Power enhancement of photovoltaic arrays under partial shading conditions by a new dynamic reconfiguration method

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Dynamic reconfiguration of photovoltaic arrays is one of the effective ways to decrease partial shading effects. In this paper, by using auxiliary modules and after a suitable fixed reconfiguration, an optimizer and economical method based on dynamic reconfiguration is presented. In this method, Auxiliary modules are arranged next to the photovoltaic array and replaced with shaded modules to maximize the energy delivery. The best connection between the auxiliary modules and the array is determined by an optimal decision process. The objective function for this decision process is energy delivery of the solar array in shadow conditions, which is maximized by the genetic algorithm. Significant improvement in the output power of the photovoltaic array and smaller number of switches than the other dynamic reconfiguration methods are the main advantages of the proposed method. Benefits and effectiveness of this method are compared with other recently dynamic configuration approaches, and the results confirm power enhancement of the photovoltaic arrays in various shadow patterns.

keywords: *Photovoltaic array, Partial shading, Dynamic reconfiguration, Power enhancement.*

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NOMENCLATURE

G	irradiance on the array modules
G_{STC}	irradiance in the standard conditions
G_{Ti}	sum of irradiances on i^{th} row of the array
G_{ij}	irradiance on the M_{ij} module
G_T	sum of irradiances on the array
G_M	average irradiance on a row without shading conditions
$G_{group(i)}$	sum of irradiances on the i^{th} row in shading conditions
g_{ij}	irradiance on the M_{ij} module in shading conditions
$G_{Diff(i)}$	difference irradiance between existing condition and non-shadow conditions in i^{th} row
I_{SC}	short circuit current of a row
I_{SC_STC}	short circuit current of a row in the standard conditions
$f(X_k)$	power enhancement objective function
N_{sw}	number of switches in the matrix switches

1. INTRODUCTION

Among the many sources of electrical power generation, solar energy is one of the largest renewable energy sources on Earth. In the meantime, photovoltaic (PV) systems are considered as one of the most commonly used solar energy applications. In the near future, a significant portion of the energy requirements of distribution networks will be provided by photovoltaic systems. Basically, for increase output voltage in a photovoltaic array modules are in series, and partial shading conditions decreases the performance of the PV array [1]. When one or more modules are placed in an array of PV under the shadow, the output power of the array is significantly reduced so that the shaded module limits the series electrical current of the other modules (Fig. 1). In partial shading conditions, the electrical performance of an array is strongly affected. Not only the output power of the shaded modules decreases, because of their electrical connection between shaded and non-shaded modules, there is an undeniable effect on the performance of the array [2]. If the current produced by non-shaded modules passes from a shaded module, negative voltage would be generated on the shaded module and causing it to become hot. This phenomenon is called hot-spot [3]. On the other hand, this partial shading creates several maximum points on the array power characteristic which makes the maximum operation complicated [4].

Partial shading losses do not relate to the shaded area, they are dependent on the shading pattern, array configuration, and shaded modules location. Several different array configurations are proposed to reduce the losses. Fig. 2 shows four general configuration methods: series-parallel (SP), bridge-linked (BL), honey-comb (HC), and total-cross-tied (TCT). The comparison of these configuration methods shows that the TCT method is more effective in reducing shadow losses [5].

Fix reconfiguration methods by changing the location of the configured array modules, based on the predictable shadow patterns, make maximum power utilization in the shadow conditions. Fix reconfiguration is an operational and economical manner to reduce partial shading effect in the photovoltaic arrays of a solar power plant [6–10]. In the recent researches, fix reconfiguration methods are presented, which can reduce the effects of all-possible mutual shadows, and by minimizing the circuit wiring reduce resistance losses. In addition, Two-sided mutual shadings in the compact solar power plant can be dispersed on the PV array surface by a fix reconfiguration method [11].

Power electronic solutions are the most expensive and of course, the most efficient way to reduce partial shading effect. Bypass diode is the simplest power electronic way for photovoltaic arrays under partial shading conditions [12]. Bypass diodes are paralleled to modules and reduce the power loss by limiting the reverse voltage at two ends of the modules, but by this solution, several maximum power points create in the output power characteristic of the array and tracking the best point is complicated [13, 14]. More complicated power electronic methods create high efficiency for a photovoltaic array under partial shading conditions [15].

Dynamics reconfiguration of PV arrays is another way to improve the shadow effect, which has special applications such as satellite PV sources. In this method, Auxiliary PV modules

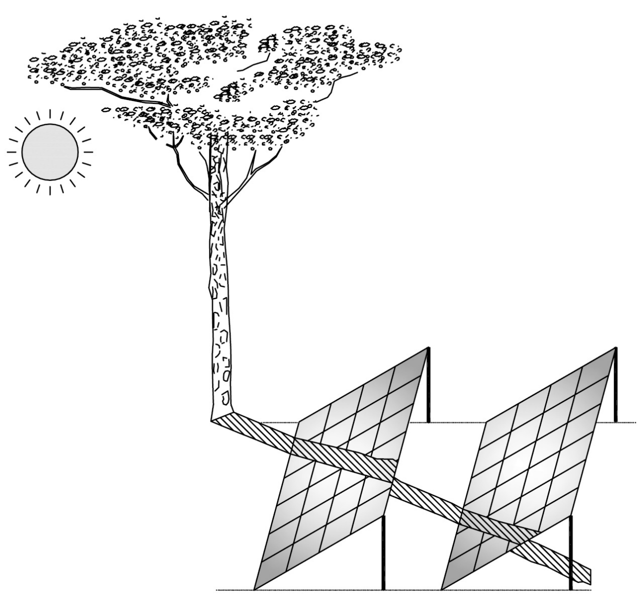

Fig. 1. A sample of partial shading on the PV arrays.

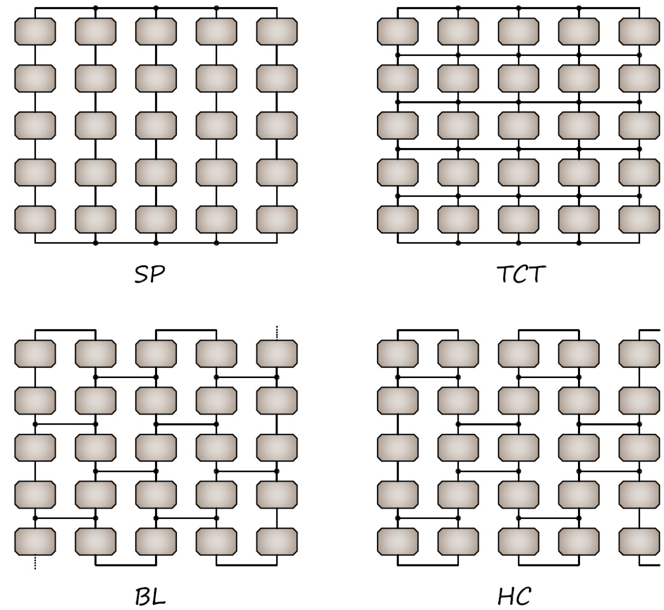

Fig. 2. PV array configurations: Series-Parallel (SP), Total-Cross-Tied (TCT), Bridge-Linked (BL) and Honey-Comb (HC).

are arranged next to the main array and replaced with shaded modules at necessary times to maximize the energy delivery. This method is more costly due to switches and sensors than the fixed reconfiguration method, but it has more impact on reducing losses and improving array output power [16, 17]. Dynamic reconfiguration methods can increase the output power of PV arrays more than fix reconfiguration procedures, especially in unpredictable shading conditions. Hence, PV arrays with dynamic reconfiguration ability are used in special applications. In addition, by development of manufacturing technology of matrix switches, dynamic reconfiguration in PV arrays will be operational.

In this paper, a dynamic method to improve the efficiency of the output power of the PV arrays is proposed. By using Auxiliary modules, shaded modules are replaced, and prevented from damage of shaded modules. The best connection between the auxiliary modules and the array is determined and improved in the output power of the PV array by smaller number of switches than the other dynamic reconfiguration methods. The advantages of this method are compared with other recently dynamic configuration approaches, and the results confirm power enhancement of the photovoltaic arrays in various shadow patterns. Simulation results approve considerable power enhancement of PV arrays under shading conditions by the proposed dynamic reconfiguration method.

2. PARTIAL SHADING PATTERNS

Dust, snow, mutual shading, and natural shadows are partial shading factors in the PV arrays. Partial shading is a common phenomenon, which occurs when some modules inside an array are shaded by buildings, birds, clouds movements, adjacent PV arrays or other objects. Shadows that arising from clouds, birds, dust, and snow are unpredictable shadows, and the shadows created by the buildings or adjacent PV arrays are predictable shadows that they have a specific behavior within the days of year. There are specific partial shading patterns for more predictable shadows. All configuration methods are based on these patterns. Fig. 3 shows general patterns of partial shadings in the PV arrays. Mutual shading of adjacent PV arrays usually causes rectangular shadow patterns. Improvement studies are performed on the power of arrays based on these shadow patterns, and in these studies, more patterns provide a better structure for the PV arrays. One of the most important advantages of dynamic reconfiguration methods is power enhancement of PV arrays in both predictable and unpredictable shadows, while fix reconfiguration algorithms are proper just for predictable shadows. Partial shading patterns are used this paper just for comparison of the proposed method against other improver methods.

3. A MATCHING FIX RECONFIGURATION

One of the most effective methods to improve the partial shading problems in the PV arrays is fix reconfiguration. The reconfiguration of photovoltaic arrays can be done in a fix, dynamic, or a combination method. Sudoku and Step-Wise are traditional fix reconfiguration methods [10, 11]. These methods cannot present an optimized reconfiguration for PV array in the triangular and diagonal shadow patterns.

In addition, fix reconfiguration cannot enhance the output power of the array in the unproductive shadows. As most shadows are predictable, fix reconfiguration before installing the PV array makes the dynamic approach more efficient. An Optimal fixed reconfiguration scheme for PV arrays power enhancement under mutual shading conditions is used to disperse the shadows on the TCT configured array surface as a part of the proposed combination method [9].

4. PROPOSED DYNAMIC RECONFIGURATION METHOD

Although dynamic reconfiguration methods are more expensive, they increase system efficiency more than the fixed methods in shadow conditions. Based on the proposed algorithm, a m×1 dynamic module bank is used alongside m×n main PV array. Dynamic modules are connected to rows of TCT array by a matrix switches depends on the shadow pattern. In order to estimate the radiation on the modules, a current sensor is used in every array row to determine the short circuit current of the row, and the best switching connection format is estimated based on a genetic algorithm. In the normal conditions and lack of

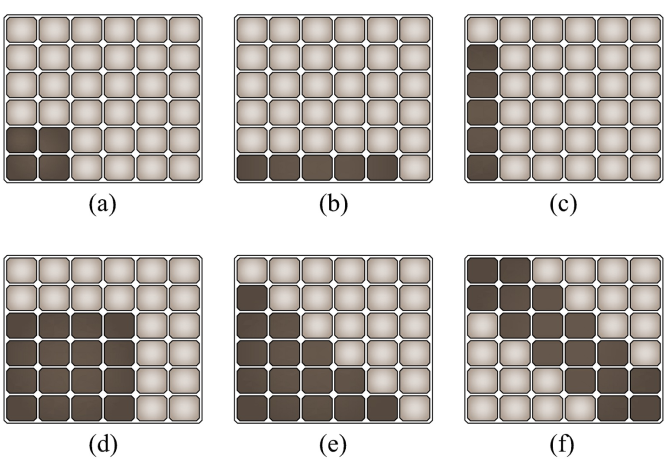

Fig. 3. PV general shadow patterns: a) short and narrow, b) snub, c) slender, d) long and wide, e) triangular, f) diagonal.

shading, each of the dynamic modules is connected to one of the array rows. Since radiation is directly related to the short-circuit current, the radiation level is given according to the following equation.

$$G = [I_{SC}/I_{SC\_STC}].G_{STC} \tag{1}$$

where; $G_{STC} = 1000\ W/m^2$ and $25°C$. Sum of irradiances on i^{th} row of the array is calculated by Eq. (2).

$$G_{Ti} = \sum_{j=1}^{n} G_{ij} \tag{2}$$

On the other hand, sum of irradiances on the array can be calculated from Eq. (3).

$$G_T = \sum_{i=1}^{m} \sum_{j=1}^{n} G_{ij} \tag{3}$$

Average irradiance on a row without shading conditions is calculated by Eq. (4).

$$G_M = G_T/m \tag{4}$$

For definition of an objective function, if the irradiance value of a module is equal to gij, then sum of irradiances on the i^{th} row in all shading conditions ($G_{group(i)}$) is given according to the following equation.

$$G_{group(1)} = \sum_{j=1}^{n} g_{1j}\ ,\ G_{group(2)} = \sum_{j=1}^{n} g_{2j}\ ,\ ... \tag{5}$$

$$G_{group(i)} = \sum_{j=1}^{n} g_{ij} \tag{6}$$

A function that indicates the difference between existing conditions and non-shadow conditions is defined as follows:

$$G_{Diff(i)} = |GM - G_{group(i)}| \tag{7}$$

The main purpose of the objective function that presented in Eq. (7) is to minimize the difference between row irradiance with the desired average irradiance by using the connection pattern of matrix switches. $G_{Diff(i)}$ determines the difference between row irradiance for i^{th} row of the array, which is equivalent to the current difference between the rows. In other words, for equalization of the rows current in shading conditions as the most important aim of the dynamic reconfiguration, sum of $G_{Diff(i)}$ must be minimized.

$$f(X_k) = min \sum_{i=1}^{m} G_{Diff(i)} \tag{8}$$

Where X_k is switch situation and k is switch number, and constraint of X_k is presented in Eq. (9).

$$1 \leq X_k \leq m \quad \forall\ k\ \in\ \{1, 2, ..., ceil(m/2)\} \tag{9}$$

In mathematics, the ceiling and floor functions map a real number to the largest previous or the smallest following integer, respectively. According to recent research, the number of necessary switches for an appropriate $m \times n$ array, along with an $m \times n_{bank}$ dynamic module bank are given by the following equation [18]:

$$N_{sw(n)} = 2 \times m \times m \times n_{bank} \tag{10}$$

and thus, the number of necessary switches for an m×1 dynamic module bank is given from Eq. (11).

$$N_{sw(1)} = 2 \times m \times m \tag{11}$$

In this proposed method, an $m \times 1$ dynamic module bank connects to main array by m switches in the non-shaded conditions. In shaded conditions and in the worst case, first to $L = floor(m/2)$ dynamic modules disconnect and connect from $L+1$ to end dynamic modules, respectively by L switches. For i^{th} row, $f(X_k)$ is minimized to balance of the rows current by using genetic algorithm and its constraint, which is presented in Eq. (9). This process has been continued since rows current balancing will be achieved. Of course, in most cases, an accurate balance of rows current is impossible and maximum balancing of the currents is desirable.

For connection of reconfigured dynamic modules to main array $H \times m$ switches are needed. On the other hand, $H = ceil(m/2)$ switches were used in the non-shaded conditions can be re-used in shadow conditions. Therefore, the number of switches in the proposed method is significantly less and is obtained from Eq. (12).

$$N_{sw(proposed)} = 2 \times (H \times m + m + L - H) \tag{12}$$

For example, the necessary number of switches for a 9×9 array with 9×1 dynamic array is 162 based on recently methods, and this number from the proposed method is 106.

5. SIMULATION RESULTS AND DISCUSSION

To examine the efficiency of the proposed method, a 6×6 array has been used that the specifications of each module in standard conditions (1000 W/m^2 and 25°C) are presented in Table 1. It is assumed that non-shaded modules and shaded modules provide 100% and 40% of their maximum power, respectively. Modules structure connections are TCT and the array has been fix reconfigured based on the mentioned shadow patterns. A 6×1 dynamic array is considered alongside the main array, which can connect to main array rows by a matrix switches.

Table 1. PV Modules Specifications at 1000 W/m^2, and 25°C

Parameters	Value
Power	3.6 W
Operating voltage(Vmpp)	6 V
Operating current (Impp)	600 mA
Open circuit voltage	7.2 V
Short circuit current	655 mA
Dimensions	175 × 175 × 2.8 mm
Number of modules in the array	36

Fig. 4(a) shows this structure with a snub shadow above it, that the main array is fix reconfigured. In this situation, created current in 5 columns of the PV array are limited by shaded modules and the efficiency of the array has drastically decreased. The primary fix reconfiguration of the array improves this condition and decreases to 2 limited columns. Fig. 4(b) shows that the shadow is dispersed by the fix reconfiguration at the array surface and there are only one or two shaded modules in each row. This is the best status to disperse a shadow.

In this proposed method, the objective function Eq. (8) is minimized by genetic algorithm based on limiting constraint and created shadow. The result of this optimization is shown in Fig. 4(c). As this figure shows, in the rows with two shaded modules, two dynamic modules are parallel with the main array. With this situation, there is only a shadowed module in some rows, and the PV array efficiency is very high in the shading conditions.

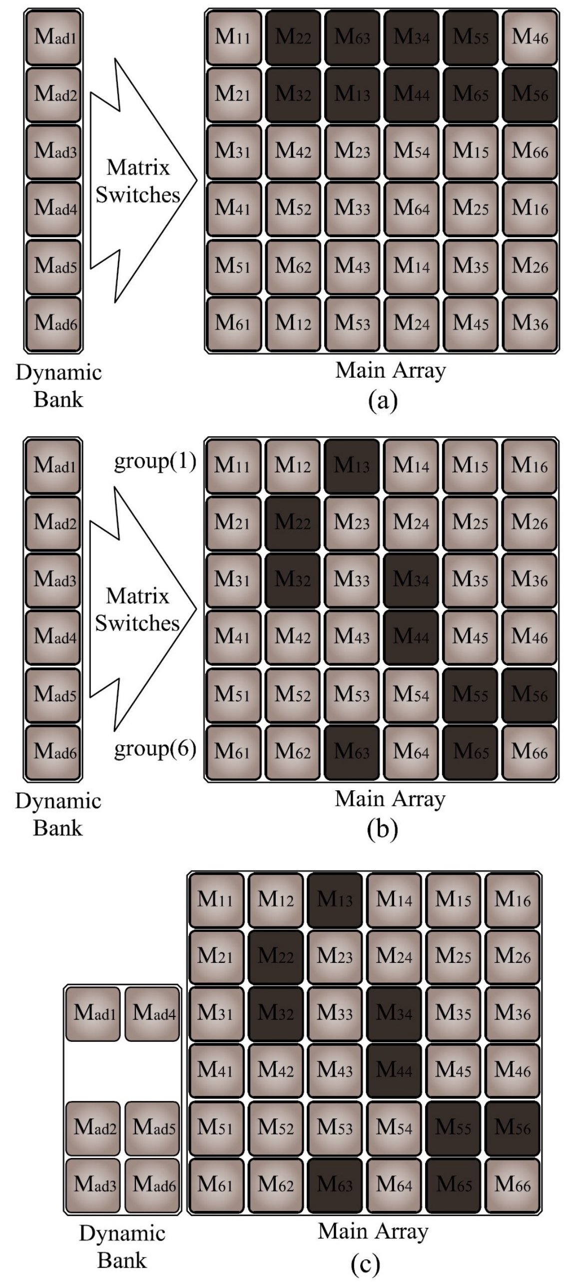

Fig. 4. Fix and dynamic configurations of the PV array with a snub shadow: a) shaded array, b) dispersed shadow by the fix reconfiguration, c) dynamic improvement.

Table 2 compares different reconfiguration methods with the proposed method for different shadow patterns. As shown in this table, the proposed method for a variety of shadow patterns has a significant effect on improving the output power of an array in shadow conditions, and in all shadow patterns it has

Table 2. Output power of the array based on reconfiguration methods for different shadow patterns in watts (W)

Configuration	short and narrow	snub	slender	long and wide	triangular	diagonal
TCT	80.64	129.66	79.12	121.82	80.60	77.68
Step-Wise	119.70	131.31	99.00	122.58	98.33	81.20
Sudoku	119.70	135.60	100.06	122.58	91.80	104.30
Proposed	125.97	143.57	103.41	127.07	109.69	109.65
Improvement than TCT	56.20%	10.73%	30.71%	4.32%	36.09%	41.16%

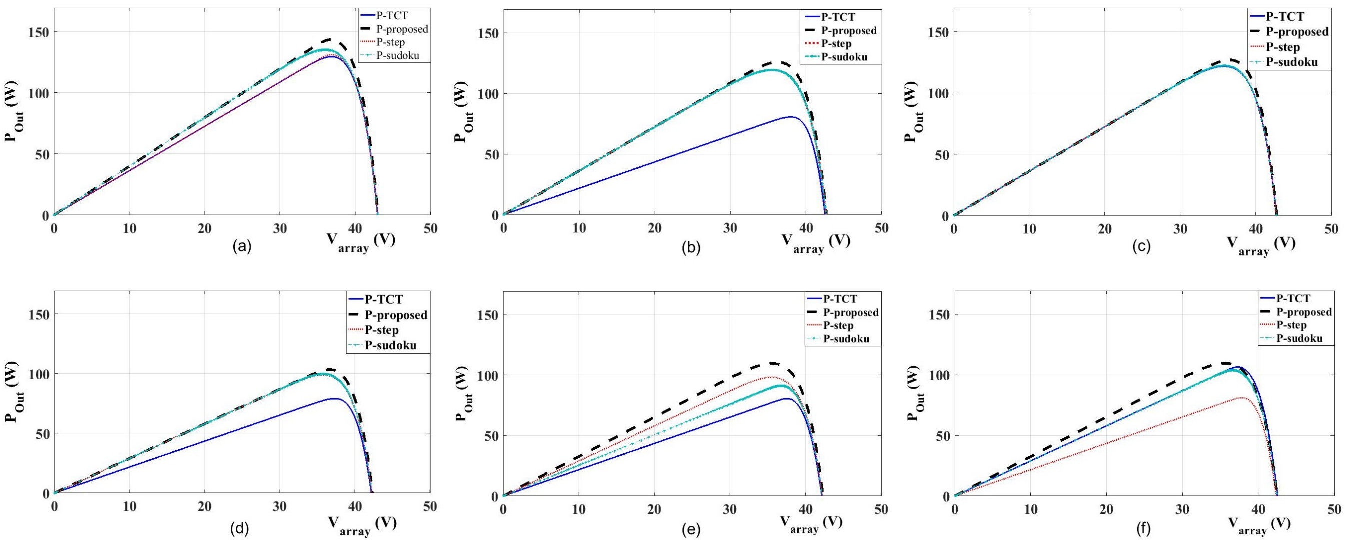

Fig. 5. P-V curves comparison for different shadow patterns: a) short and narrow, b) snub, c) slender, d) long and wide, e) triangular, f) diagonal.

more output power.

Also, Fig. 5 shows the power characteristics of the PV array for different shadow patterns. In these figures, the maximum output power of Sudoku, Step-Wise, TCT, and proposed reconfiguration method are compared. As shown in these figures, the major effect of the proposed method is on the triangular shadow pattern. However, the fixed reconfiguration of the Sudoku can only be implemented for square arrays, but it has the most impact on the maximum output power of the PV arrays among the fix reconfiguration methods.

6. CONCLUSION

In recent years, many efforts have been made to reduce the effects of partial shading in photovoltaic power generation systems. In this paper, an effective dynamic reconfiguration method is proposed based on a combined structure. In this method, auxiliary modules of an m×1 dynamic array replace with shaded modules by a matrix switches. By this way, the shadows disperse on the PV array surface by a fix reconfiguration, and then shaded modules are replaced with dynamic modules in the necessary rows based on the proposed dynamic reconfiguration method. The best connection between the auxiliary modules and the array is determined based on an optimal decision process by using genetic algorithm. One of the features of the proposed method is to significantly reduce the connector switches between dynamic array and main PV array than other methods, as shown in an example, the number of connected switches in the proposed method decreased by 35% compared to the other dynamic reconfiguration methods. Also, Simulation results show that this method improves the output power of an array compared to simple TCT, Sudoku, and Step-Wise configuration. The superiority of this method is better performance in the diagonal and triangular shadow patterns. The results are approved output power improvement for the PV array under partial shading conditions and output power in some shadow patterns has been improved up to 56%.

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