and the negative pole switch on the circuit are closed, while the two poles of the parallel connection are activated using the line switches connected to the two black vertical metallic connections. With the opening and closing of the different sets of switches, the original connection of the solar panels will change, creating a new connection circuit to ensure the overall structure is still SP but the solar panel can gain a different position.

3.2. SP-based reconfiguration method

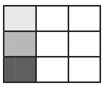
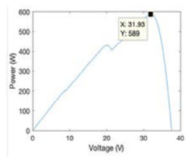
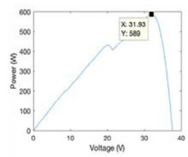
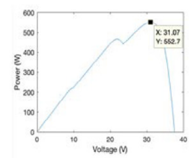
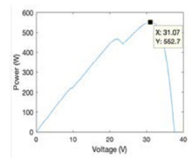
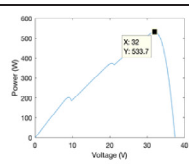
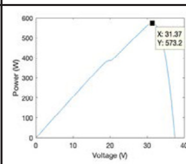
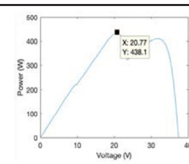
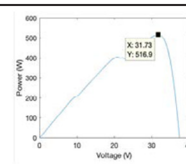
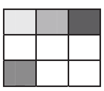
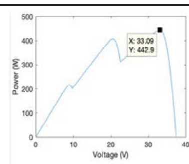
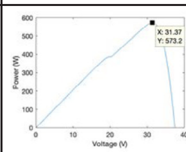
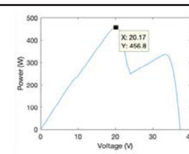
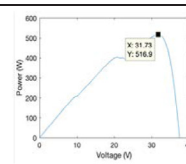
The general method for improving the efficiency of the PV systems using the SP connection circuit is depicted in Fig. 5.

The order of execution of each of the steps represented in Fig. 5 is outlined below.

Steps 1–2: From the initial connection configuration, using current and voltage measuring devices, current and voltage of each solar panel is acquired.

Step 3: The irradiance is deducted starting from measured values. To do so, the solar irradiance estimation is thus assessed:

Table 2
Extensive comparison of more shading patterns.

Shading patterns	TCT before reconfiguration	TCT after reconfiguration	SP before reconfiguration	SP after reconfiguration
				
	$P_{MPP} = 589W$	$P_{MPP} = 589W$	$P_{MPP} = 552.7W$	$P_{MPP} = 552.7W$
				
	$P_{MPP} = 533.7W$	$P_{MPP} = 573.2W$	$P_{MPP} = 438.1W$	$P_{MPP} = 516.9W$
				
	$P_{MPP} = 442.9W$	$P_{MPP} = 573.2W$	$P_{MPP} = 456.8W$	$P_{MPP} = 516.9W$

Partial shading degree: 0 % 20% 40% 60% 80%

Table 3
Starting configuration for numerical example.

300	600	900
600	900	1000
900	1000	1000

Table 4
Value array A for the starting configuration in Table 3.

300	600	900	600	900	1000	900	1000	1000
A0	A1	A2	A3	A4	A5	A6	A7	A8

$$G = \frac{G_{STC}}{I_{LSTC} + \mu_{1sc}(T_c - T_{CSTC})}\left[I + I_0\left(e^{\frac{V+IR_S}{N_S A k \frac{T_c}{q}}} - 1\right) + \frac{V + IR_S}{R_{Sh}}\right], \quad (1)$$

where

G is the solar irradiance measured in W/m^2,
I, V respectively are the measured current and voltage of the solar panel,
GSTC the solar irradiance in standard conditions,
I_{LSTC} is the PV cell light-generated current at STC,
μ_{1sc} is the short-circuit current temperature coefficient,
T_c the temperature of cell,
T_{CSTC} the temperature at STC (298.15 K),
I_0 the diode reverse saturation current,
RS and RSH respectively the cell series and shunt resistance,
NS the number of cells series-connected,
A the ideality factor,
k is the Boltzmann's constant,
q the electron charge,
Tc the temperature of cell.

The irradiance of each solar panel, is based on acquired parameters and measured current and voltage as in (Li Vigni et al., 2015).

Step 4: Application of the optimal connection configuration algorithm for the SP connection circuit and finding of the connection configuration for the best performance of the solar plant.
Step 5: Checking of the optimal connection configuration against the initial connection configuration, if there is sufficiently large (to be defined within prescribed tolerance) improvement, control the switching matrix to change the connection of the solar energy system from the initial connection to the optimal connection.

3.3. Algorithm for finding optimal configuration in SP topology

Many articles propose a method for optimal reconfiguration based on SP topology, (Riva Sanseverino et al., 2016; Murillo-Soto and Meza, 2017; Badwaik, 2017; Vicente et al., 2015). In this paper, the algorithm for finding the optimum connection configuration suggests the new location of the solar panels so that after their rearrangement, the solar panels on the same series circuit have the least solar irradiance difference.

The difference in irradiance between the solar panels in the serial circuit is proportional to the difference in current generated between the panels. In the ideal case, n solar panels in serial circuits have the same solar irradiance. In the real case, it may happen that some of them experience a different irradiance level. If G_{ij} is the irradiance on the solar panel at row i and column j in the SP connection circuit, the maximum irradiance difference in a serial circuit j can be calculated using Eq. (2) as follows:

$$EI_j = max(G_{ij}) - min(G_{ij}), \quad \forall j = 1, \cdots, n \quad (2)$$

The goal function of the algorithm is to minimize the maximum difference that can be appreciated, as follows:

$$EI = min(max(EI_j)), \quad \forall j = 1, ..., m \quad (3)$$

Thus, the configuration with the lowest value of EI is the optimal

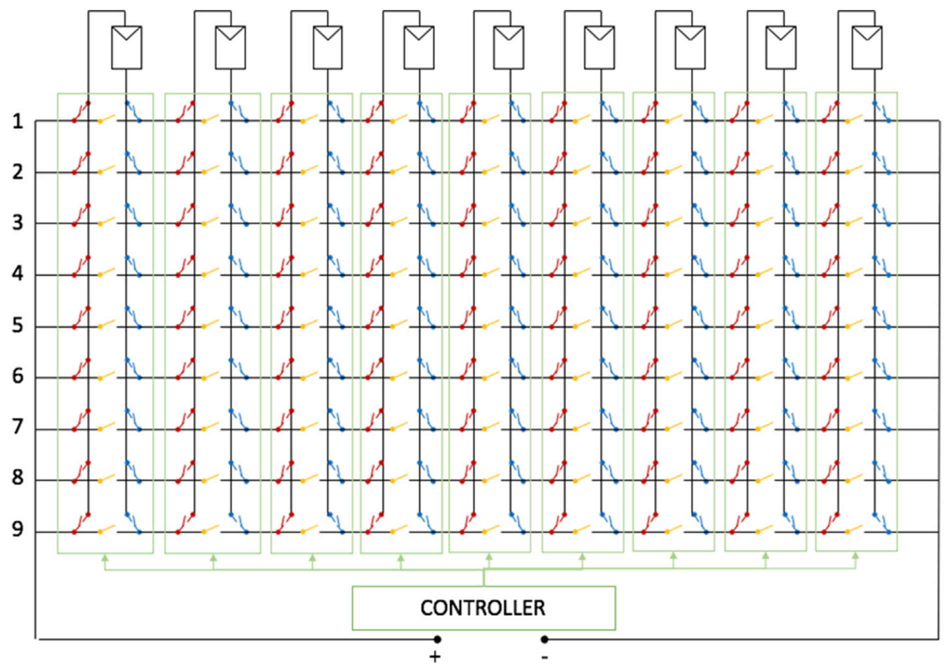


Fig. 4. Switching matrix.

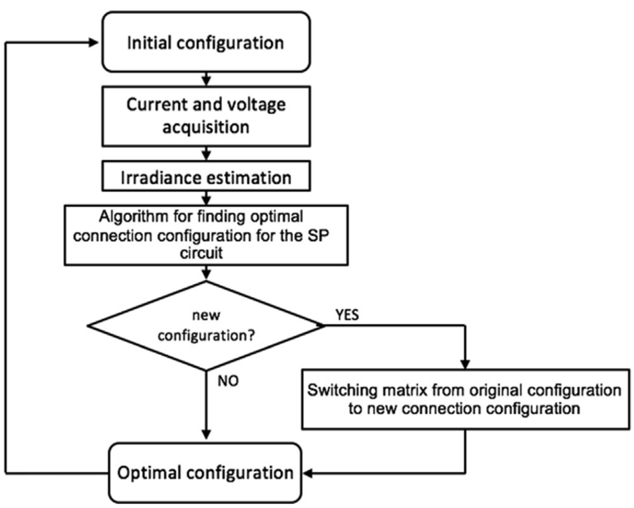


Fig. 5. Scheme of optimal reconfiguration for SP connection PV circuits.

configuration. In the case of multiple configurations with the same EI, configurations attainable with the minimum number of switching operations will be selected.

The flowchart shown in Fig. 6 depicts the process.

The algorithm will be explained for the SP connection. Consider the general solar PV system in Fig. 3a.

The panel in row i, column j receives a solar irradiance G_{ij}.

Step 1: Transforming the original matrix into a data array Ai.
Step 2: Using the QuickSort (Hoare, 1961), sorting of the Ai data array in descending order.
Step 3: Create a matrix B of the same size as the matrix G.
Step 4: In turn, arrange the elements of array A into matrix B in the top-to-bottom direction, from left to right.

In order to explain the method, a numerical example is here given. Consider a solar PV system that includes 9 solar panels, SP connected, receiving different irradiance levels as in the table below.

G_{ij} corresponding to the value of solar irradiance in row i, column j.

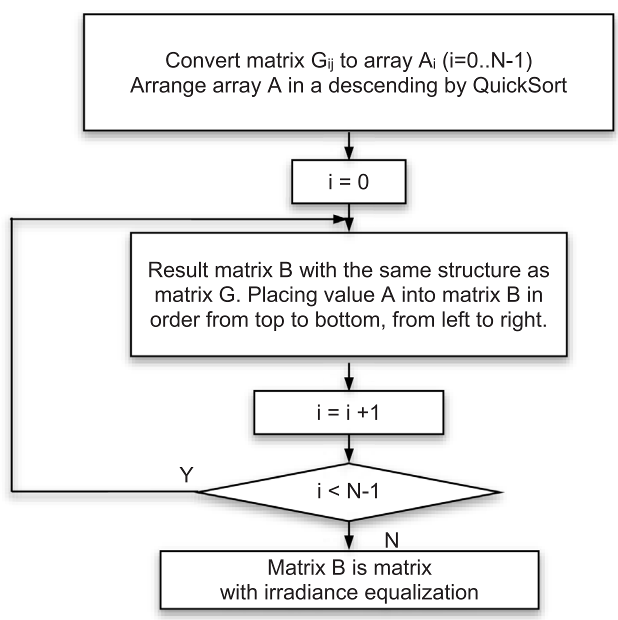


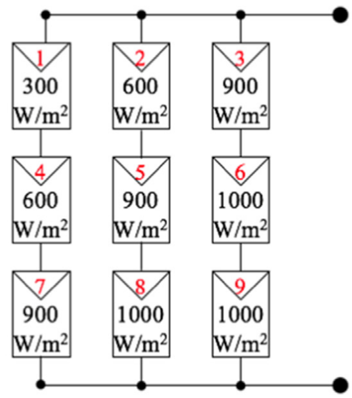
Fig. 6. Scheme of an algorithm for finding the optimal connection configuration of the SP circuit.

Table 5
Value array A after Quicksort for the starting configuration in Table 4.

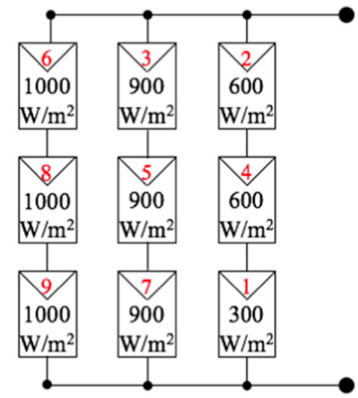
1000	1000	1000	900	900	900	600	600	300
A0	A1	A2	A3	A4	A5	A6	A7	A8

Table 6
B matrix.

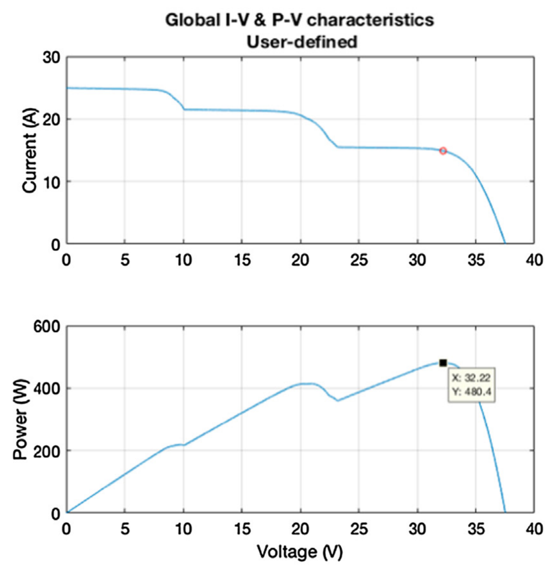
1000	900	600
1000	900	600
1000	900	300



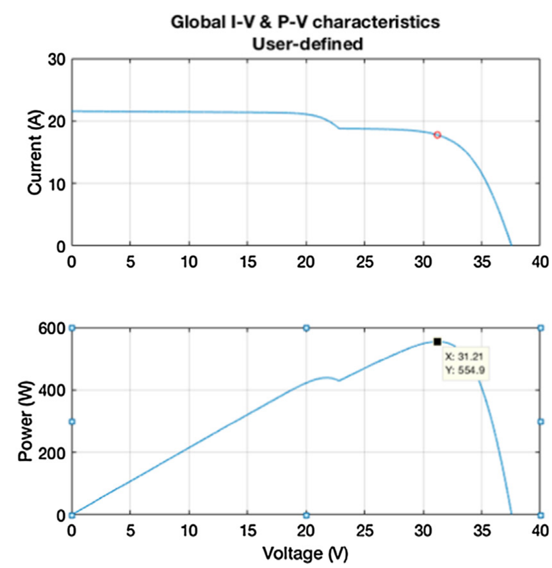
(a) SP connection circuit before reconfiguration



(c) SP connection circuit after reconfiguration



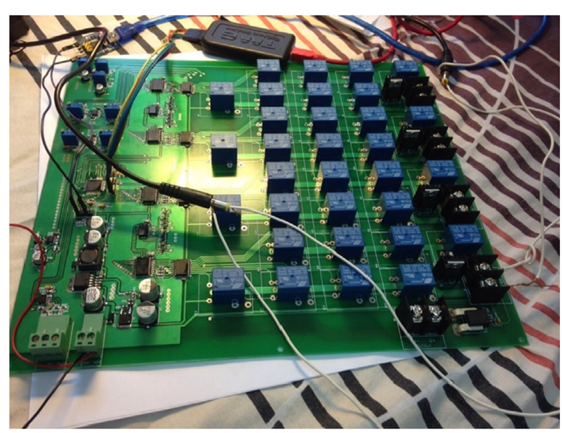
(b) PV system capacity before reconfiguration (P_{MPPT} = 480.4W)



(d) PV System Capacity Chart after reconfiguration (P_{MPPT} = 554.9W)

Fig. 7. Simulation of the numerical example of the methodology for enhancing the efficiency of the SP connected PV plant, (a, b) show the original system with the P_{MPPT} = 480.4 W, (c, d) after reconfiguration with the P_{MPPT} = 554.9 W.

(a)



(b)

Fig. 8. PV system with reconfigurator: (a) PV panels; (b) Switching matrix for SP topology.

The G_{ij} matrix is then changed into the following array A.

Using the QuickSort, the sorting of the A array in a descending order is carried out and the following array is obtained (see Table 5).

Finally the Bij matrix, with size of 3 × 3 similar to the original Gij matrix, is created arranging the elements of ordered A array into matrix B in the top-down direction, from left to right as described in Table 6.

Results of the simulation carried out using Matlab Simulink for this system are reported in the figures below.

Table 7
Electrical features of PV panels at 25 °C.

V_{MPP}	I_{MPP}	P_{MPP}	V_{OC}	I_{SC}
36.4 V	7.42 A	270 W	43.63 V	7.9 A

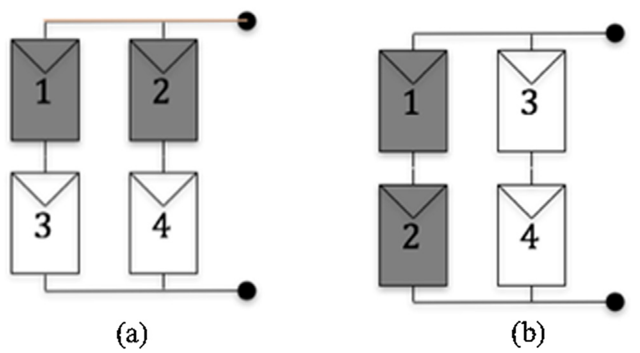


Fig. 9. Connection of PV system before (a) and after (b) reconfiguration.

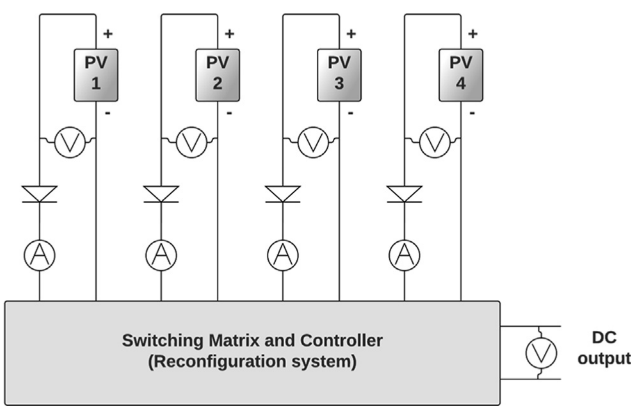


Fig. 10. Diagram connection for measure current and voltage of each PV panel.

Fig. 7 shows the comparison between the original system with an irradiance mismatch and the relevant P-V curve (a, b) and the optimized system (c, d). As it can be noted the maximum power grows from 480.4 W to 554.9 W.

4. Experimental setup for SP reconfiguration algorithm

The experimental part of this work has been carried out at the laboratory at the Institute of Energy Science- Vietnam Academy of Science and Technology, Hanoi Vietnam.

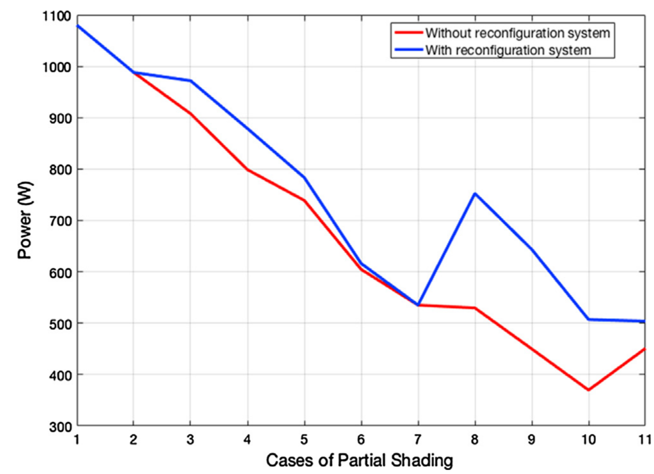


Fig. 11. Diagram comparing the output power of the solar power system with the reconfiguration system and without reconfiguration system when in partial shading situations.

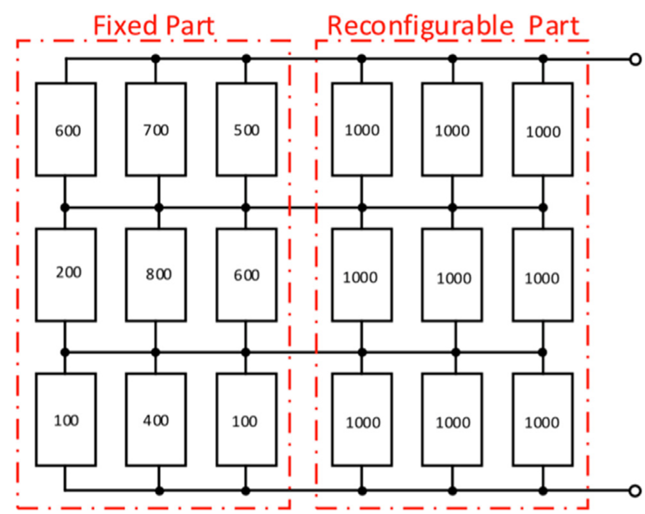


Fig. 12. One situation in which the system proposed in Tubniyom et al. (2019) would not work (partial shading only on Fixed Part).

The experiment was applied to the 1 kWp solar PV system, consisting of 4 panels type ET-P672270WB (Fig. 8a), whose parameters are reported in Table 7.

The switching matrix for the SP topology is implemented as shown in Fig. 9 b. It consists of 4 current and voltage acquisition systems for the 4 panels; 1 current and voltage acquisition for output power of PV

Table 8
Operation of reconfiguration system for optimal PV system in 11 cases of partial shading.

Case	Degree of partial shading (%)				Connection		Number of switching	Output power (W)		Increasing efficiency (%)
	Panel 1	Panel 2	Panel 3	Panel 4	Initial	After reconfiguration		Initial	after reconfiguration	
1	0	0	0	0	{1—3}||{2—4}	{1—3}||{2—4}	0	1080	1080	0.00
2	10	10	10	0	{1—3}||{2—4}	{1—3}||{2—4}	0	987.9	987.9	0.00
3	20	20	0	10	{1—3}||{2—4}	{1—2}||{3—4}	2	907.6	971.8	7.07
4	30	30	10	0	{1—3}||{2—4}	{1—2}||{3—4}	2	798.7	878.8	10.03
5	40	30	20	10	{1—3}||{2—4}	{1—2}||{3—4}	2	738.9	783.3	6.01
6	50	40	30	40	{1—3}||{2—4}	{1—2}||{3—4}	2	604.7	616.2	1.90
7	50	50	50	50	{1—3}||{2—4}	{1—3}||{2—4}	0	535.2	535.2	0.00
8	60	60	0	0	{1—3}||{2—4}	{1—2}||{3—4}	2	529.7	752.5	42.06
9	65	65	15	15	{1—3}||{2—4}	{1—2}||{3—4}	2	450	643.7	43.04
10	75	75	30	30	{1—3}||{2—4}	{1—2}||{3—4}	2	369.8	507.1	37.13
11	50	60	60	40	{1—3}||{2—4}	{1—2}||{3—4}	2	450.9	504	39.29

Table 9
Electrical characteristics of SUNNY TRIPOWER 15,000TL.

Technical data	Sunny Tripower 15,000TL
Max. DC power/DC rated power	15,340 W/15,340 W
Max. input voltage	1000 V
MPP Voltage range/rated input voltage	360–800 V/600 V
Min. input voltage/initial input voltage	150 V/188 V
Max. input current input A/input B1	33 A/11 A
Max. input current per string input A1/input B1	40 A/12.5 A
Max. DC short-circuit current input A/input B	50 A/17 A
Number of independent MPP inputs/strings per MPP input	2/A:5; B:1

Table 10
Electrical characteristics of PV plant.

Number of modules n.	60
Rated power W_P	14.400 W
Rated voltage at STC (Standard Test Conditions) V_{max}	456 V
Maximum output power current I_{max}	31.64 A
Open circuit voltage V_{oc}	555 V
Short circuit current I_{sc}	34.44 A

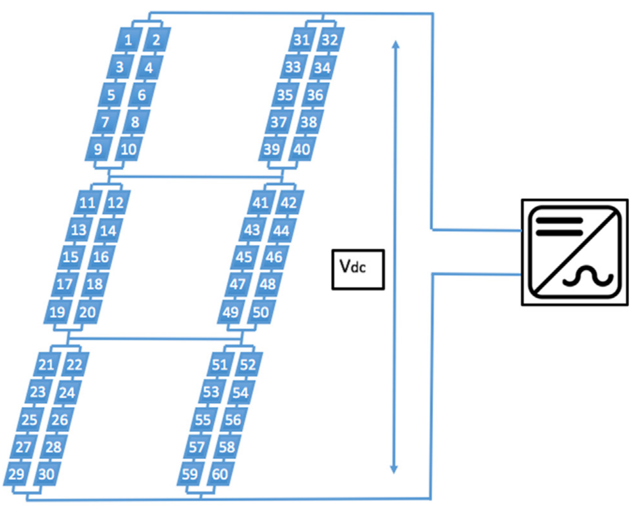


Fig. 13. Subgroup design diagram of PV system.

Table 11
Groups of PV panels in SP topology.

Group 1	Group 2	Group 3	Group 4	Group 5	Group 6
{1, 2, …, 10}	{11, 12, …, 20}	{21, 22, …, 30}	{31, 32, …, 40}	{41, 42, …, 50}	{51, 52, …, 60}

system; switching matrix (Fig. 4). The circuit connection for measurements is shown in Fig. 10.

In Fig. 10, the method for measuring voltage online for each PV panel is shown. In this case, there is no need to disconnect the PV panels when measuring voltage. According to Fig. 10, each PV panel needs a fixed diode connected in series before the switching matrix. Thus the voltage across each PV panel is measured directly online separately without the need to disconnect the PV panel from Switching matrix.

+ Disadvantage: Due to the diode connected, each pin looses a small amount of voltage across the diode (depending on semiconductor material and load current).

+ Advantages: Continuous monitoring, uninterruptible power supply; Durability of PV panel and components is improved, less noise that affects the quality of power because not continuous cutting the PV panel for measurements.

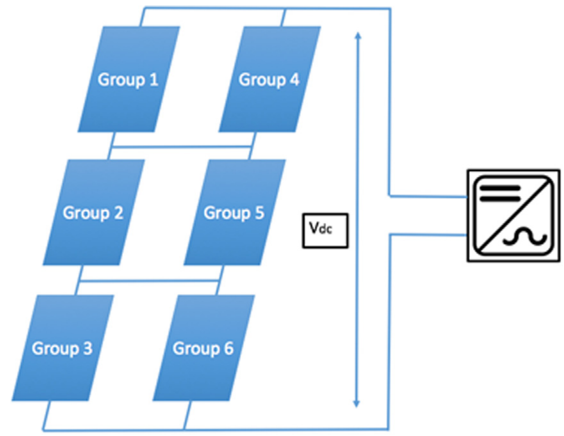


Fig. 14. 6 subgroups connected in TCT topology.

In automation mode, at each minute, the measuring system gets the voltage at each solar panel during the PV system normal operation. -

If voltage variation exceeds allowed limitation, the reconfiguration system will disconnect all PV panels, and then, measure current of each PV panel, the irradiance on each panel is calculated using (1). After that, the reconfiguration system shall automatically sent data to a PC (running an algorithm for finding the optimal configuration). In this case, the reconfiguration algorithm is run and the new configuration is implemented. If new configuration is different from the initial configuration, the PC sends the control data to the Switching matrix, and switches are controlled for changing the configuration from initial to the optimal one. Therefore if the system is shaded for a short time (below 1 min) or shaded below the limitation, the reconfiguration system shall not operate. The efficiency of the reconfiguration system is then checked by shading each part of solar panels with various shading degrees chronologically. Output power is then measured and compared in case of reconfiguration system activation or not.

Solar power system with automatic reconfiguration system operated well as shown by the results reported in Table 8 and Fig. 10. In some cases the improvement in efficiency is of more than 43%.

In Table 8, the configuration {1—3}||{2—4} corresponds to the connections depicted in Fig. 9(a).

Fig. 11 shows the improvements implementing the reconfiguration system for all the possible shadings reported in Table 8.

5. Application of reconfiguration strategy for a large PV system

In Mahmoud and El-Saadany (2017), the authors propose a reconfiguration method for TCT topology, applied to a large PV system. The proposed reconfiguration method divides the PV panels into two groups, the Fixed Part and the Reconfigurable Part. The advantage of the method is the reduction of the number of switches in the switching matrix, depending on the number of PV panels in Reconfigurable Part. The biggest disadvantage of the proposed method is that it is not possible to rearrange all PV panels. Indeed only the connection of PV panels in the Reconfigurable Part can be changed, so in many cases the reconfiguration system will not be able to operate effectively. For example, a situation of partial shading on the Fixed Part which cannot be improved using reconfiguration is shown in Fig. 12.

In this paper, we propose a reconfiguration method for larger PV systems, which could rearrange the position of all the PV panels while minimizing the number of switches.

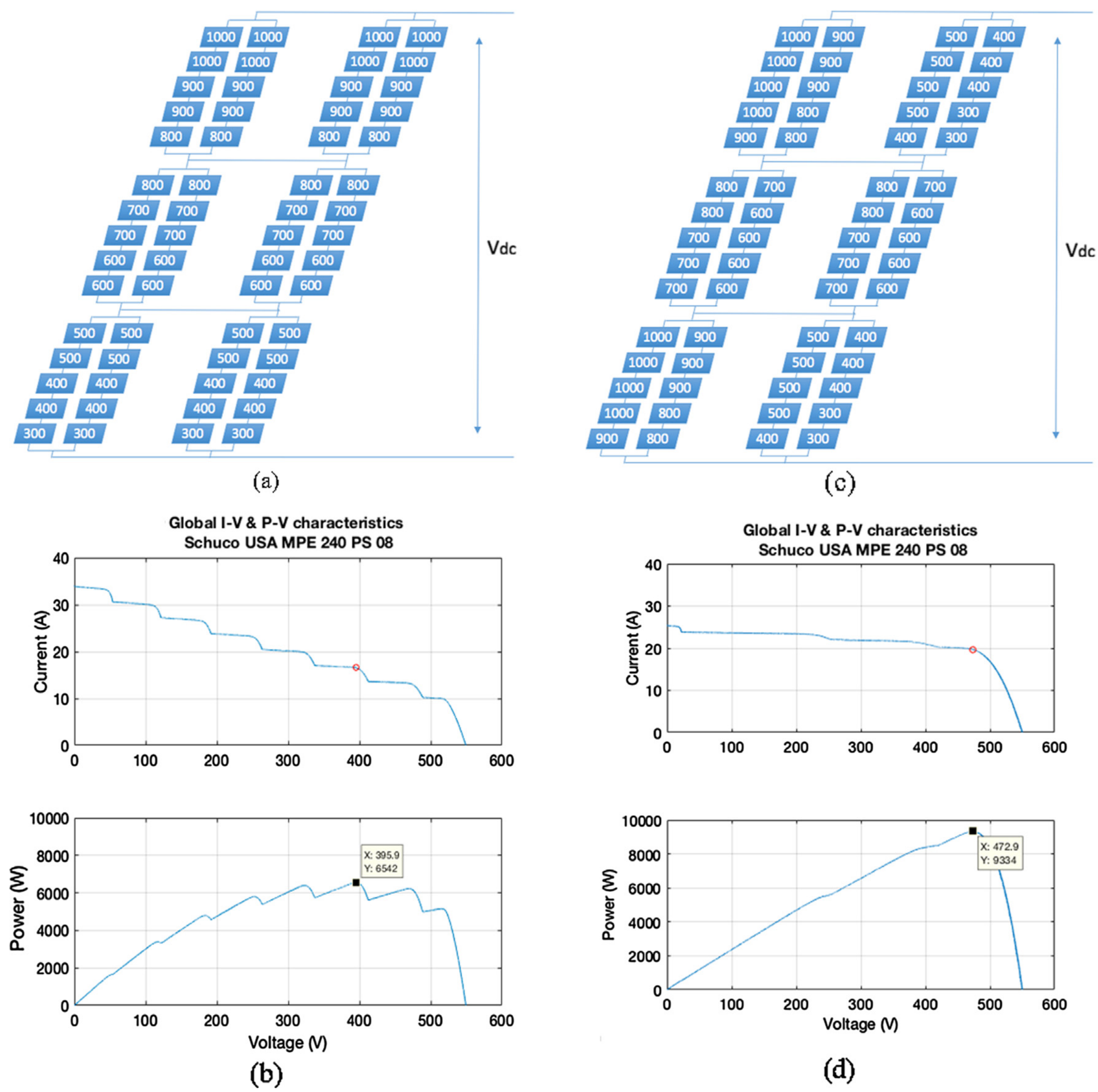


Fig. 15. Diagram comparing the output power of the solar power system with (a) the reconfiguration system P_{max} = 9334 W and without (b) reconfiguration system P_{max} = 6542 W when in PS situations.

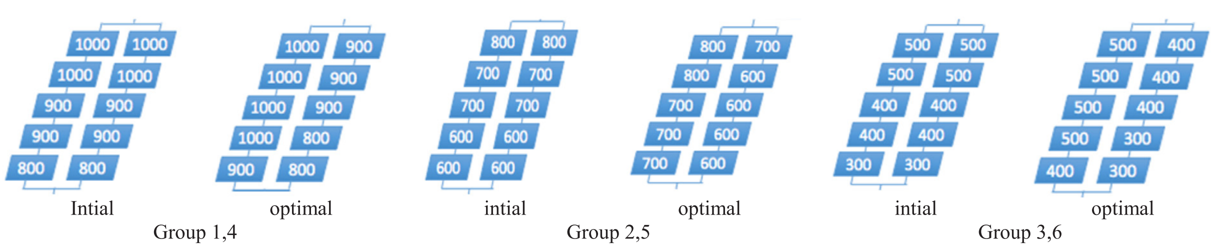


Fig. 16. Initial and Optimal configuration of each group in SP topology.

5.1. System design

The biggest problem of reconfiguration methods for TCT and SP topologies is the size of the switching matrix (Riva Sanseverino et al., 2015; Ngo et al., 2016, 2017). The number of switches is at least $N \times K \times M$ where N is the number of PV panels, K is number of switches for each PV panel (in TCT: $K = 2$ and in SP: $K = 3$), M is maximum number of PV panels to connect in series.

In order to minimize the cost of the proposed system, the authors recommend a method for splitting the groups of PV panels using the TCT connection structure. In this way, the TCT connection groups the SP connected panels. The reconfiguration strategy is applied to the TCT and SP connection circuits to increase the local performance of each group, thereby increasing the overall system performance.

Consider a 14.4 kW peak solar PV plant consisting of 60 PV panels Schüco International KG MPE 240 PS 04. The rating of each panel is reported in Table 1.

The inverter used for this plant is a SUNNY TRIPOWER 15,000TL whose rated values are reported in Table 1. Peak power of the system is 14.4 kW (see Tables 9 and 10).

Instead of developing the system with a basic connection, the authors propose the construction of a 60 PV panels system connected to 6

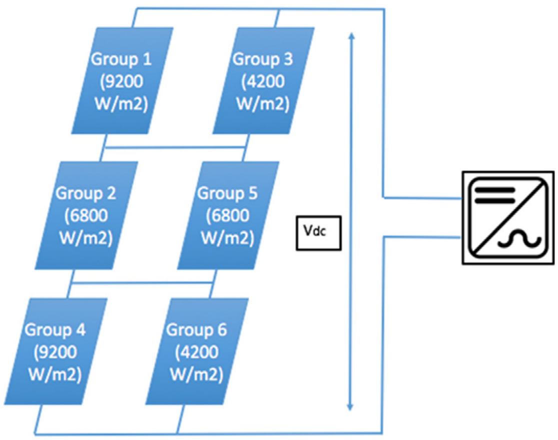


Fig. 17. Optimal configuration of groups in TCT topology.

groups, each with 10 PV panels using SP topology. 6 groups connected in TCT topology. The output of the TCT circuit connected to the SUNNY TRIPOWER 15,000TL inverter as shown in Fig. 13.

The switching matrix design for the system:

- Each group in SP topology: 150 relays.
- 6 groups connected in TCT topology: 78 relays.

Total number of relays: 150 * 6 + 78 = 978 relays.

3-phase Inverters SMA Solar Technology AG, Sunny Tripower 15,000TL PWM forced commutation, with MPPT algorithm. The inverters will be parallel connected at the outputs.

Input Voltage of the DC/AC inverter: 456 V
Input current of the DC/AC inverter: 31.64 A

The PV system includes 60 PV panels, divided into 6 groups, each group composed of 10 panels connected in SP topology as in Table 11. Each group is connected to a lower level reconfiguration system for SP

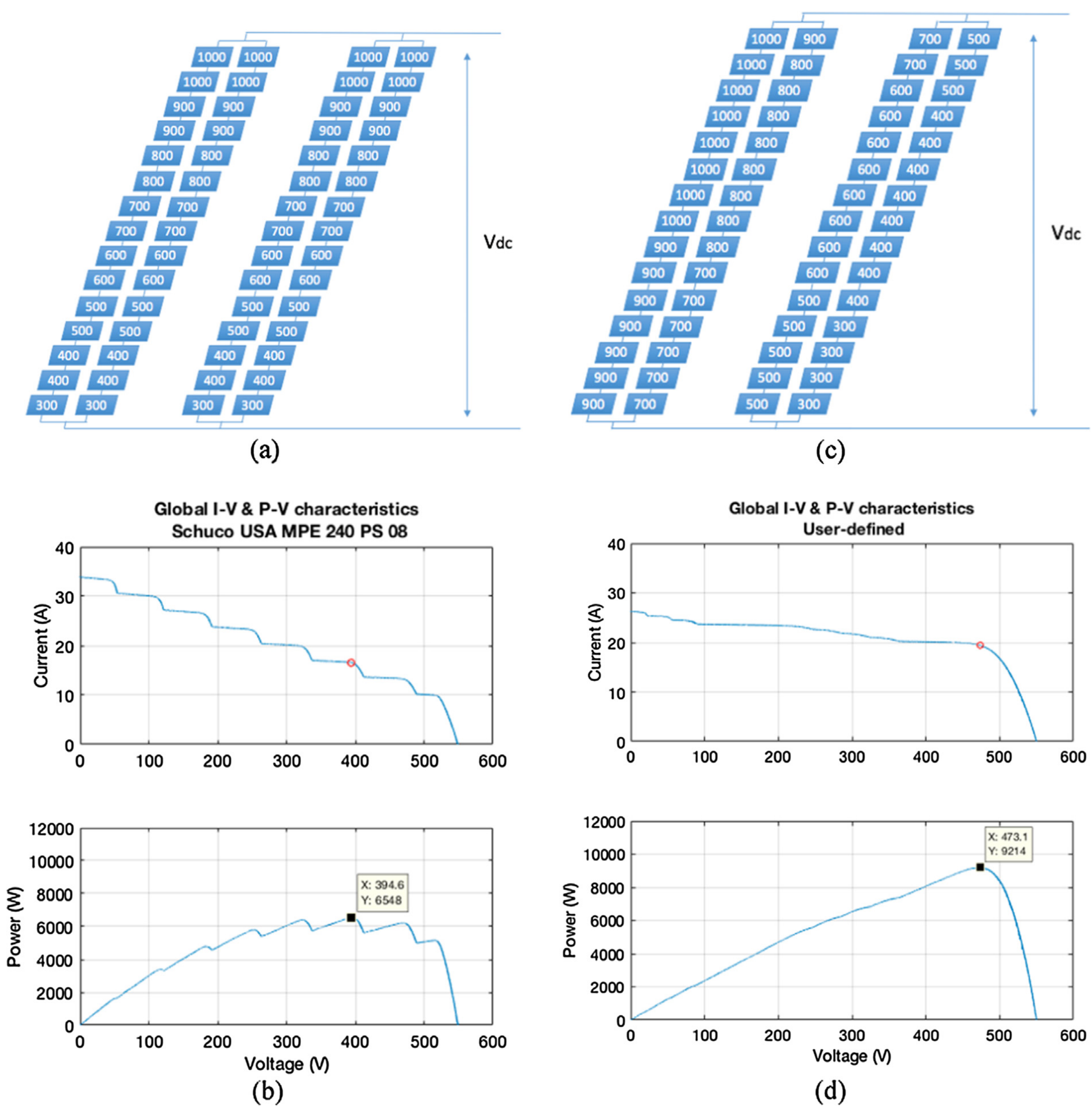


Fig. 18. Diagram comparing the output power of the solar power system with fully controllable Switching matrix in SP topology.

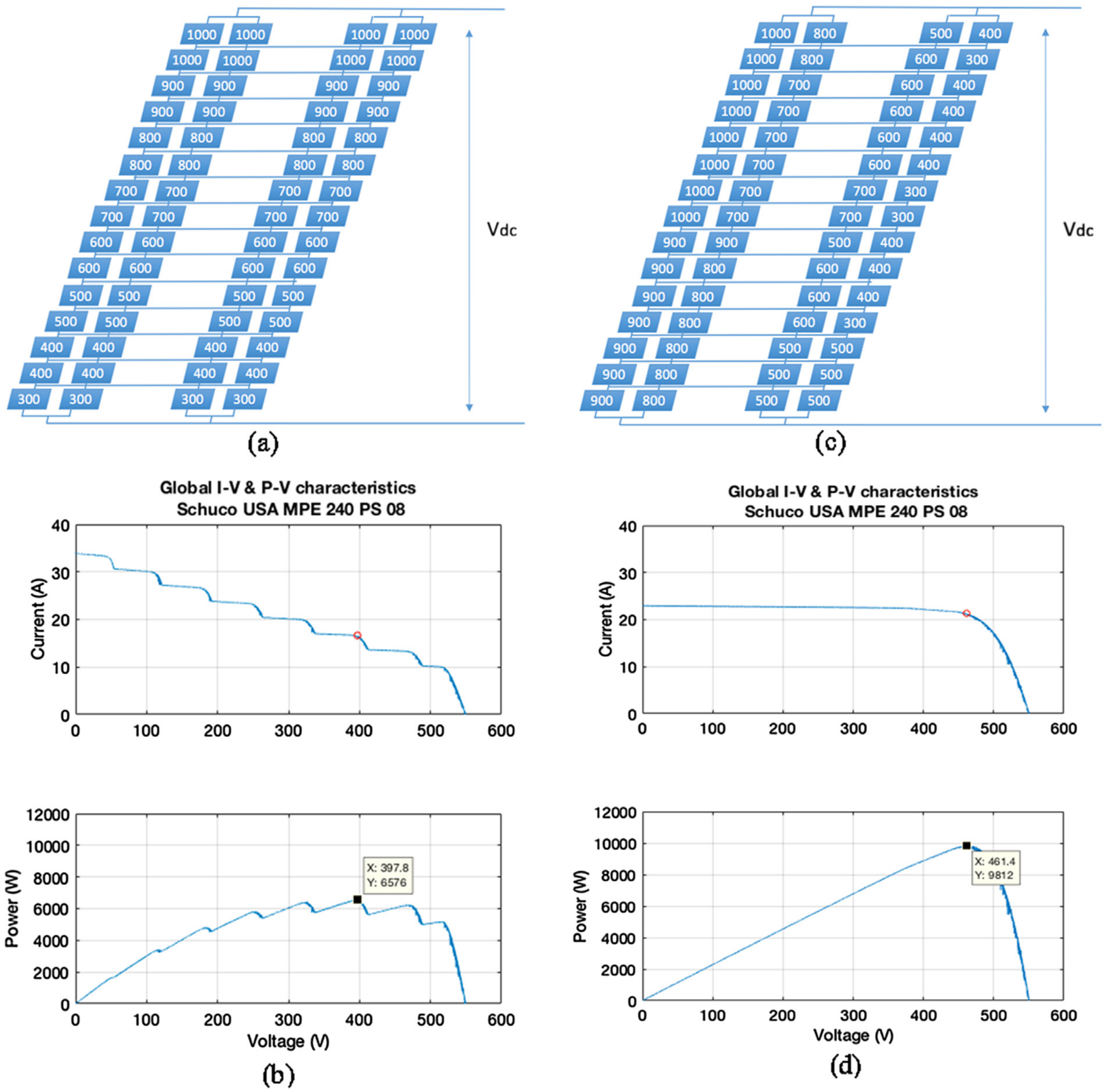


Fig. 19. Diagram comparing the output power of the solar power system with fully controllable Switching matrix in TCT topology.

Table 12
Comparison.

Reconfiguration method	Number of relays	P_{MPPT} (W)	
		Before reconfiguration	After reconfiguration
Hierarchical topology	978	6542	9334
Full reconfiguration in TCT topology	3630	6576	9812
Full reconfiguration in SP topology	5400	6548	9214

topology, whose switching matrix is described in Section 3. In each group, panels can be put in different positions, but the number of panels per string is fixed to 5.

The reconfiguration algorithm within each group of 10 PV panels was described in Section 4. With the described reconfiguration system, each group of solar panels gives the maximum output. The output of each group is of course in DC.

At the higher hierarchical level, a TCT reconfigurator manages the 6 groups (Fig. 14) as described in Section 2.1.

The advantages of a system that uses a hierarchical reconfiguration, as compared to a conventional system, are listed below:

- During the operation, when the system is partially shaded, always reconfigure to increase the performance of the system.
- In cases, especially low light, when 3 groups of serial connected SP topology do not meet the input voltage for the inverter (< 360 V), the TCT may serially connects more SP groups to meet the input voltage requirement of the inverter (> 360 V).

At each minute, the reconfiguration system for SP topology work within each group. Current and voltage are measured and based on the voltage difference measured across the panels, the automation is triggered or not. Then the connections of each group to the optimal configuration are changed if necessary.

If at least two groups change the connections within different rows, the Reconfiguration for TCT topology will start, based on the sum of irradiances calculated in each group and change the initial connection into the optimal one if necessary.

The important constraint is that the output voltage of the PV system must be within the input range of the inverter.

5.2. Matlab simulation

As an example a simulation was made in Matlab environment and results are reported in Fig. 15a. In this case, the clouds are shadowing the PV system from bottom to top. The initial condition is depicted in Fig. 15a. The number in the boxes indicating the real irradiance in W/m^2.

As a result the lower level reconfigurator starts in each group; the reconfiguration system for SP topology optimizes the output power of each group as depicted in Fig. 16.

The higher hierarchical level reconfigurator starts as more than two groups have changed their configuration at the lower level. Therefore, the reconfiguration system for TCT topology optimizes the output power of the overall system as depicted in Fig. 17 (where irradiances are indicated as the sum of the irradiances of the panels within the group).

After changing the connection of the PV system's panels, the system increased the performance from 6542 W (Fig. 15b) to 9334 W (Fig. 15d), increasing the system's performance by 42.67%.

5.3. Comparison with fully reconfigurable systems

In a fully controllable Switching matrix design for 60 PV panels in SP topology, 30 PV panels can be series connected. In cases, with strong shading or low irradiation, when 3 groups of serial connected SP topology do not meet the input voltage for the inverter (< 360 V), the TCT can serially connect more SP groups to meet the input voltage requirement of the inverter (> 360 V). In this case, it is needed to design a Switching matrix with 60 * 3 * 30 = 5400 relays. With the same case in Section 5.1, using the Matlab simulink framework, we have the result in Fig. 18.

As you can see in Fig. 19b, before reconfiguration, output power of PV system P_{MPPT} is 6548 W, after reconfiguration P_{MPPT} is 9214 W. In this case, the output is smaller than the one in hierarchical topology (in Fig. 16d is P_{MPPT} = 9334 W). Indeed in general TCT connection offers a larger power output and the PV system in hierarchical topology uses both SP topology and TCT topology.

The comparison is shown in Table 12.

As it can be observed the output power considering the hierarchical topology is only 4.87% lesser as compared to a full reconfiguration TCT for this case, but the number of switches is much smaller.

The shadowing case here considered can be retained as the most meaningful situation. Since shadowing from left to right and viceversa would not be a significant case for reconfiguration, especially if shadowing affects all panels in one series connected row. Other cases with shadowing in diagonal can still be easily reconducted to the case here studied. The convenience of such reconfiguration techniques can be assessed by considering the economic benefits (Viola et al., 2017; Caruso et al., 2017; Caruso et al., 2018).

Future work will consider also the switching losses as faced in (Velasco-Quesada et al., 2009; Tubniyom et al., 2019), in order to reduce the switches and the switching number.

6. Conclusion

In recent research publications, to cope with the problem of mismatch in small PV fields, the authors proposed a solution to improve the performance of solar energy systems based on reconfiguration using a Total-Cross-Tied topology (TCT) (Riva Sanseverino et al., 2015; Ngo et al., 2016, 2017). In this study, the authors propose a solution for improving the efficiency of solar-powered systems using the SP configuration (Series-Parallel topology) as basic topology. The latter is more common in existing PV generators. To solve the reconfiguration problem over SP-based PV systems, the proposed author's solution consists of two main parts: a Switching matrix and QuickSort method to find the optimal connection configuration for the SP connection. The method uses the QuickSort with the complexity On (logn) which allows for application in large solar energy systems. In addition, the authors propose a new hierarchical architecture to limit the number of switches in reconfigurable systems and at the same time provide a solution for larger PV fields. PV panels are grouped into SP-based smaller units at the lower level. Inside each group the proposed SP-based optimal reconfiguration is carried out. While at the higher level, the groups are considered as single entities and a TCT based topology supports the reconfiguration of the groups of panels. An experimental application shows the efficiency of the SP based reconfiguration used for the lower level, while a simulation demonstrates the practical applicability of the whole hierarchical optimal reconfiguration strategy proposed by the authors. Further studies will address the consideration of other efficient methodologies for coping with uneven irradiation on photovoltaic power plants. These methodologies, such as ZigZag (Belhaouas et al., 2017), and SuDoKu (Horoufiany and Ghandehari, 2018), are devoted to the design of fixed electrical connections so as to limit the effect of mutual shadowing or shadowings whose origin can be considered in advance. These prove to be very effective and further analysis are needed to consider these techniques against the proposed one even in large plants.

Acknowledgements

The authors especially thank the IES – VAST for providing fund and creating favour in carrying out experimental part of this work during the implementation of the study. This paper is developed as a subsidiary component of the study “Study on methodology and building device increasing efficiency of photovoltaic systems under non-homogeneous solar irradiation” Code DL0000.01/18-19.

References

Abdel-Salam, M., et al., 2018. An improved perturb-and-observe based MPPT method for PV systems under varying irradiation levels. Sol. Energy 1 (171), 547–561.

Akrami, M., Pourhossein, K., 2018. A novel reconfiguration procedure to extract maximum power from partially-shaded photovoltaic arrays. Sol. Energy 173, 110–119.

Badwaik, K.N., 2017. Reconfiguration methods for solar photovoltaic array and economic evolution of solar cell. Int. J. Adv. Eng. Res. Dev. 4 (7).

Balato, M., Costanzo, L., Vitelli, M., 2016. Maximum power point tracking techniques. Wiley Encyclopedia Electr. Electron. Eng. 1–26.

Belhaouas, N., et al., 2017. PV array power output maximization under partial shading using new shifted PV array arrangements. Appl. Energy 187.

Caruso, M., et al., 2018. Dynamic reconfiguration of electrical connections for partially shaded PV modules: technical and economical performances of an arduino-based prototype. Int. J. Renew. Energy Res. – IJRER 8 (1).

Caruso, M., et al., 2017. PV reconfiguration systems: a technical and economic study. J. Electr. Syst. 13 (1), 55–73.

Cheddadi, Y., et al., 2018. Design and verification of photovoltaic MPPT algorithm as an automotive-based embedded software. Sol. Energy 171 (414-425).

El-Dein, M.Z.S., Kazerani, M., Salama, M.M.A., 2012. Optimal photovoltaic array reconfiguration to reduce partial shading losses. IEEE Trans. Sustain. Energy 4 (1), 9.

Femia, N., Petrone, G., Spagnuolo, G., Vitelli, M., 2012. Power electronics and control techniques for maximum energy harvesting in photovoltaic systems.

Hermann, W., Wiesner, W., Vaaben, W., 1997. Hot spot investigations on PV modules-new concepts for a test standard and consequences for module design with respect to bypass diodes. Photovoltaic Specialists Conference, 1997. Conference Record of the Twenty-sixth IEEE.

Hoare, C.A.R., 1961. Algorithm 64: Quicksort. Commun. ACM 4 (7), 321.

Horoufiany, M., Ghandehari, R., 2018. Optimization of the Sudoku based reconfiguration technique for PV arrays power enhancement under mutual shading conditions. Sol. Energy 1 (159), 1037–1046.

International Energy Agency: Trends in photovoltaic applications. Survey report of selected IEA countries between 1992 and 2012.

Kouchaki, A., Iman-Eini, H., Asaei, B., 2013. A new maximum power point tracking strategy for PV arrays under uniform and non-uniform insolation conditions. Sol. Energy 91, 221–232.

La Manna, D., Li Vigni, V., Riva Sanseverino, E., Di Dio, V., Romano, P., 2014. Reconfigurable electrical interconnection strategies for photovoltaic arrays: a review. Renew. Sustain. Energy Rev.

Li Vigni, V., Manna, D.L., Sanseverino, E.R., di Dio, V., Romano, P., di Buono, P., Pinto, M., Miceli, R., Giaconia, C., 2015. Proof of concept of an irradiance estimation system

for reconfigurable photovoltaic arrays. Energies 8, 6641–6657.
Lynn, P.A., 2011. Electricity from sunlight: an introduction to photovoltaics. Choice: Curr. Rev. Acad. Libraries 48 (5), 933-933.
Matam, M., ReddyBarry, V., Govind, A.R., 2018. Optimized reconfigurable PV array based photovoltaic water-pumping system. Sol. Energy 170, 1063–1073.
McCormick, P.G., Suehrcke, H., 2018. The effect of intermittent solar radiation on the performance of PV systems. Sol. Energy 1 (171), 667–674.
Murillo-Soto, L.D., Meza, C., 2017. Voltage measurement in a reconfigurable solar array with series-parallel topology. 2017 IEEE 37th Central America and Panama Convention (CONCAPAN XXXVII), 15-17 Nov. 2017.
Ngo, N.T., Nguyen, P.Q., Pham, T.C., 2016. Improved control algorithm for increase efficiency of photovoltaic system under non-homogeneous solar irradiance. Special Issue Control Autom. 16, 12.
Ngo, N.T., Nguyen, P.Q., Nguyen, T.L., Riva Sanseverino, E., Romano, P., Viola, F., 2017. *Increasing efficiency of photovoltaic systems under non-homogeneous solar irradiation using improved Dynamic Programming methods. Sol. Energy* 150, 325–334 *ISSN 0038-092X*.
Patnaik, B., Sharma, P., Trimurthulu, E., Duttagupta, S.P., Agarwal, V., 2011. Reconfiguration strategy for optimization of solar photovoltaic array under non-uniform illumination conditions. 2011 37th IEEE Photovoltaic Specialists Conference, Seattle, WA 001859–001864.
Po-Cheng, Chena, Po-Yen, Chena, Yi-Hua, Liua, Jing-Hsiao, Chena, Yi-Feng, Luob, 2015. A comparative study on maximum power point tracking techniques for photovoltaic generation systems operating under fast changing environments. Sol. Energy 119, 261–276.
Mahmoud, Y., El-Saadany, E.F., 2017. Enhanced reconfiguration method for reducing mismatch losses in PV systems. IEEE J. Photovolt. 7.
Riva Sanseverino, E., Ngo, N.T., Cardinale, M., Li Vigni, V., Musso, D., Romano, P., Viola, F., 2015. *Dynamic programming and Munkres algorithm for Optimal Photovoltaic Arrays Reconfiguration. Sol. Energy* 122, 347–358.
Riva Sanseverino, E., et al., 2016. *An optimization device for Series Parallel connected PV plants. International Conference on Applications in Electronics Pervading Industry, Environment and Society* 227–236.
Salimi, M., 2018. Practical implementation of the Lyapunov based nonlinear controller in DC-DC boost converter for MPPT of the PV systems. Sol. Energy 173, 246–255.
Tubniyom, C., Chatthaworn, R., Suksri, A., Wongwuttanasatian, T., 2019. Minimization of losses in solar photovoltaic modules by reconfiguration under various patterns of partial shading. Energies 12, 24.
Veerachary, M., Senjyu, T., Uezato, K., 2002. Voltage-based maximum power point tracking control of PV system. IEEE Trans. Aerosp. Electron. Syst. 38 (1), 262–270.
Velasco-Quesada, G., Guinjoan-Gispert, F., Pique-Lopez, R., Roman-Lumbreras, M., Conesa-Roca, A., 2009. Electrical PV array reconfiguration strategy for energy extraction improvement in grid-connected PV systems. IEEE Trans. Ind. Electron. 56 (11), 4319–4331.
Vicente, P.d.S., Pimenta, T.C., Ribeiro, E.R., 2015. Photovoltaic array reconfiguration strategy for maximization of energy production. Int. J. Photoenergy.
Viola, F., Romano, P., Miceli, R., Spataro, C., Schettino, G., 2017. *Technical and economical evaluation on the use of reconfiguration systems in some EU countries for PV plants*. IEEE Trans. Ind. Appl. 53 (2), 1308–1315. https://doi.org/10.1109/TIA.2016.2625771.
Woytea, A., Nijsa, J., Belmans, R., 2003. Partial shadowing of photovoltaic arrays with different system configurations: literature review and field test results. Sol. Energy 74, 17.
Yadav, A.S., Mukherjee, V., 2018. Line losses reduction techniques in puzzled PV array configuration under different shading conditions. Sol. Energy 1 (171), 774–783.
Yi-Hua, Liua, Jing-Hsiao, Chena, Jia-Wei, Huangb, 2014. Global maximum power point tracking algorithm for PV systems operating under partially shaded conditions using the segmentation search method. Sol. Energy 103, 350–363.
Zhang, F., Maddy, J., Premier, G., Guwy, A., 2015. Novel current sensing photovoltaic maximum power point tracking based on sliding mode control strategy. Sol. Energy 118, 80–86.
Zhaoa, J., Zhoub, X., Mab, Y., Liub, W., 2015. A novel maximum power point tracking strategy based on optimal voltage control for photovoltaic systems under variable environmental conditions. Sol. Energy 122, 640–649.