Peer-Reviewed Article

Reconfiguration Technique for Optimization of the Photovoltaic Array Output Power under Partial Shading Conditions

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A partial shading condition is a case under which the PV array is exposed to many problems such as losses of the output power of the PV array, and the PV array has more than one maximum power point (MPP), which makes it so difficult to track the MPP. This paper presents the effect of different partial shading patterns on PV array characteristics and the effect on the output power of the PV array, and provides a comparative literature review on methods to mitigate these effects and the drawbacks of these methods. It also proposed a new reconfiguration strategy that increases the output power of the PV array by 13.8 % from the total power under shadow condition, and a new technique for enhancing the output power of the PV array by 20 % of the total power under fully illumining conditions by controlling the switch matrix between the photovoltaic array and adaptive batteries bank. This paper gives a solution for the problem of the difficulty of tracking the MPP, because the proposed strategy makes only one MPP. The simulation was carried out by using MATLAB Simulink under different shading patterns.

1. Introduction

The use of photovoltaic (PV) cells for producing electricity has been recently increased due to reduced costs and increased efficiency of the energy conversion. They are widely used in many applications to reduce the effect of CO_2 emission. However, two of the problems that still affect the performance and reliability of PV modules are shading and mismatch. Shading occurs, when PV system has been installed in some locations where exposure to shading is inevitable. For example, there is not enough land available to build a PV installation to prevent all types of shading. Shading of PV may also occur in the case of leaves, bird droppings or dirt falling on PV cells as well as surrounding structures (building and trees) and the shadows casting over PV cells. The effect of partial shading will reduce the output power of the PV array, and the mismatch may be occurring because cells with different characteristic performance are combined together in an array. The condition of a mismatch may cause power loss. When the characteristic of cells within the

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PV array differs, individual cells may not operate at the optimal condition. As a result, some shaded cells consume power from the unshaded cells, and the output power of the PV array reduces and the shaded cells overheat. This phenomenon is called hot spot and it may cause damage of the PV cells. Bypass diodes are commonly used in PV arrays to protect against the effect of partial shading and hotspot power dissipation. A bypass diode is connected in parallel but in opposite polarity with the PV cell. Under normal operation, each solar cell will be forward biased and therefore the bypass diode will be reverse biased. Typically, one bypass diode is connected with a string [1]. Since the string has the same current because of the series connection, but the shaded cell is reverse biased to conduct the large current of unshaded cells [2-3]. The activation of bypass diodes causes presence of multiple maximum power peaks that make it difficult to track the maximum power point (MPP). This paper presents a solution for optimization of the maximum output power of the PV array and enhancement of the PV array performance. The remaining of the paper is organized as the following: Section 2 Literature review, Section 3 Modelling of the PV array, Section 4 Research method, Section 5 Simulation and results, and Section 6 Conclusions.

2. Literature Review

Some authors discussed a great number of methods to track the global MPP of the PV array under partial shading conditions. Ref [4] covered a comparison between some techniques for tracking of the global MPP.

Ref [5] studied the effect of the interconnection of the array according to the shading pattern. The author made simulation on three interconnections of PV: array series-parallel connection (SP), total cross tie connection (TCT) and bridge linked connection (BL) at different shading patterns. The author concluded that Series-Parallel (SP) interconnection produces the maximum power as compared to Total-Cross-Tied (TCT) interconnection when shadow is portended to be progress on the last row of horizontal modules, while TCT interconnection produces the maximum power as compared to SP interconnections when shadow is portended to be progress on the left column of vertical modules. The drawback of this technique is that the shading pattern must be known.

In Ref [6], a DC–DC converter controlled by a DC signal of adjustable amplitude was used to track the global MPP.

Ref [7] discussed the optimal layout of PV modules within a PV array giving the maximum output power. Author found that the scheme of parallel connection of all the panels of the system was the best possible configuration.

In Ref [8], a reconfiguration of the shaded modules was made within the fixed PV array by using adaptive bank PV modules and switching matrix. The drawbacks of this technique are the high cost of adaptive bank of PV modules and some of this adaptive bank PV modules may be shaded.

In Ref [9], reconfiguration of the PV array by using the rough set technique (RST) was done. This technique depends on a complex mathematical method for reconfiguration of the PV array.

Ref [10] developed a power optimizer software for executing a power conversion and distributing maximum power point tracking to capture maximum PV array tied to the

electric grid by taking input parameter data about panel, array, shading obstacles, weather data and using this information to perform plane of array irradiance mapping and using this data to develop annual simulation software for power recovery in array during complete or partial shading. But this system required annual update for data and it didn't work accurately if there are unpredictable reason for shading.

In Ref [11], a basic boost converter with several channels was used and the output of the two channel boosts was combined with an uncoupled reactor. This two-channel boost converter increased the output power and efficiency of the PV array, and reduced the harmonic in the output power. This system was controlled by pulse width modulation (PWM) based PI voltage mode controller. However, this converter has non-linearity and non-stability due to its parameter variation and is suitable for low power application only. If the power increased, the size of reactor and the cost increased.

These literature reviews can be summarized as follows: Some authors used different methods for reconfiguration of photovoltaic array during normal operation condition such as ref. [5, 7-9]. Ref. [5] required the user to predict the shading pattern and use the appropriate system configuration, but still there are power losses that didn't substitute. Ref. [4] didn't consider the reconfiguration due to unpredictable condition such as birds and clouds. Ref. [7] suggested a good method for reconfiguration under different shading conditions and ref. [8] substituted the loss occurring due to partial shading by using adaptive PV array, but didn't take in account that the partial shading occurs in the main and alternative PV arrays due to clouds. Ref. [9] suggested a complex method for reconfiguration of the PV array depending on data entry about the shading pattern. If this parameter changed, the system won't work correctly.

Some authors such as ref. [6] and [11] substituted the loss during partial shading by using a power electronics converter that causes the output power of the photovoltaic array to generate multiple power points and causes losses. Some authors suggested different methods for maximum power point such as ref. [4] and [10].

3. Modelling of the PV Array Circuit

3.1 Electrical Model of PV Module (five parameter model)

There are three models of the PV cell, *i.e.,* ideal model, single diode model and two diode model. In this paper, a single diode five parameter model is used as illustrated in Fig. 1. This electrical circuit of the PV cell represents the behavior of the real cell. This model is called a single diode five parameter model because it depends on five parameters that are the nominal PV current, diode current, series resistance, parallel resistance and output voltage of the PV array. These parameters can be estimated as shown in the literature [12].
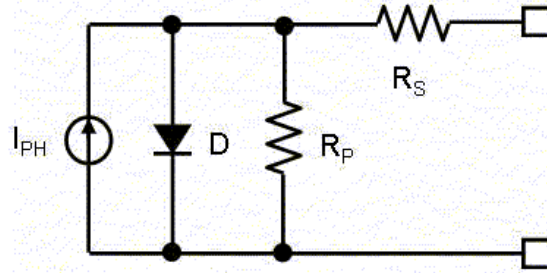
Figure 1. Equivalent circuit of PV cell single diode five parameter model

3.2 Mathematical Model of PV Module (five parameter model)

For the circuit shown in Fig. 1 it is possible to obtain Eq. 1:

$$I = IpH - ID \left(e^{\frac{V}{a\,vt}} - 1 \right) - \frac{V+IRs}{Rp} \tag{1}$$

Where IPH is the photovoltaic current, ID is the diode current, V is the PV output voltage, Vt is the thermal voltage and Rs is the series resistance. Rp is the parallel resistance and I is the PV output current. The solution of Eq. 1 gives the I-V characteristic curve of the PV array.

- Thermal voltage

The thermal voltage of a module with Nc cells is given by the Eq. 2.

$$Vth = \frac{K\,T}{q} \tag{2}$$

Where the k is the Boltzmann's constant (1.38×10^{-23} J/K), q is the electron charge (1.6×10^{-19} C) and T is the temperature.

- Diode reverse saturation current (ID)

The diode reverse saturation current can be calculated by substituting the open circuit conditions (V=Voc, I=0) as shown in Eq. 3.

$$ID = \frac{Isc}{\exp\left(\frac{Voc}{aNcVth}\right) - 1} \tag{3}$$

Where Voc is the open circuit voltage, Isc is the short circuit current, a is the ideality factor of the diode and Nc is the number of cells.

- Photovoltaic current (IPH)

The photovoltaic current IPH depends on the temperature and the solar irradiation as shown in Eq. 4.

$$IpH = (Iph, reference + Kt(T - Tref)) \frac{G}{Gref} \tag{4}$$

Where Iph, ref is the photovoltaic current at reference irradiance and temperature (1000 w/m^2 and 25ºC), G is the incident irradiation (w/m^2), Tref is the reference temperature at normal condition (25ºC) and Gref is the reference irradiance or nominal irradiance (1000 w/m^2).

4. Methods and Results

4.1 Proposed Reconfiguration Strategy

The PV array under partial shading conditions has a preferable performance and output power when the shaded modules are located in the same column or in a limited number of columns. Therefore, to obtain optimal optimization of the output power of the

PV array during shading conditions, it is required to reconfigure the electrical connection of the PV array where the new reconfiguration of the electrical connection of the PV array must make the shaded modules in the same column or in a limited number of columns. The implementation of this task required using of some components (such as a current transformer to measure (Ib) the current passes through a bypass diode and a potential transformer to measure the voltage (v) across the module) and using of electronic switches to make automatic reconfiguration of the modules when the shading occurs. The controller takes order from the current transformer and potential transformer to control the switching of the modules to achieve the best reconfiguration.

The processes of reconfiguration of a PV matrix M × N where M is the number of rows and N is the number of columns are shown in the following flow chart (Fig. 2).
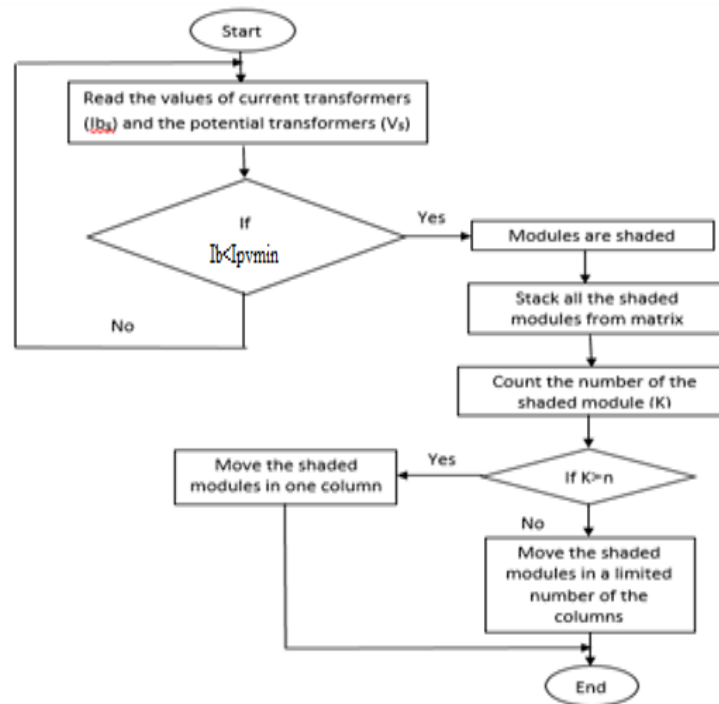

Figure 2.   Flow chart of the proposed reconfiguration strategy

4.2 The Principle of Operation of the Proposed Unit

The reconfiguration strategy makes optimization of the output power of the PV array during partial shading condition, but the output power of the array is still lower than the output of the PV array under fully illumining condition. Therefore, a new technique as shown in Fig. 3 is used for substituting this loss of the output power of the PV array during partial shading conditions by using a lead acid battery connected in parallel with the PV array. The parameters of the lead acid battery are shown in Table 1. The voltage of battery is equal to the minimum voltage of series modules under uniform irradiation. When the partial shading occurs, the output current of the photovoltaic array reduced due to partial shading. The current transformer senses the current of the PV array (Ib) and sends the

signal to the controller. The controller compares the current value sent by the current transformer with the preset value of the current (Ipvm) equal to the minimum value of the PV array current under uniform irradiation. If the current measurement of the current transformers of some modules is lower than Ipvm, then the controller will send commands for electronic switches to stack all shaded modules from the matrix and count all shaded modules. If the number of the shaded modules is equal to the number of the columns, then the controller connects all shaded modules in one column for optimization of the output of the PV array and the battery substitutes these losses due to shadowing. If the number of shaded modules is more than / less than the number of columns, then the controller will connect the shaded modules in less number of columns as shown in m-file shown in Appendix.

Table 1. The parameters of lead acid battery

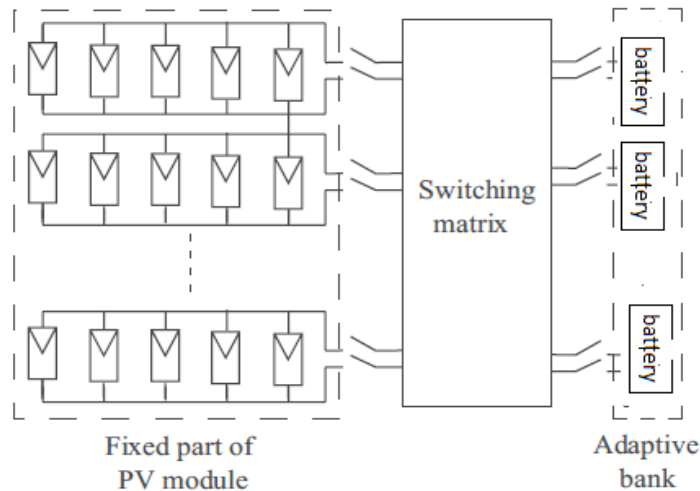| Parameter	Value
Nominal voltage	30 V
Rated capacity	0.4 AH
Fully charged voltage	38.87 V
Nominal discharge current	0.08 A
Internal resistance	0.03 Ω

Figure 3. The new proposed unit

5. The Simulation

The simulated PV array system of 3×3 matrix as shown in Fig. 4. The PV module's parameters were taken from National Renewable Energy Laboratory (NREL)'s System advisor model (January 2014) and sorted in Table 2.

Table 2. The parameters of the PV module

Parameter	Value
I_{MPP}	8.07 A
V_{MPP}	10.32 V
P_{MPP}	83.28 W
$I_{s.c.n.}$	8.62 A
$V_{o.c.n.}$	13.30 V
$I_{0.n}$	1.4176e-10A
a	0.99132
Rs	0.098 ohms
Rp	82.11 ohms
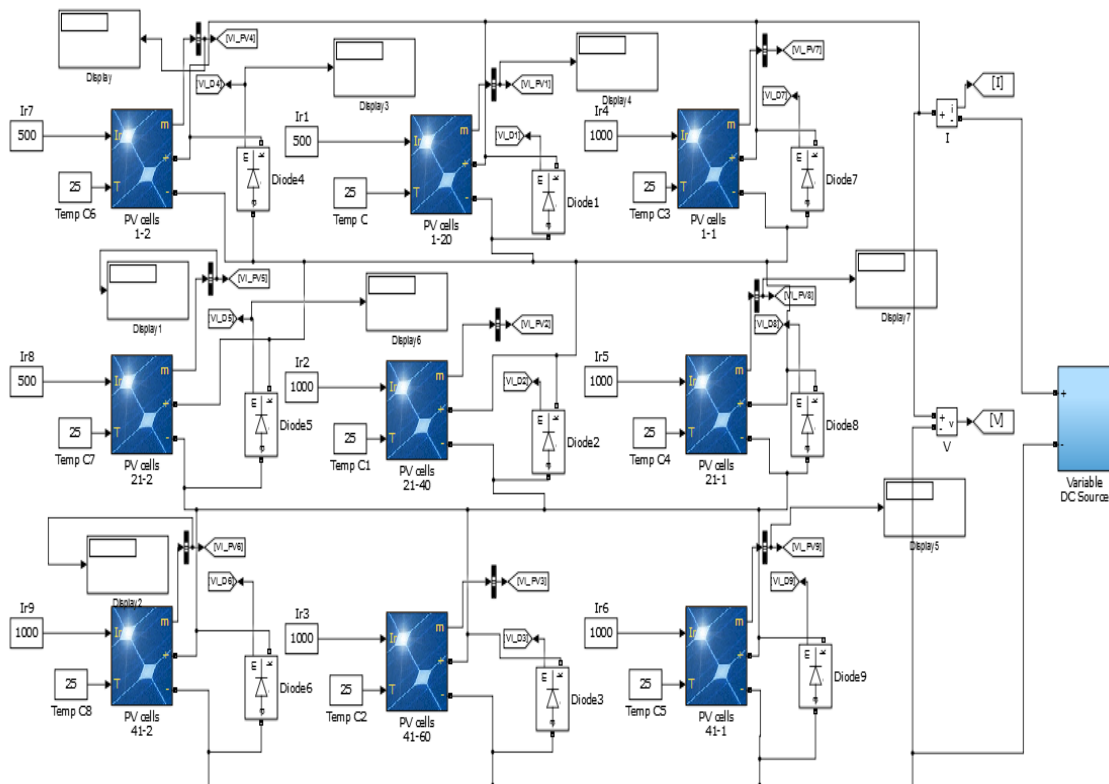
Figure 4.   The simulated PV array matrix.

The simulated system was exposed to different irradiance conditions:

5.1 Uniform Illumination Condition

The simulated PV array system under uniform illumination condition where all modules are exposed to the same irradiance of 1000 w/m². Fig. 5(a) shows the I-V and P-V curve characteristics of the simulated system under uniform illumination condition.
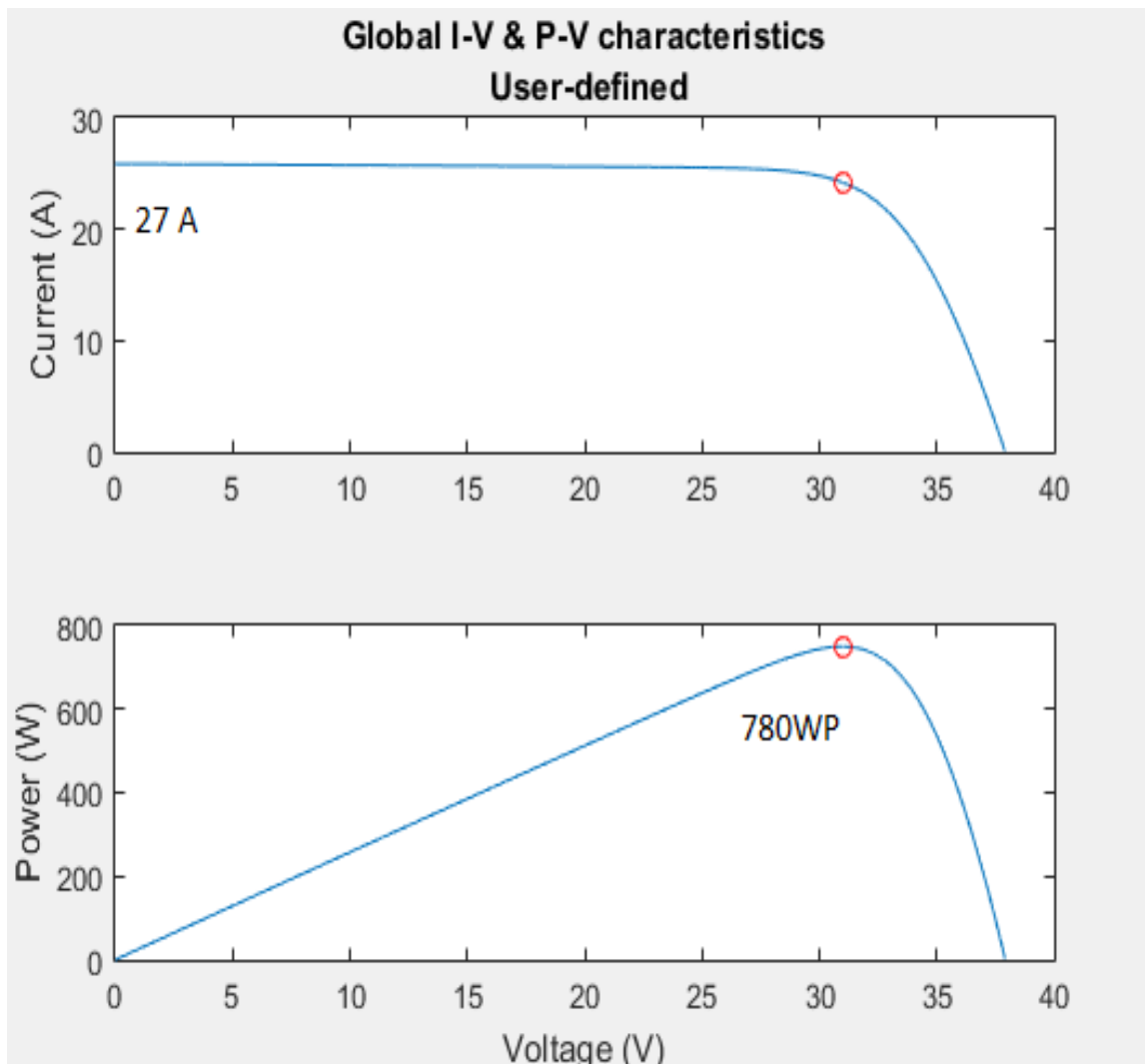
Global I-V & P-V characteristics
User-defined

27 A

780WP

Figure 5 (a). The characteristics of PV matrix under uniform irradiance

5.2 Partial Shading Condition

The influence of the shading on the output power of the PV array is discussed with some simulations. The reference pattern is fully illuminated modules that is an array of 3×3 matrix at irradiance 1000 w/m^2 and temperature of 25ºC. This array of 9 modules with its progressive shading is analyzed. Several simulations are carried out considering that the modules from 0 to 9 are shaded. The percentage of the shaded modules to all modules are 33.33%, *i.e.,* three modules are shaded from the matrix. The shading pattern may occur in different manners in the same column or in different columns. The different cases of shading pattern are simulated, and the results are shown in Fig. 5 (b, c, d).
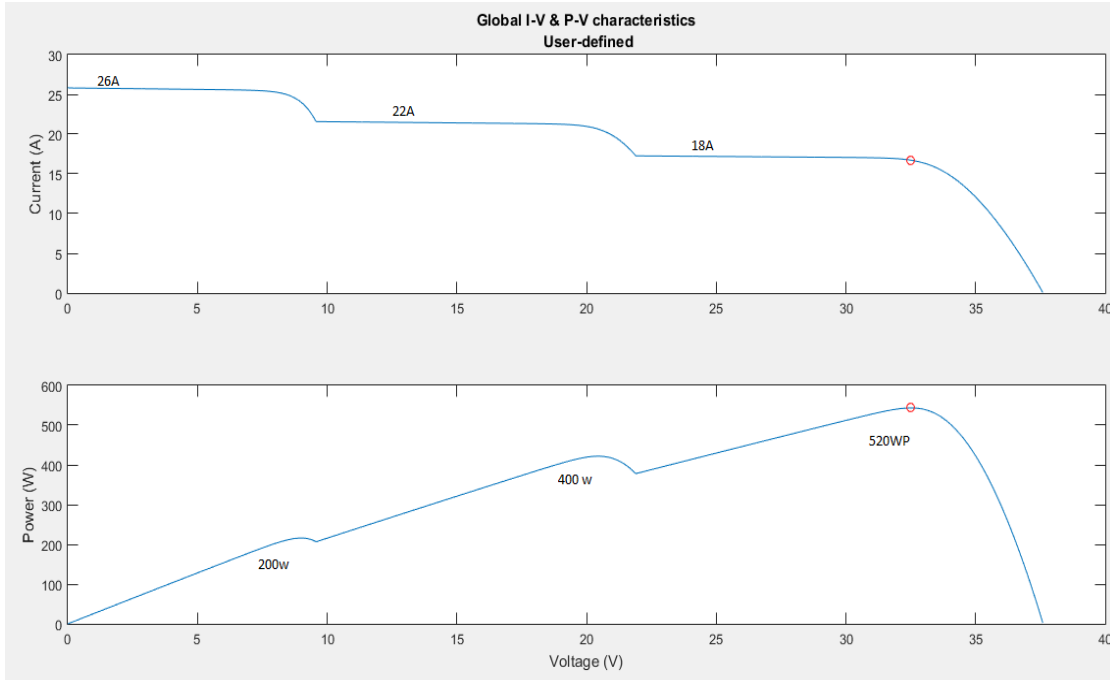
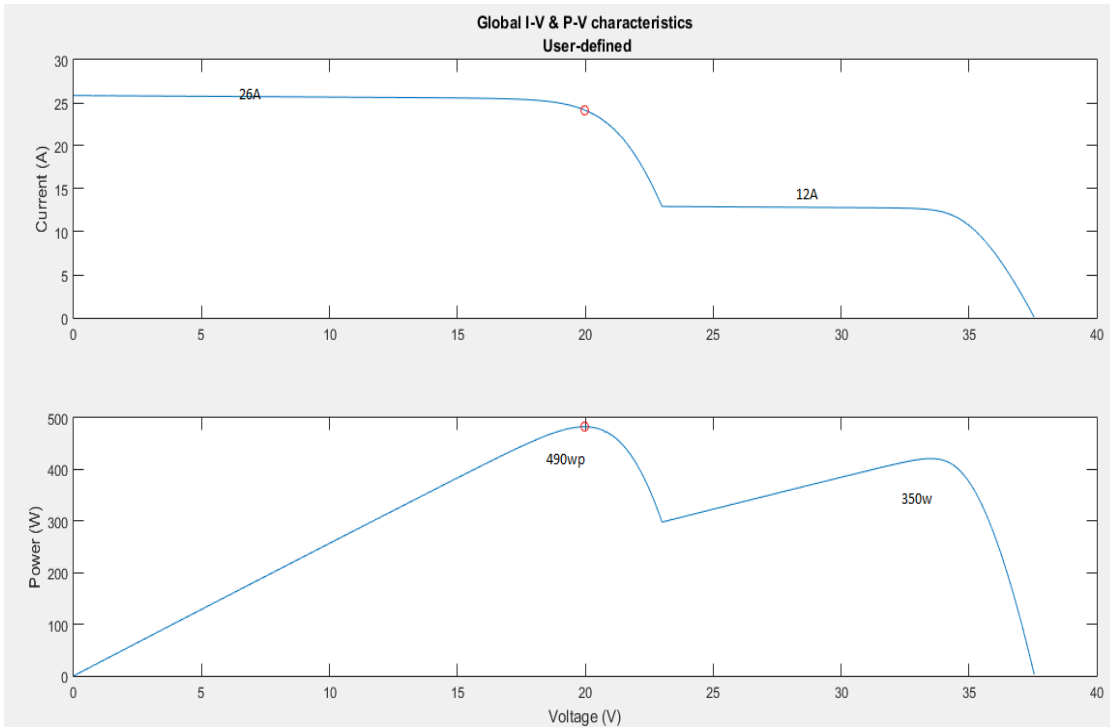**Figure 5 (b).** The characteristics of PV matrix under shading pattern in different columns

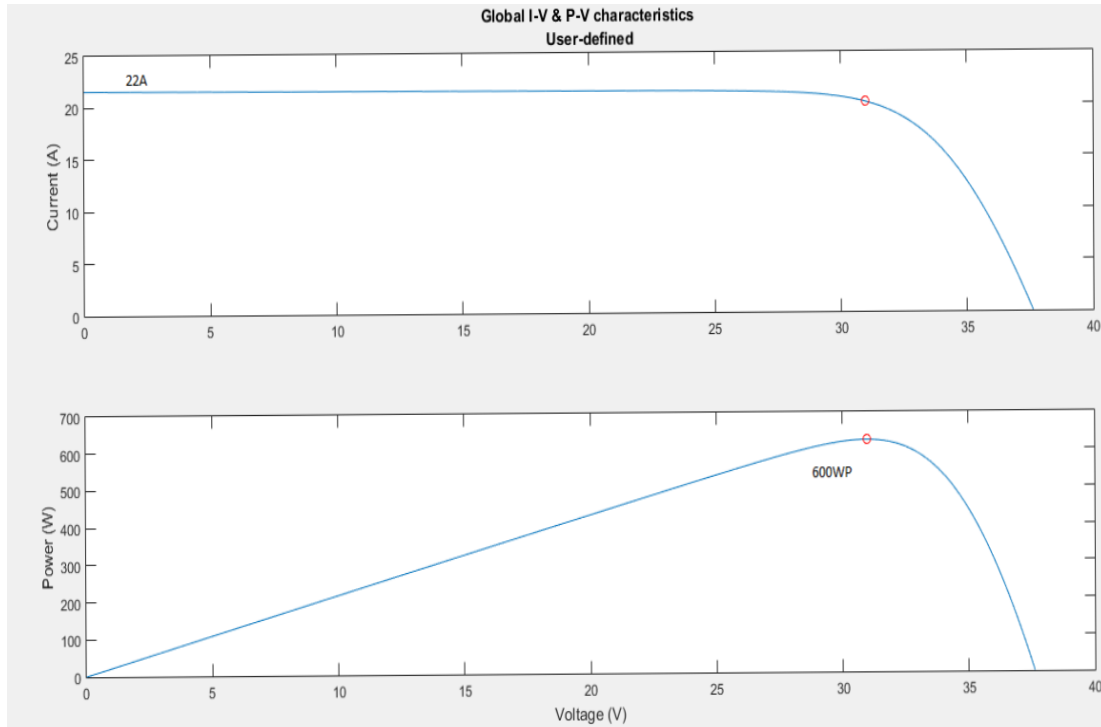**Figure 5 (c).** The characteristics of PV matrix under shading pattern in the same row

Figure 5 (d). The characteristics of PV matrix under shading pattern in the same column

It's shown from the simulation of the PV matrix under different shading pattern cases that the maximum output power occurred, when all shaded modules in the same columns or in minimum numbers of columns. The maximum power (600 Wp) of the shaded modules in the same column is about 13.8 % higher than the maximum power (490 Wp) of the shaded modules in the same row. Table 3 shows the output power for different reconfiguration at different percentages of shading.

Table 3. The output power for different reconfiguration at different percentage of shading

Percentage of shading	Number of the shaded modules	Pout (the shaded modules in the same row)	Pout (the shaded module in the same column)	Pout (the shaded module in different columns)
10%	1	700 Wp	700 Wp	700 Wp
20%	2	580 Wp	650 Wp	650 Wp
30%	3	490 Wp	600 Wp	520 Wp
40%	4	400 WP	500 Wp	500 Wp
50%	5	480 Wp	480 Wp	480 Wp

The simulated system of the proposed unit is shown in Fig. 6(a). The output power of the PV array will increase by 20% of the total output power during fully illumining by using the new technique as shown in Fig. 6 (b).
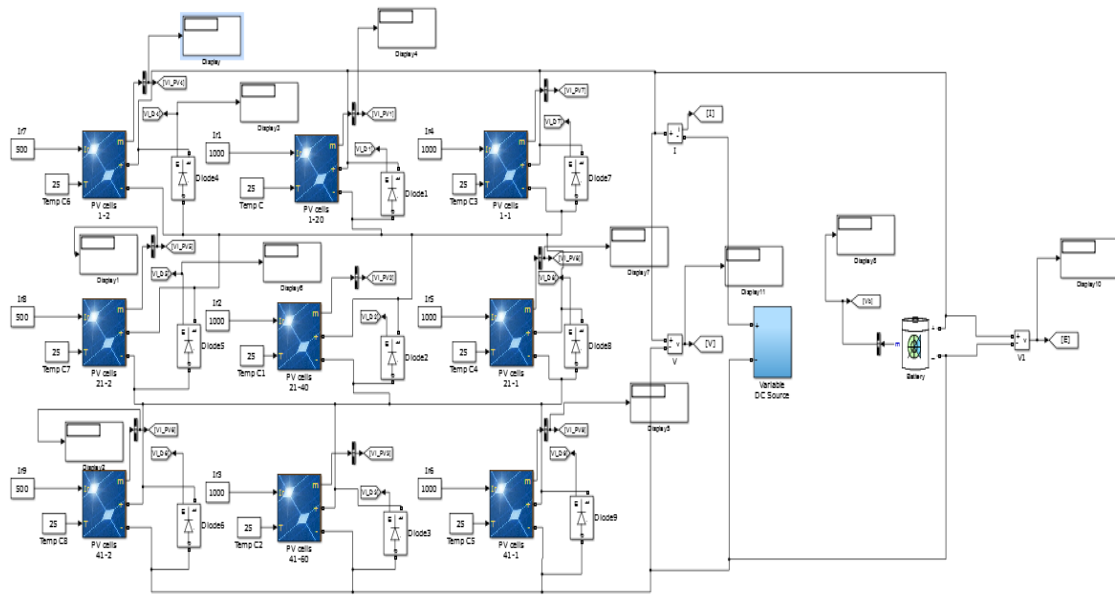
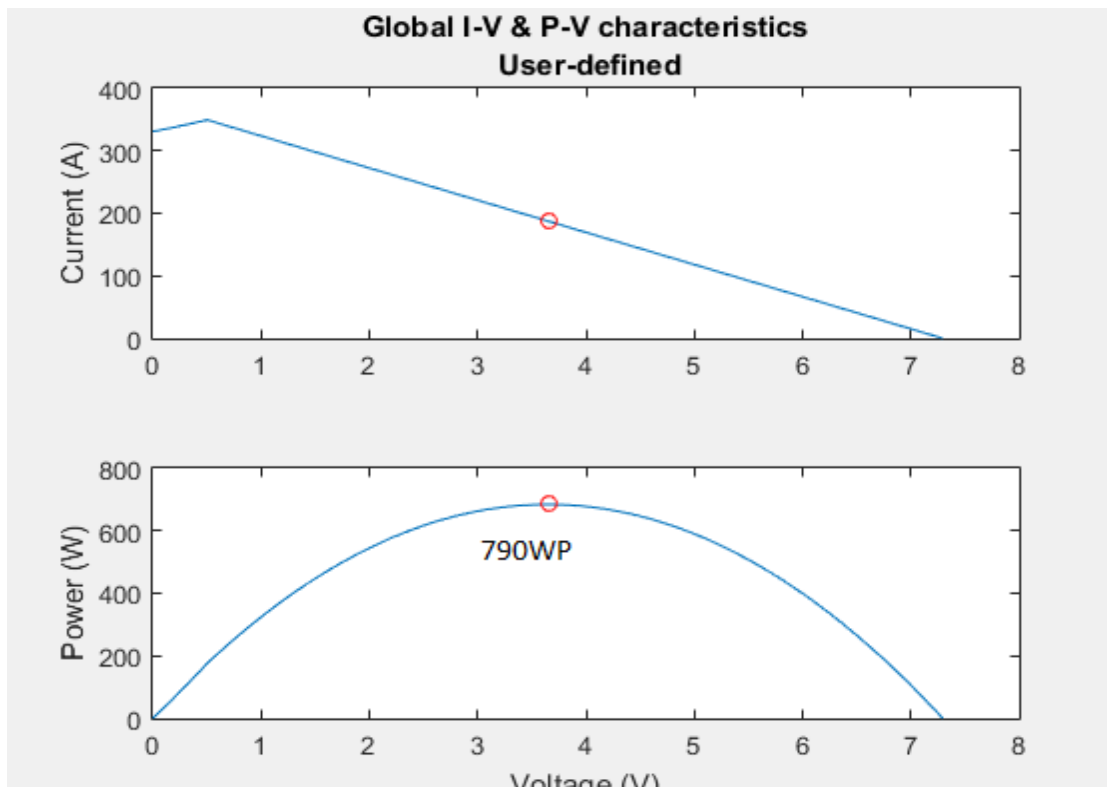**Figure 6 (a).** The proposed unit of PV 3×3 matrix by using a new technique

Figure 6 (b). The characteristic of PV 3×3 matrix by using a new technique

5.3   A Comparison of Power Enhancement of the Proposed Method with Different Existing Methods

There are three existing methods for reconfiguration of the PV array under partial shading conditions. In the literature [8], authors made reconfiguration during the partial shading and substituted the loss of power by using alternative PV modules. But this method isn't an effective approach when the partial shading is due to clouds covering the main and alternative PV modules. The proposed technique in this paper used a storage device (a battery) to substitute the loss that occurs during the partial shading condition and also minimize the loss during partial shading. In the literature [9], authors made reconfiguration by a complex method and didn't substitute the loss of the power. In the literature [13], authors maximized the output power of the PV array by using a battery, but the output of the PV array has multiple power peaks that cause problem for MPPT. In this paper, the output waveform has a unique MPP.

6. Conclusions

In this paper, a novel strategy for reconfiguration of the PV array under partial shading conditions is presented. This new strategy increases the output power during the partial shading by 13.8%, prevents producing multiple MPPs, and solves the problems of tracking the MPP during the partial shading. A new technique with using a lead acid battery is presented to increase the output power of the PV under shading condition by 20%, which is similar to the output power of the array under fully illumining condition. The paper simulated the PV array with different shading parameters to optimize the output power during partial shading.

CONFLICTS OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this paper.

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Appendix

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 4 -    m=input('Enter the number of rows')
 5 -    n=input('Enter the number of columns')
 6 -    ipvmin=input('Enter the minimum PV array current under unform irradiation')
 7 -    pvconfiguration=ones(m,n);
 8 -    k1=m*n;
 9 - □for i=1:m
10 - □   for j=1:n
11 -         i;
12 -         j;
13
14 -         if (i==2)
15 -             k0=3;
16 -         else
17 -             k0=0;
18 -         end
19 -         ipv_min(i,j)=ipvmin;
20 -         i_b=input('Enter the measured value of the current transormer');
21 -         ib(i,j)=i_b;
22 -         if ib(i,j)<ipv_min(i,j);
23 -             k=(k0+j);
24 -             Pvnewconfiguration (i,j)=0;
25 -         else
26 -             pvnewconfiguration (i,j)=1;
27 -             end
28 -       end
29 - └end
30
31 -    pvnewnconfiguration=find(pvnewconfiguration==0);
32 -    if k==n
33 -        pvnewconfiguration(pvnewnconfiguration)=1;
34 -    end
```