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Increasing efficiency of photovoltaic systems under non-homogeneous solar irradiation using improved Dynamic Programming methods

Thanh Ngo Ngoc [a,b], Quang Nguyen Phung [c], Linh Nguyen Tung [a], Eleonora Riva Sanseverino [d], Pietro Romano [d], Fabio Viola [d,*]

[a] Electric Power University, HaNoi, Viet Nam
[b] Vietnam Academy of Science and Technology, Viet Nam
[c] Hanoi University of Science and Technology, HaNoi, Viet Nam
[d] DEIM, University of Palermo, Palermo, Italy

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ABSTRACT

The paper presents a complete technique, based on the combination of algorithms, devoted to minimize losses and increase efficiency of Total Cross Tied (TCT) connected photovoltaic (PV) systems under non-homogeneous solar irradiation, based on 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.

In this paper, the authors introduce two algorithms. The first one is SmartChoice (SC) algorithm, which is combined with Dynamic Programming (DP) in order to create a hybrid method and obtain better results as compared to established methods for irradiance equalization. The second one is the control algorithm improvement method from Munkres' Assignment Algorithm (MAA) that helps to increase processing speed and lengthen the lifetime of the solar power system by 56% compared with the older MAA.

By emulating and experiencing the operation of the PV system under non-homogeneous irradiation condition, obtained results show efficiency and benefits of the proposed method applied to the solar power system operation while lengthening the lifetime of the switching matrix.

1. Introduction

Power crisis is becoming prominent issue, not only endangering the global economic growth but also international security and peace. Fossil power source, an extremely precious present that nature grants for society, is gradually exhausting. Thus, renewable energy has become a hot topic on the international agenda. The European Union has committed to reduce the emissions of greenhouse gas by at least 20% below the level in 1990 and by almost 100% by 2050. Consumption coverage from renewables must also reach 20% by 2020 and almost 100% by 2050.

In this context, solar power plays an important role due to the fact that it is a green source. The solar power generates electricity from solar irradiation without emitting direct carbon dioxide and greenhouse gas. Besides, electrical power supply from power plants to remote consumption locations can be very costly especially in developing countries. Small solar power plants may solve these issues by bringing power sources to be near the power charging station to minimize or replace completely the usage of generators that use diesel fuel. This will bring long-term public economic benefits without any environmental and economic cost. On the other hand, building a solar power plant needs a more expensive investment as compared to other power plants (i.e. hydropower plant, thermal power plant, etc.). Although Levelized Cost of Energy is progressively reducing (Adnan, 2015) driven by the reduction of the cost of modules. Researchers on solar power technologies in the near future is now promoted strongly to reduce power production costs to make it competitive with other power resources (International Energy Agency, 2013; Lynn, 2011). In recent scientific papers, a big amount of publications is devoted to algorithms development, architectures and control techniques in applications of the PV system for Maximum Power Point Tracking (MPPT) (Veerachary et al., 2002; Alireza et al., 2013; Balato et al., 2016; Liu et al., 2014; Zhao et al., 2015; Chen et al., 2015; Zhang et al., 2015).

However, during operation, there are many cases in which PV panels in the solar power plants can receive non-homogeneous radiation levels. The causes may be a lot such as shadow due to clouds, trees, houses and antenna pole. This results in inefficiency

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

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Nomenclature

avg	average sum of irradiance on the row after reconfiguration
DES	Dynamic Electrical Scheme
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

in operation of most of techniques on MPPT (Femia et al., 2012) leading the falling of the output power. Moreover, it can cause hot-spot phenomenon at shaded solar cell panels, thus damaging directly solar cells (Woyte et al., 2003; Shams El-Dein et al., 2012).

Effects due to partial shading (PS) of the PV system are given in Woyte et al. (2003) and in; Shams El-Dein et al. (2012). When in shading, the system is not only subjected to possible damage but also to misleading phenomena for the MPPT algorithm. The latter indeed will find many sub optimal working points.

With respect to this phenomenon, power loss of the solar power system is divided into two parts: recoverable loss and non-recoverable loss. At present, operative techniques for recovering losses could be grouped into the following main three categories:

- Distributed MPPT;
- Multilevel inverters;
- Photovoltaic array reconfiguration.

An exhaustive description of distributed MPPT and the employment of multilevel inverters is beyond the scope of this article, based on the array reconfiguration. One main research scope for power losses recovery is to develop the reconfiguration strategy of the solar power system (Velasco et al., 2005; Belhachat and Larbes, 2015; Nguyen and Lehman, 2008; Alahmada et al., 2012; Velasco et al., 2009; Obane et al., 2012; Storey et al., 2012; La Manna et al., 2014). The reconfiguration is an efficient rearrangement of connections of solar panels in order to increase the output power and protect the equipment when the system is working under non-homogeneous solar irradiation conditions. For instance, when one or more solar panels in the connection circuit is shaded, the generated power will be decreased causing an increase of the power losses in the system (Delinea et al., 2013).

In Riva Sanseverino et al. (2015), authors offered Dynamic programming (DP) method to find out the optimal connection configuration for PV panels and used Munkres Assignment Algorithm (MAA) to find out the best switching configuration in order to increase the lifetime of the switching matrix. Through analysis and simulation, these proposed methods obtained better results than those presented in Velasco et al. (2009), Storey et al. (2012) and Romano et al. (2013).

In this paper, authors initially propose a new heuristic algorithm, Smart Choice, which, combined to DP, improves the selection of the arrangement of the panels. The paper then introduces an improvement to the MAA that produces a computation time reduction. Finally, extensive simulations prove the efficiency of the proposed algorithms and finally a prototype allows to assess the effectiveness and accuracy of the proposed overall technique.

2. Reconfiguration strategy for TCT topology

Reconfiguration strategy for TCT topology is shown in details in Riva Sanseverino et al. (2015). The TCT topology (Fig. 1a) combined with a Dynamic Electrical Scheme (DES) switching matrix (Romano et al., 2013) (Fig. 1b) allows, through switching operations, to move from the initial TCT interconnection to a new TCT interconnection with any configuration (Fig. 1c).

Ampere meter and voltmeter are installed at each PV panel to measure current and voltage. Based on the current and the voltage measured from each PV panel, the formula to calculate the

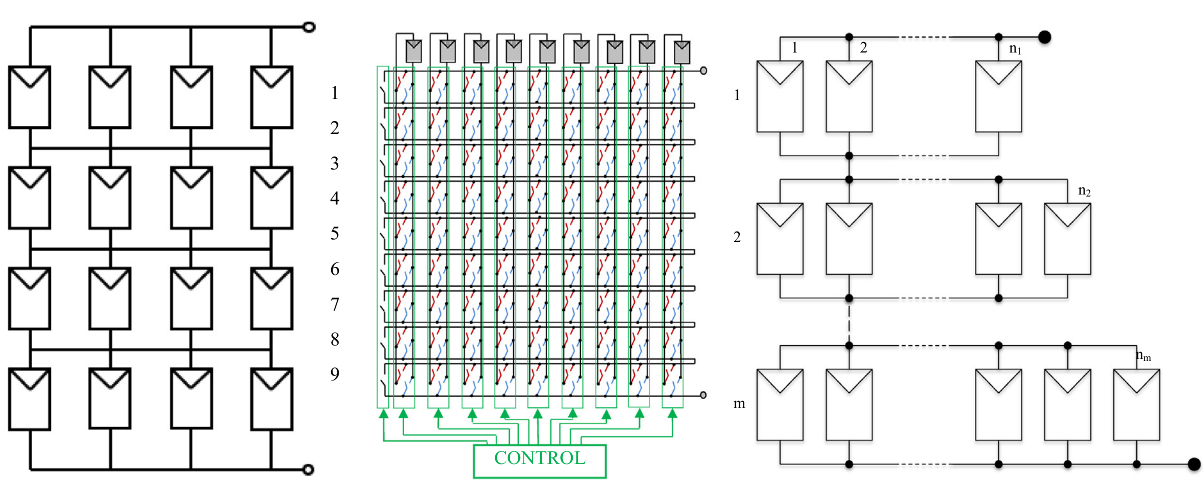


Fig. 1. (a) TCT topology; (b) Dynamic Electrical Scheme (DES) switching matrix (Romano et al., 2013), (c) generator topology.

irradiation level (Velasco et al., 2009) can be used to estimate the irradiation level obtained from the PV panels.

In the general connection diagram shown in Fig. 1c, if G_{ij} is the irradiance value of the PV panel located on row i and column j in TCT circuit, then the total irradiation of row i known as G_i is defined as:

$$G_i = \sum_{j=1}^{n_i} G_{ij} \tag{1}$$

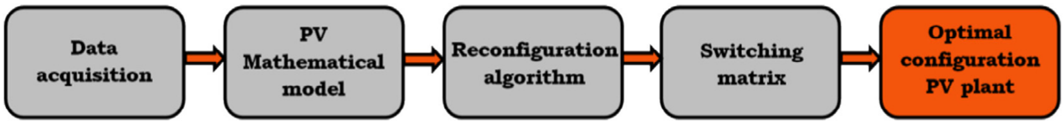


Fig. 2. Dynamic reconfiguration system for PV plant: flow chart for optimal design (Picault et al., 2010).

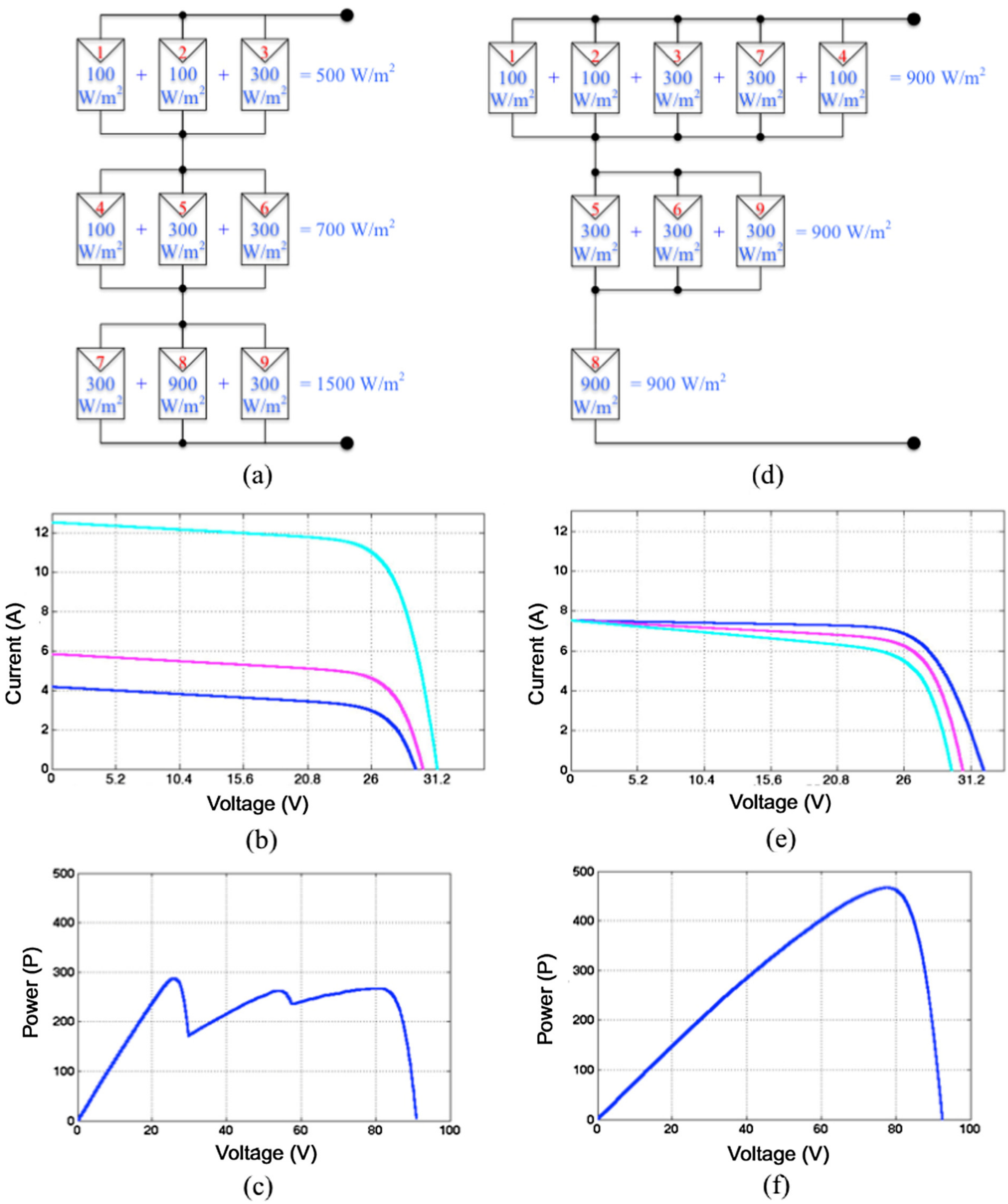


Fig. 3. PV system (a), I-V characteristic of each row (b), P-V characteristic (c) before reconfiguration and after reconfiguration (d–f) with equalization DES.

The total irradiation G is equal to:

$$G = \sum_{i=1}^{m} G_i \tag{2}$$

The number of modules N is equal to:

$$N = \sum_{i=1}^{m} n_i \tag{3}$$

where n_i is the number of PV panels that were connected in parallel and are located on row i. The number of rows in which the TCT circuit can be arranged m must be compatible with the inverter input voltage operating range. In order to maximize the output power of the TCT connection, the sum of irradiance on each row after reconfiguration should be equal or close to the average level.

$$avg = \frac{G}{m} \tag{4}$$

After reconfiguration, Equalization Index (EI) (Picault et al., 2010) for the new configuration is equal to:

$$EI = \max_i(G_i) - \min_i(G_i) \tag{5}$$

The configuration with the minimum EI index that generates the maximum output power is an optimal configuration and shall be selected.

A next important issue is to reduce the number of switching operations from the initial configuration to the optimal configuration. For the configurations with similar EI index, the configuration with the most reasonable times of transversion shall be selected. This shall lengthen the lifetime of the switching matrix so that aging of all the switches is homogeneous. Increasing the operation efficiency of the solar power systems based on irradiance equalization can be summarized according to the flow chart in Fig. 2 (La Manna et al., 2014).

Efficiency of this method is shown in Fig. 3. After reconfiguration, efficiency of the system increases by 60% and transversion from the initial configuration to the optimal configuration needs only 3 times of switching operations (Riva Sanseverino et al., 2015).

150	150	1000
1000	1000	1000
1000	1000	1000
Initial P matrix		

1000	1000	150	150	**= 2300**
1000	1000			**= 2000**
1000	1000	1000		**= 3000**
After using DP				

Fig. 4. Irradiance equalization using DP.

150	150	1000
1000	1000	1000
1000	1000	1000
Initial P matrix		

1000	1000	150	**=2150**
1000	1000	150	**=2150**
1000	1000	1000	**=3000**
The best result			

Fig. 5. An improved result due a smart reconfiguration.

620	500	600	300	**= 2020**
540	420	320	480	**= 1760**
280	460	400	560	**= 1700**
360	340	300	240	**= 1240**

Fig. 6. Matrix G, case of study.

3. Reconfiguration algorithms

3.1. Dynamic Programming (DP)

DP algorithm (Riva Sanseverino et al., 2015) is used for Subset Sum problem in "Knapsack problems" (Martello and Toth, 1990). DP technique assesses for each panel the power able to be supplied and inserts it into a dynamic array, which will give rise to the connections between panels. With an intelligent method, DP shall select panels with total irradiation that are equal or close to the *avg* and then arrange them in a separated row.

3.2. SmartChoice (SC)

Dynamic Programming (DP) offers the best result in almost all cases, but in some special cases DP will not bring good results. Fig. 4 shows the DES in matrix form. Each entry of the matrix shows the irradiance level. Initial matrix gives average value avg = 2433 W/m^2, as explained in Riva Sanseverino et al. (2015) DP tries to fill the first row, by summing elements, in order to obtain a value that is equal or close to the average. In this way, first row has irradiance of 2300 W/m^2. According to Eq. (4), by considering DP selection, the EI index is:

$$EI_{DP} = 3000 - 2000 = 1000 \tag{6}$$

A better result can be obtained by considering Fig. 5, in which initial matrix is the same but a better reconfiguration has been used. In such a way, EI becomes:

$$EI_{BestResult} = 3000 - 2150 = 850 \tag{7}$$

To overcome the above-mentioned issue, the authors propose a second algorithm, the Smart Choice algorithm (SC), whose results can be compared on line with those of the DP algorithm, to choose the most performing strategy. The SC algorithm is described as follows.

In the first step, SC shall convert the starting matrix G into the data array A with N (Eq. (3)) elements. By QuickSort arrangement method, array A shall be sorted from high to low level of the irradiation value. Initialize the matrix B with m rows, then arrange some parts in the array A into rows of matrix B so that temporary EI index (applied for the matrix B) is the minimum value in each step.

Example to explain *SC* algorithm.

Initial matrix G is shown in Fig. 6.

By converting matrix G into an array A, Fig. 7 is obtained.

By sorting array A with QuickSort (Hoare, 1961), Array B, shown in Fig. 8, is obtained.

Matrix B is obtained by putting each element of the array B (from i = 0 to 15) as explained in Fig. 9.

Flow chart of SC is shown in Fig. 10.

To find out the optimal result of the irradiation equalization problem, the authors propose to use a Hybrid method using both SC and DP running in parallel, which give improved results.

4. Algorithm for optimal lifetime of DES

After obtaining the result of the irradiation equalization problem, the MAA algorithm (Munkres, 1957) is used in order to minimize the switching operations in DES switching matrix to

620	500	600	300	540	420	320	480	280	460	400	560	360	340	300	240
A(0)	A(1)	A(2)	A(3)	A(4)	A(5)	A(6)	A(7)	A(8)	A(9)	A(10)	A(11)	A(12)	A(13)	A(14)	A(15)

Fig. 7. Array A obtained by matrix G.

620	600	560	540	500	480	460	420	400	360	340	320	300	300	280	240
A(0)	A(1)	A(2)	A(3)	A(4)	A(5)	A(6)	A(7)	A(8)	A(9)	A(10)	A(11)	A(12)	A(13)	A(14)	A(15)

Fig. 8. Sorted array B.

Step a					Step b					Step c				
620				**= 620**	620				**= 620**	620				**= 620**
				= 0	600				**= 600**	600				**= 600**
				= 0	560				**= 560**	560				**= 560**
				= 0	540				**= 540**	540	500			**= 1040**
Step d					**Step e**					**Step f**				
620	420			**= 1040**	620	420	400		**= 1440**	620	420	400		**= 1440**
600	460			**= 1060**	600	460			**= 1060**	600	460			**= 1060**
560	480			**= 1040**	560	480			**= 1040**	560	480	360		**= 1400**
540	500			**= 1040**	540	500			**= 1040**	540	500			**= 1040**
Step g					**Step h**					**Step i**				
620	420	400		**= 1440**	620	420	400		**= 1440**	620	420	400	240	**= 1680**
600	460	320		**= 1380**	600	460	320		**= 1380**	600	460	320	300	**= 1680**
560	480	360		**= 1400**	560	480	360		**= 1400**	560	480	360	280	**= 1680**
540	500	340		**= 1380**	540	500	340	300	**= 1680**	540	500	340	300	**= 1680**

Fig. 9. Matrix B. Step a: element i = 0 of array B is put as first element. Step b: first column is completed with i = 1:3. Step c: element 4 is put in the minimum row value. Step d: column 2 takes remaining elements, the bigger value of array B on the minimum row value. Step e: the bigger element of array B is set on the minimum sum of the row values. Step f: the bigger element of array B is set on the minimum sum of the row values. Step g: 3th column is completed. Step h: first element of 4th in the minimum value of sum of the rows. Step i: 4th is completed.

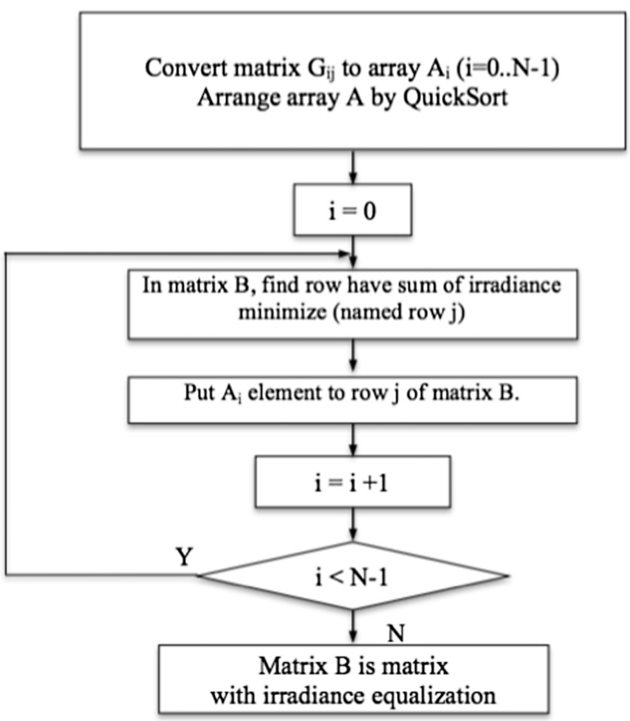


Fig. 10. Flowchart of SC algorithm.

convert the starting matrix into the optimal matrix. Optimization of switching operations in DES switching matrix shall increase the lifetime of the switching matrix and the PV systems as well. However, in fact, if in the DES switching matrix, there is only one switch damaged, then all systems shall be repaired and replaced. So, if we just focus on minimization of switching operations in each reconfiguration without paying attention to switching operations of the whole switching matrix, it will cause non-homogeneous usage among switches. The lifetime of the system shall depend on the lifetime of most-operated switches.

In Riva Sanseverino et al. (2015), the authors proposed a method to balance the switching operations of DES choosing the best among several optimal configurations. Therefore, instead of selecting a configuration with the minimum number of switching operations, a suboptimal configuration with homogenous aging of all switches in the matrix was chosen. This proposed method is presented in Fig. 11. Based on the features of DP, it could generate many solutions with similar EI indices, that are close to the minimum. Then, the MAA algorithm, based on the current situation of the DES switching matrix, can provide a result so that switches in the switching matrix are used in a balanced way.

Fig. 11 shows that different configurations are achieved, some with minor changes and others with major, from the starting

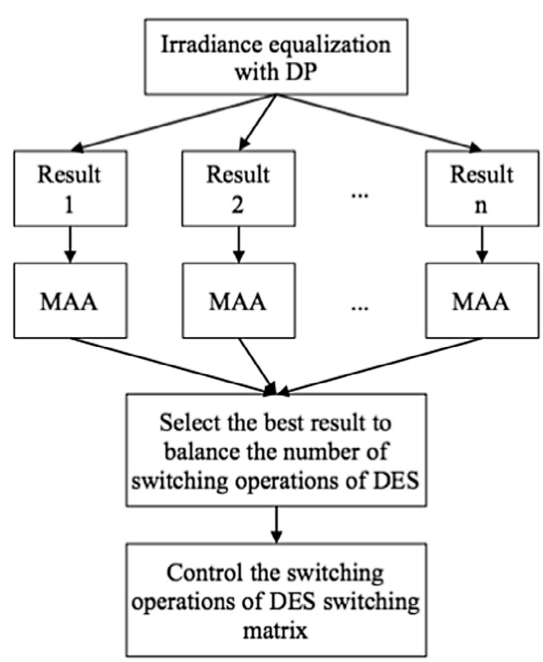


Fig. 11. Balancing method for switching operation with MAA algorithm.

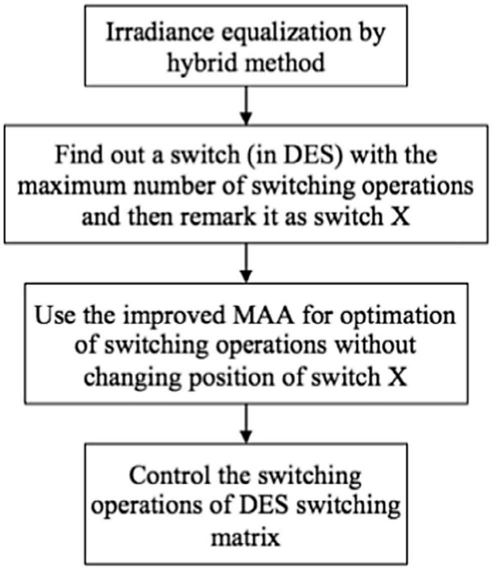


Fig. 12. Balancing method for switching operation with improved MAA algorithm.

configuration. By giving a priority to the balancing of the switches usage, it can happen that, between two suboptimal configurations, the one involving a slightly higher number of switching operations may be chosen.

It can be realized that, as proposed by the method in Fig. 11, running the MAA many times will increase the overall processing time. Therefore, the authors propose an improved strategy as described in Fig. 12.

By using the improved strategy still using MAA, the switch with maximum number of switching operations shall be fixed and the method shall control the switching operations of other switches so that results of irradiance equalization do not change, still ensuring the switching operation balancing of switches in the DES matrix in order to increase the lifetime of the system. When the solar power systems is in operation, PV panels could be shaded by the shadow of trees, buildings, electric lines and columns. This further leads to the problem that some panels shall be shaded several times in a day and switches of such panels shall operate more than switches of other panels. The improved MAA solves this situation. In addition, in the improved MAA method, MAA algorithm is run once helping to reduce the processing speed as compared to the old method.

5. Method to increase efficiency of the solar power systems

Based on the above-described algorithms, the overall methodology for increasing the efficiency of the PV system by reconfiguration is summarized in the flow chart shown in Fig. 13. As it can be observed, after the irradiance estimation both DP and SC are run in parallel and the best performing solution is taken. Then the improved MAA is adopted to minimize the aging of the switching matrix.

6. Experiments

6.1. Simulation

In order to prove the efficiency of the improved method, the simulation of a solar power system including 35 PV panels

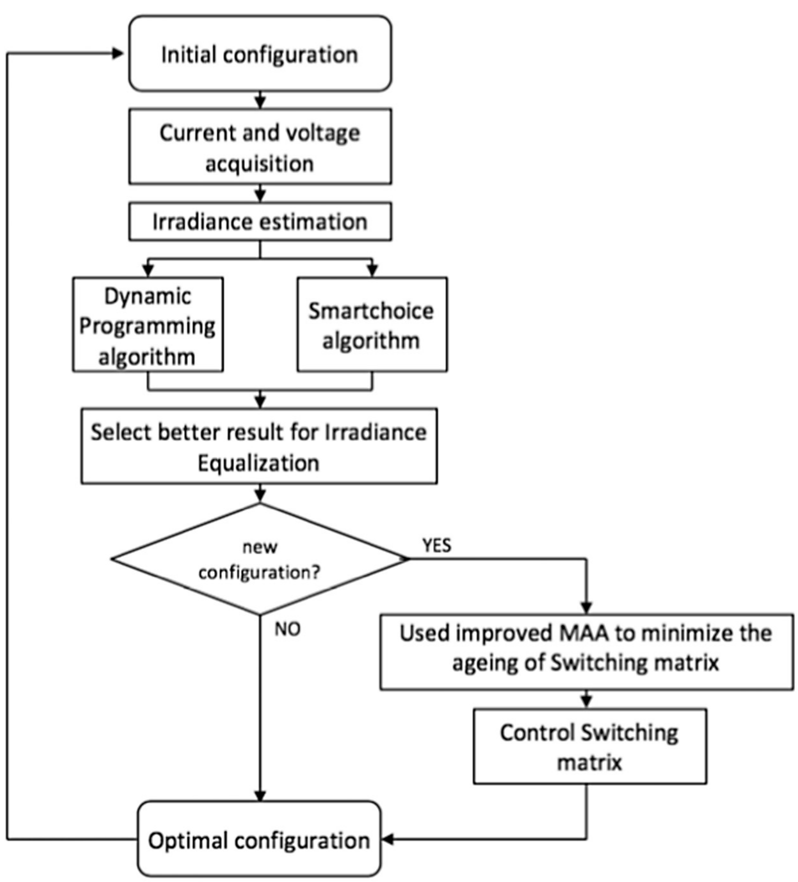
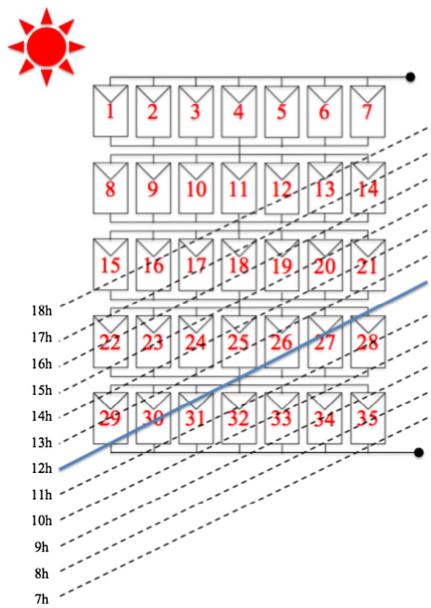


Fig. 13. Flow chart of reconfiguration method for solar power systems.

connected in TCT topology is illustrated in Fig. 14a. The PV system is partially shaded by a line passing through. Depending on position of the sun in a day, the panels (12, 13, 14,..., 35) shall be shaded partially with various degree.

The authors establish a solar radiation database in 12 times in a day with various shading degree of the panels (Fig. 14). DES switching matrix (Fig. 1b) is installed to rearrange to connect 35 panels with 5 rows each, so 175 switches shall be used.



(a)

No.	Time	Radiation degree (W/m^2) Non-partial shading	Partial shading	Partial shading solar panel
1	7h	500	150	(35)
2	8h	650	300	(34, 35)
3	9h	750	350	(33, 34, 35)
4	10h	850	350	(32, 33, 34, 28)
5	11h	950	400	(30, 31, 32, 33, 27, 28)
6	12h	1000	450	(29, 30, 31, 26, 27, 28)
7	13h	950	400	(29, 30, 25, 26, 21)
8	14h	850	350	(29, 23, 24, 25, 20, 21)
9	15h	750	350	(22, 23, 24, 19, 20, 21)
10	16h	650	300	(22, 23, 18, 19, 14)
11	17h	500	150	(22, 16, 17, 18, 13, 14)
12	18h	400	100	(15, 16, 17, 12, 13, 14)

(b)

Fig. 14. Data of partial shading of the simulation solar system: PV array under partial shading (a) irradiance of PV panel under partial shading (b).

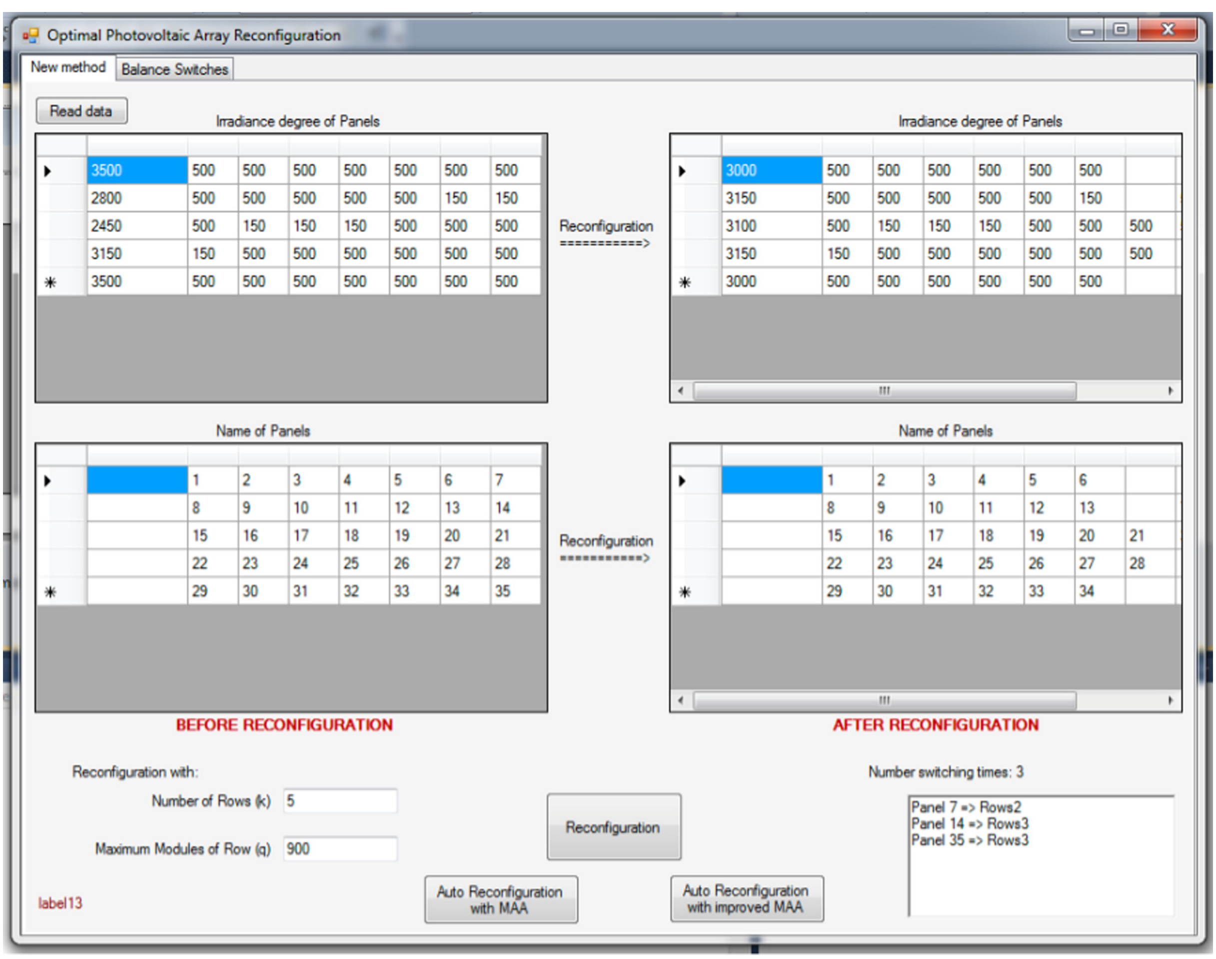


Fig. 15. Optimal photovoltaic array reconfiguration software.

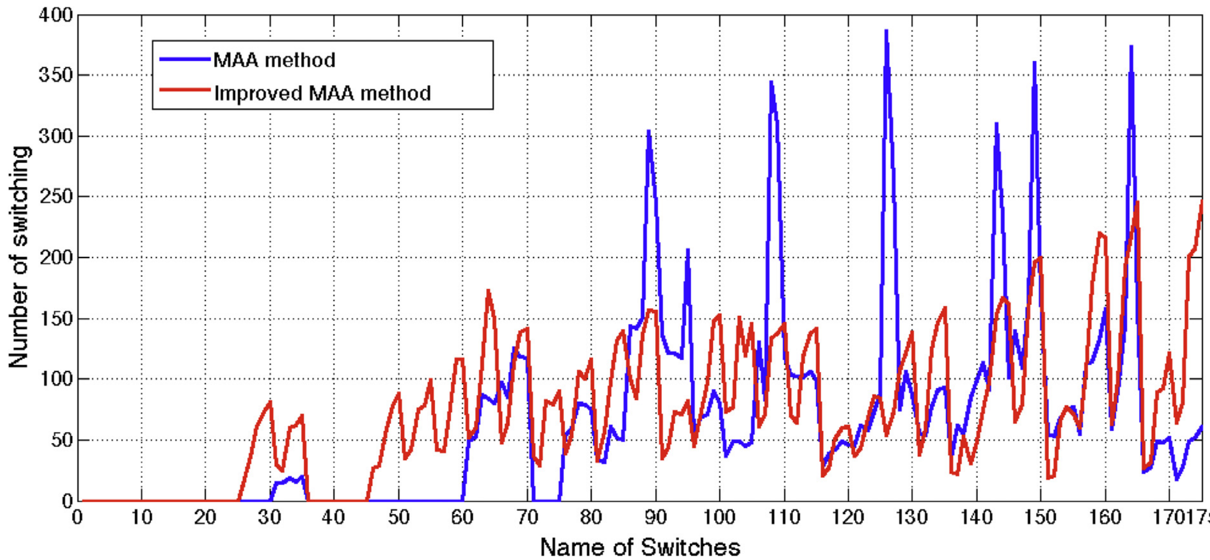


Fig. 16. Comparison of switching operations between (a) the old MAA method and (b) the improved MAA method.

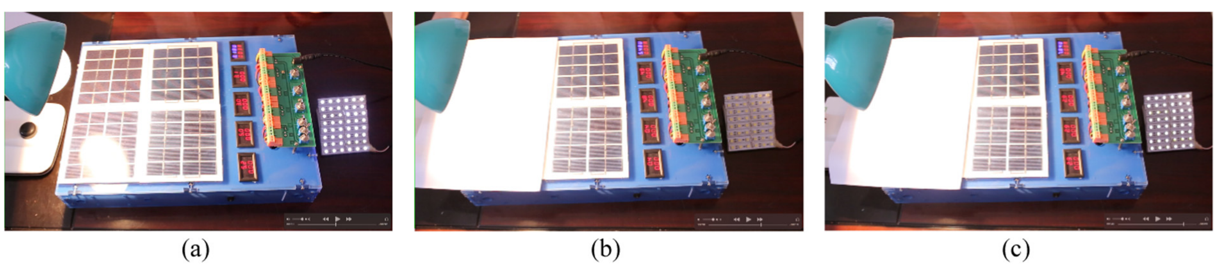


Fig. 17. PV system with reconfigurator: (a) Normal; (b) partial shading; (c) after reconfiguration.

Simulation software is written on C# base by Microsoft Visual Studio 2010 a snapshot of which is reported in Fig. 15. By simulating the operation of the solar system (Fig. 14) with 12 cases of daily various shading, this procedure is repeated for 365 days/year. Diagram in Fig. 16 shows in details the number of switching operations for 175 switches of 35 solar panels in a year. Blue line is the simulation case by MAA method with the number of switching operations in which the maximum number of operation of a switch can reach 386. Fig. 16 shows the improved MAA method in which the number of operations of switches is more homogenous and the maximum number of switching operations is 246. It can be realized that the total number of switching operations in the new method (12,958 times) is more than in the old method (11,405 times) but the aging degree of switches is more homogenous. Therefore, the lifetime of the whole switching matrix would increase by 56% in this simulation case. Indeed the maximum number of switching operations using MAA method is 386; using improved MAA is 246; then $(386 - 246)/246 * 100\% = 56\%$. The aging of the reconfigurator is an important issue: recovered energy, with the particular feed-in tariff, has to repay the cost of the reconfigurator, an unexpected falling-out of the device may preclude the achievement of the trade-off (Campoccia et al., 2014; Campoccia et al., 2008; Viola et al., 2014; Viola et al., 2015).

6.2. Laboratory experiment

The experimental part of this work has been carried out at the laboratory at the Electric Power University in Hanoi Vietnam.

Table 1
Electrical characteristics of PV used modules at 25 °C.

V_{MPP}	I_{MPP}	P_{MPP}	V_{OC}	I_{SC}
18 V	0.33 A	6 W	21.6 V	0.4 A

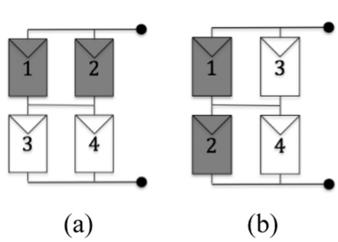


Fig. 18. Connection of PV system before (a) and after (b) reconfiguration.

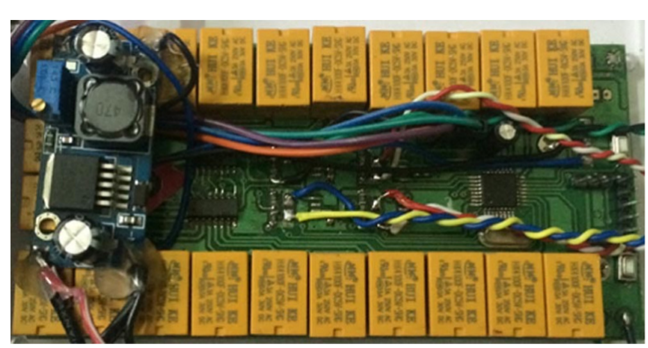


Fig. 19. Reconfiguration system.

Table 2
Operation of reconfiguration system for optimal PV system in 13 case of patial 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||2}–{3||4}	{1||2}–{3||4}	0	23.75	23.75	0.00
2	10	0	0	0	{1||2}–{3||4}	{1||2}–{3||4}	0	23.04	23.04	0.00
3	10	10	0	0	{1||2}–{3||4}	{1||3}–{2||4}	2	22.13	22.6	2.12
4	20	20	0	0	{1||2}–{3||4}	{1||3}–{2||4}	2	20.03	21.38	6.74
5	30	30	0	0	{1||2}–{3||4}	{1||3}–{2||4}	2	17.73	20.18	13.82
6	40	40	0	0	{1||2}–{3||4}	{1||3}–{2||4}	2	15.34	18.98	23.73
7	50	50	10	10	{1||2}–{3||4}	{1||3}–{2||4}	2	12.8	16.6	29.69
8	60	60	60	0	{1||2}–{3||4}	{1||2||3}–{4}	1	10.18	12.33	21.12
9	70	70	70	0	{1||2}–{3||4}	{1||2||3}–{4}	1	7.66	11	43.60
10	75	75	0	50	{1||2}–{3||4}	{1||2||4}–{3}	1	8.54	11.79	38.06
11	80	80	80	40	{1||2}–{3||4}	{1||2||3}–{4}	1	5.04	7.02	39.29
12	75	75	50	50	{1||2}–{3||4}	{1||3}–{2||4}	2	6.34	8.8	38.80
13	75	75	75	75	{1||2}–{3||4}	{1||2}–{3||4}	0	5.81	5.81	0.00

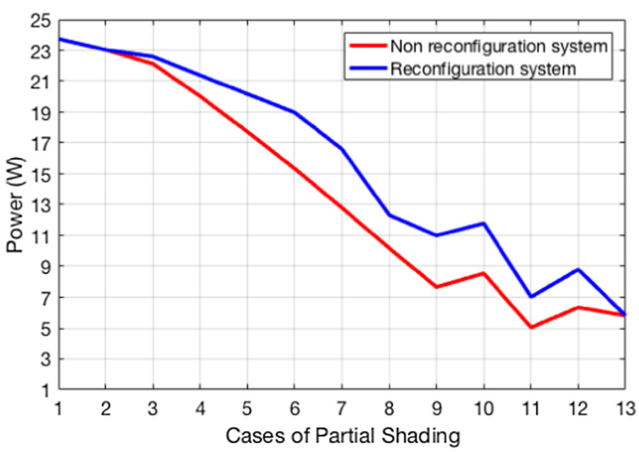


Fig. 20. Diagram comparing the output power of the solar power system with the reconfiguration system and without reconfiguration system when in PS situations.

To assess the efficiency of the proposed algorithm, the authors have implemented at laboratory scale a PV system (Fig. 17) including: a solar simulator, 4 solar panels (rated power shown in Table 1); 4 current and voltage acquisition systems for the 4 panels; 1 current and voltage acquisition for output power of PV system; DES switching matrix and a LED lighting is the load of PV system.

Fig. 13 describes the operation process of a reconfiguration system for PV system in DC current. Fig. 17a shows the PV system that is operating in normal mode where LED lights are very bright, non-partial shading. Fig. 17b shows the system in the case in which the panel 1 and panel 2 are shaded (as you can see in Fig. 18a), LED lights are falling due to the inefficiency of the source. Besides, Fig. 17c shows the PV system after reconfiguration (as connection in Fig. 18b), that helps to recover a part of power generated due to partial shading. At this moment, LED lights are bright again but they are not as bright as initially.

In self-operating mode, the reconfiguration system (including DES switching matrix and Controller chips), shown in details in Fig. 19, that is programmed for operation in each minute shall measure the current and voltage on each solar panel, then, the irradiation degree on each panel is calculated. Compared with the previously calculated result, if irradiation variance exceeds allowable limitation, the reconfiguration system shall automatically calculate and control the switching matrix to obtain the optimal configuration for output power. And, in case the system is shaded for a short time (below 1 min) or less shaded (not exceed 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 degree chronologically. Output power is then measured and compared in case of reconfiguration system activation and no reconfiguration system activation.

Solar power system with automatic reconfiguration system operated well as shown by the results reported in Table 2 and Fig. 20.

7. Conclusion

The method proposed in this paper should be applied to small PV systems, although one of the objectives of this work is to propose similar strategies for larger photovoltaic fields. In those cases, improvement in output power could bring large benefits in terms of feed-in tariffs when available or simply produced clean energy. Another possible evolution of this work is the use of solid state switches. In this case the problem of obsolescence would not be anymore a big issue. However, these switches do not still seem to be easily controllable while showing some problems for high power applications and thus electromechanical relays still seem to be the best option at this stage. This paper presents improved methods in order to increase the efficiency of the solar power system and lengthen the lifetime of the system by balancing the switching operations of the switching matrix based on electromechanical relays. By running in parallel the newly proposed Smart Choice algorithm and a Dynamic Programming algorithm an optimal result for the irradiance equalization problem is attained. Then an improvement of the MAA algorithm helps to further save operation time of the system and offer an optimal switching operation control result while increasing the lifetime of the system. The operation of a reconfiguration system on a solar power system with 35 panels with various shading degrees in a day is simulated, then, experimental results on a smaller system demonstrated the efficiency of the new method. This improved method could be applied in real time to increase the quality of current solar systems. Future work about the same issue will imply the extension of the methodology to larger systems and a detailed economical analysis based on the results of (Viola et al., 2016; Caruso et al., 2017) to assess the return on investment time of the whole system.

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