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A new maximum power point tracking strategy for PV arrays under uniform and non-uniform insolation conditions

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Abstract

This paper presents a new maximum power point tracking method based on the current–voltage characteristic of photovoltaic arrays. The new approach is not only capable to track the maximum power point like the conventional methods under uniform insolation conditions, but also capable to find the global maximum power point efficiently and rapidly under partially shaded conditions. The proposed algorithm could find a new MPP quickly when a sudden change occurs in the insolation level. To verify the performance of the proposed method, several simulations have been carried out in MATLAB/Simulink environment. Experimental investigations have also been performed to confirm the validity of simulation results.

Keywords: PV array configuration; Uniform isolation condition; Non-uniform insolation condition; Partial shading condition; Maximum power point tracking; PV array characteristics

1. Introduction

Nowadays, demand for renewable energy is rapidly growing and undoubtedly, solar energy plays an important role towards achieving long lasting, sustainable, environment friendly renewable energy resource to fulfill the energy needs for mankind. A Photovoltaic source has several advantages as an electrical source such as low maintenance cost, no need for fuel, pollution free, and contributes to grid decentralization. But low conversion efficiency, nonlinear characteristics of PV arrays, and dependency on irradiation level, and temperature has made some difficulties to extract the maximum power from them. Over the past decades, many papers have focused on finding optimum maximum power point (MPP) for PV arrays (Esram and Chapman, 2007; Salas et al., 2006; Hohm and Ropp, 2000; Xiao and Dunford, 2004; Sera et al., 2008; Mutoh et al., 2006; Tafticht et al., 2008; Larbes et al., 2009). Among the proposed methods, some of them have focused on the study of sudden changes in irradiation level (Sera et al., 2008; Mutoh et al., 2006; Tafticht et al., 2008; Larbes et al., 2009). The difference of these algorithms is related to their performance, convergence speed and hardware complexity. The well-known MPPT methods are Perturbation and Observation (P&O), Hill climbing (HC), and Incremental Conductance (InC) method (Esram and Chapman, 2007; Salas et al., 2006; Hohm and Ropp, 2000; Xiao and Dunford, 2004; Sera et al., 2008). These methods, however, fail to track MPP when the insolation condition is not uniform for all modules and have been partially shaded. In this condition, the shaded modules (those receive low irradiation level in comparison with the rest modules) consume part of the generated power and behave as load (Ji et al., 2011; Shimizu et al., 2001; Karatepe et al., 2007). This condition reduces the total power generation and may cause hot spot problem. To protect modules from hot spot

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Nomenclature

a	diode ideality constant
G	irradiation level in W/m^2
G_n	nominal irradiation level (in 1000 W/m^2)
G_{sub1}	irradiation level in subassembly$_1$
G_{sub2}	irradiation level in subassembly$_2$
G_{sub3}	irradiation level in subassembly$_3$
I_A	PV array current
I_C	array current when the array voltage is a little perturbed around the MPP
I_{MPP}	current of maximum power point
$I_{sc,n}$	nominal short circuit current of a module
I_{PV}	photovoltaic current
I_0	PV array saturation current
K_I	short circuit current coefficient
K_V	open circuit voltage coefficient
l_s	number of series modules in subassembly$_3$
m_s	number of series modules in subassembly$_2$
m_{s_i}	number of series connected shaded modules in the ith group
N_p	number of parallel strings
n_{pi}	number of parallel strings in the ith group
N_S	number of series modules
n_s	number of series modules in subassembly$_1$
R_p	parallel resistance
R_s	series resistance
V	PV array voltage
V_d	diode forward voltage
V_{MPP}	voltage of maximum power point
V_{shaded_i}	voltage of a single shaded module in a group
$V_{oc,n}$	nominal open circuit voltage of a module
V_{sub1}	subassembly$_1$ voltage
V_{sub2}	subassembly$_2$ voltage
V_t	array thermal voltage
V_1	voltage of one module in subassembly$_1$
V_2	voltage of one module in subassembly$_2$
ΔI_{ps}	current variation around the peak point under partially shaded condition
ΔI_u	current variation around the peak point under uniform insolation condition
$\Delta I/I_C$	normalized current variation around the peak point
$(\Delta I/I_C)_{\mathrm{ref}}$	reference value of $\Delta I/I_C$ at $G = 1$ kW/m^2
T_n	nominal temperature (298 K)
ΔT	variation from the nominal temperature

problem, a bypass diode is connected in parallel with each PV module. But, P–V curve with multiple peak points is the result of bypass diodes in partially shaded conditions. Moreover, the I–V characteristic equation of PV array is no longer valid. For partially shaded conditions, (Ahmed et al., 2013) has derived a mathematical equation to describe the I–V characteristic of PV arrays. CHun et al. (2010) has categorized the MPPT methods which are applicable under non-uniform insolation conditions into two groups: software based algorithms (Ji et al., 2011; Patel and Agarwal, 2008; Syafaruddin et al., 2012, 2009; Nguyen and Low, 2010; Renaudineau et al., 2011; Kobayashi et al., 2006; Salam et al., 2012; Balaji et al., 2012; Carannante et al., 2009) and hardware based algorithms (Shimizu et al., 2003, 2001).

The software based methods track the global peak among the multiple peaks during partially shaded conditions. In Ji et al. (2011), the proposed approach is based on the movement of the operating point by a linear function around the entire P–V curve; then, the conventional MPPT is used to track the global peak. (Patel and Agarwal, 2008) has proposed a two-stage method based on P&O algorithm to track the global peak point. It finds global peak among the local peaks without scanning the entire of P–V curve. However, it fails to track MPP when the difference between the irradiation level of the shaded modules and non-shaded modules is large and the number of shaded modules is more than non-shaded modules. Since the artificial neural network (ANN) is successfully compatible with optimization problem of PV systems, some researchers have employed ANN to find the global peak point among the local peak points (Syafaruddin et al., 2012, 2009). The proposed method in Syafaruddin et al. (2012) is based on "radial basis function neural network" which has been recognized by its fast training process. The proposed ANN method in Syafaruddin et al. (2009) has acceptable performance under uniform and non-uniform insolation conditions and negligible error of voltage and power references, but the accuracy of outputs depends directly on the number of inputs. In addition, the ANN has to be restructured and retrained when the configuration of PV array changes.

Nguyen and Low (2010) has proposed global maximum power point tracking based on the direct search algorithm. The proposed two-stage MPPT algorithm in Renaudineau et al. (2011) and Kobayashi et al. (2006) have tried to find the global peak through adjusting the load line. Salam et al. (2012) has proposed a method based on the Particle Swarm Optimization (PSO) which mitigates some drawbacks of the conventional PSO such as difficulty in real-time implementation and oscillation around the maximum power point. Among the vast variety of the software based methods, Fibonacci search algorithm is commonly used as a MPPT method. However, it fails to track MPP during partially shaded conditions and needs a powerful processor. Balaji et al. (2012) has modified the Fibonacci search algorithm to find the MPP under partially shaded conditions.

Unlike the software base methods, hardware based algorithms try to avoid the multi-peaking effects of the bypass diodes in non-uniform insolation conditions (Shimizu et al., 2003, 2001). In Shimizu et al. (2003), the P–V curve has only one MPP by choosing an optimum combination of off duty ratios when partially shaded conditions occur. But that topology is economically viable only for a limited number of modules, since it uses an additional switch for each module.

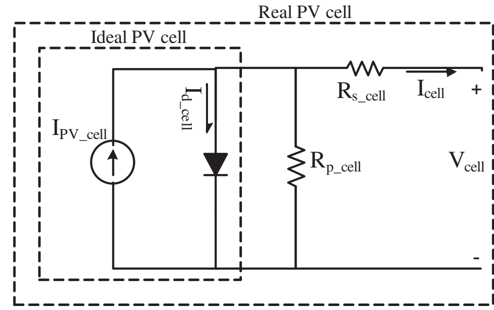
The challenge of tracking MPP in partially shaded conditions has also been evaluated by finding appropriate configurations for PV arrays. In order to determine which configuration is less susceptible to non-uniform effects, Karatepe et al. (2007) has investigated three configurations: Series-Parallel (SP), Bridge Link (BL) and Total Cross Tied (TCT) connection. To make a fair comparison among the various configurations, several partial shading scenarios have been evaluated in Karatepe et al. (2007). The study shows that if a configuration could provide more current paths for non-shaded modules, higher output power can be achieved. Therefore, the TCT connection is preferable to other configurations because of providing more current paths in the structure. In addition to previous connections, Wang and Hsu (2011) has proposed another configuration for PV arrays and has derived an analytical model for evaluation of different cell connections. The efficiency of different configurations with the most commonly used hill climbing technique has been investigated in Karatepe et al. (2009). Although, the proposed system based on TCT connection cannot track the global peak point in some shading patterns, it can reduce the negative effect of mismatching problem. In addition to these references, Picault et al. (2012) has compared four common PV array configurations and proposed a guideline (based on the appropriate PV array configuration) for maximum power point tracking in partially shaded conditions.

This paper proposes a new software based MPPT method which works correctly in both uniform and non-uniform insolation conditions. The proposed method employs an analytic condition for quick determination of partially shaded conditions from normal conditions. The reminder of this paper is organized as follows. Section 2 studies the behavior of a PV array under uniform and partially shaded conditions. Section 3 introduces an analytical condition for identifying partially shaded conditions. Using the proposed analytical condition a new MPPT algorithm is introduced in Section 4. In Section 5, simulation results are presented to evaluate the performance of the proposed algorithm; and it will be confirmed by experimental results in Section 6. Finally, the conclusions are summarized in Section 7.

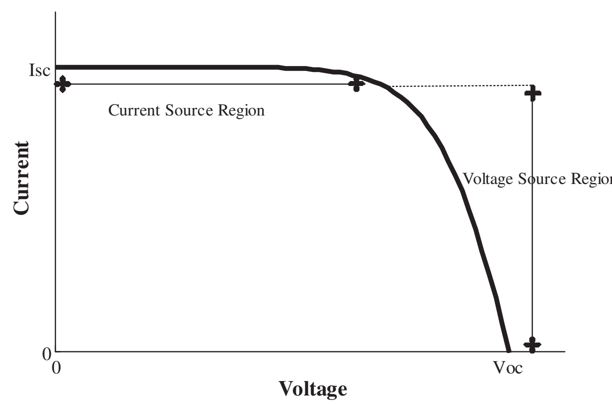
2. Analytical observation of PV array under uniform and non-uniform insolation conditions

2.1. Nonlinear characteristic of PV arrays under uniform insolation conditions

The I–V characteristic of a PV array can be extracted using the single-diode model of a PV cell which has been shown in Fig. 1a, (Villalva et al., 2009):



(a)



(b)

Fig. 1. Single-diode model of a PV cell. (a) Block diagram of PV cell and (b) I–V curve of PV cell.

$$I_A = I_{PV} - I_0\left[\exp\left(\frac{V + (N_s/N_P)R_sI}{aN_sV_t}\right) - 1\right] - \frac{V + (N_s/N_P)R_sI}{(N_s/N_P)R_p} \tag{1}$$

where I_A is the array output current, V is the array output voltage, R_s is the equivalent series resistance of the array and R_p is the equivalent parallel resistance. N_s is the number of series modules and N_P is the number of parallel strings. I_{PV} is the photovoltaic current of the array, I_0 is the saturation current, and a is the diode ideality constant. I_{PV} and I_0 are expressed as (Villalva et al., 2009):

$$I_0 = N_P\frac{I_{sc,n} + K_I\Delta T}{\exp\left(\frac{N_s(V_{oc,n}+K_V\Delta T)}{aN_sV_t}\right) - 1} \tag{2}$$

$$I_{PV} = N_P(I_{sc,n} + K_I\Delta T)\frac{G}{G_n} \tag{3}$$

where K_V and K_I are the voltage coefficient and the current coefficient, respectively. $I_{sc,n}$ is the short circuit current and $V_{oc,n}$ is the open circuit voltage of PV module in standard test condition (STC). G is the irradiation level in W/m^2 and G_n is the nominal irradiation level in 1 kW/m^2.

Hereafter in this paper, the effect of series and shunt resistances are neglected (Mutoh et al., 2006). This assumption is necessary to find an analytical condition for determining partially shaded conditions. Using this assumption, the PV array is assumed to be ideal. However, the validity of analytic condition will be confirmed by several simulations and experiments for non-ideal PV arrays.

2.2. Nonlinear characteristic of PV arrays under partially shaded conditions

As it was mentioned before, in partially shaded conditions, those modules which receive a lower amount of irradiation face hot spot problem. To protect these modules, bypass diodes are employed in parallel with each PV module. Although the bypass diodes solve the hot spot problem, they cause complexity in the array P–V characteristic. In this case, the P–V curve will have several peak points under non-uniform insolation conditions.

According to Patel and Agarwal (2008), a PV array consists of several groups, where a group is composed of several strings with identical P–V characteristics. Each string itself is made of several subassemblies, which have similar irradiation levels. For example, Fig. 2a demonstrates a PV array consisting of n groups, where the ith group consists of n_{pi} parallel strings and three subassemblies. In order to obtain the characteristic equation for a PV array under partially shaded conditions, first the characteristic equation of an arbitrary group, e.g. the ith group in Fig. 2a is calculated.

Assuming the irradiation level of subassembly$_3$ (in Fig. 2a) is lower than subassembly$_2$ and irradiation level of subassembly$_2$ is lower than subassembly$_1$, the corresponding I–V curves for these subassemblies are derived and shown in Fig. 2b. According to the demonstrated I–V curves in Fig. 2b, three different regions are recognized. Depending on the operating region, the characteristic equation for these regions is derived as follows:

Region 1): Group current is higher than I_{sc2}. In this region, the bypass diodes in subassembly 2 and 3 will be forward biased and the characteristic equation will be determined by subassembly$_1$ as follows:

$$V = n_s V_1 - (m_s + l_s) \times V_d \quad I_{sc2} < I_{ithgroup} < I_{sc1} \tag{4}$$

where n_s represents the number of series modules in subassembly$_1$, m_s is the number of series modules in subassembly$_2$, and l_s is the number of series modules in subassembly$_3$, according to Fig. 2a.

Noting to Eq. (4), the group current is derived as:

$$I_{ithgroup} = n_{p_i} \frac{G_{sub1}}{G_n} (I_{sc,n} + K_I \Delta T) - \frac{n_{p_i}(I_{sc,n} + K_I \Delta T)}{\exp\left(\frac{(V_{oc,n} + K_V \Delta T)}{aV_t}\right) - 1} \left[\exp\left(\frac{V}{aV_t}\right) - 1\right] \tag{5}$$

where G_{sub1} is the irradiation level of subassembly$_1$.

Region 2): Group current is between I_{sc1} and I_{sc2}. Similar to above analysis, the array voltage is derived as:

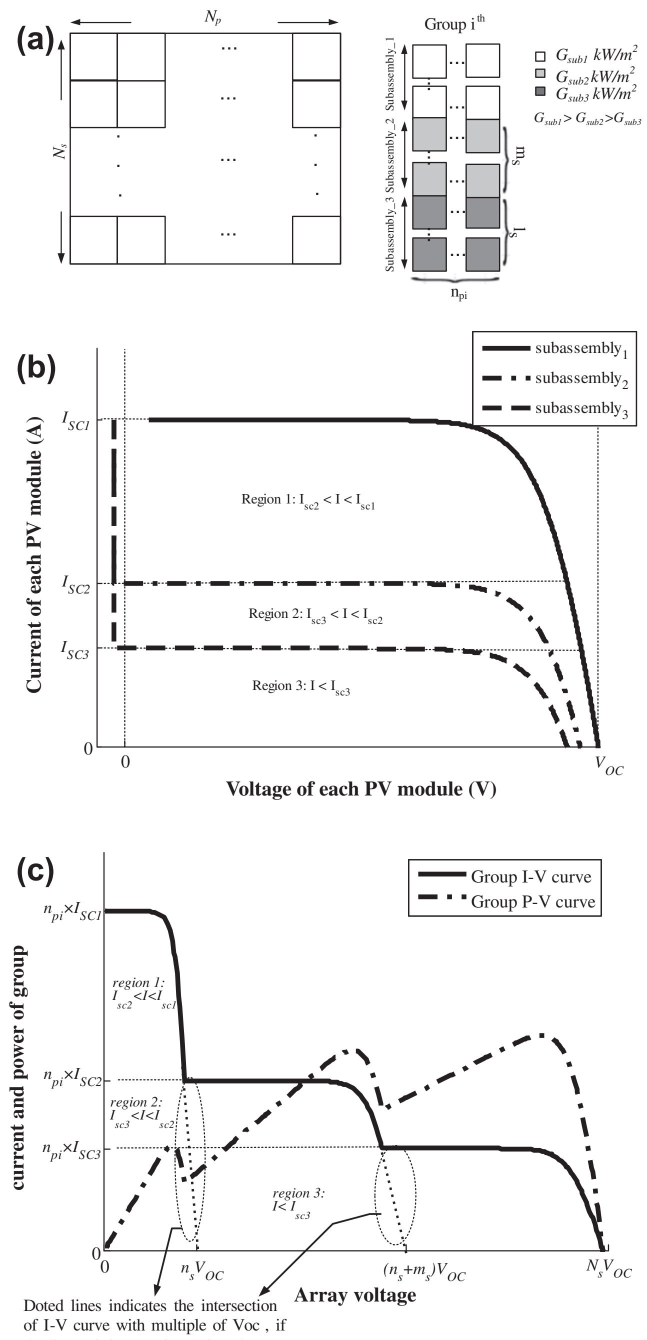


Fig. 2. Derivation of characteristic equation for a group of modules under partially shaded conditions. (a) Sample PV array, (b) corresponding I–V curves of the subassemblies in the ith group and (c) corresponding group I–V and P–V curves.

$$V \cong V_{sub1} + m_s V_2 - l_s \times V_d \qquad I_{sc3} < I_{ithgroup} < I_{sc2} \tag{6}$$

where V_{sub1} (subassembly$_1$ voltage) is approximately equal to $n_s V_{oc}$ (the open circuit voltage of subassembly$_1$) according to Villalva et al. (2009). V_2 is the voltage of one module in subassembly$_2$.

In region 2, the group current can be derived from Eq. (5), by replacing G_{sub2} with G_{sub1}.

Region 3): Group current is lower than I_{sc3}. The corresponding array voltage will be:

$$V \cong V_{sub1} + V_{sub2} + l_s \times V_3 \qquad I_{ithgroup} < I_{sc2} \tag{7}$$

where V_{sub2} (subassembly$_2$ voltage) is equal approximately to $m_s V_{oc}$ and V_{sub1} is $n_s V_{oc}$.

After derivation of characteristic equation for an arbitrary group, the characteristic equation for a PV array under partially shaded condition can be derived as follows:

$$I_A = \sum_{i=1}^{k} n_{p_i} \frac{G_i}{G_n}(I_{sc,n} + K_I \Delta T) - \frac{n_{p_i}(I_{sc,n} + K_I \Delta T)}{\exp\left(\frac{(V_{oc,n}+K_V \Delta T)}{aV_t}\right) - 1}\left[\exp\left(\frac{V}{aV_t}\right) - 1\right] \tag{8}$$

where G_i corresponds to the irradiation level of *i*th group.

Investigation of demonstrated *P–V* curves in Fig. 2c shows that there are three peak points on the studied group *P–V* curve, and the location of peak points can be determined from Eqs. (4), (6), and (7). In brief, it can be said that:

(1) In uniform insolation conditions, the corresponding voltage and current of the MPP are approximately $0.8N_s V_{oc}$ and $0.85N_p I_{sc}$, respectively (Esram and Chapman, 2007; Salas et al., 2006; Hohm and Ropp, 2000; Xiao and Dunford, 2004; Sera et al., 2008).

(2) In partially shaded condition, if the operating point is in *region* 1 and subassembly$_1$ works close to MPP, the array voltage will become:

$$V_{\max 1} = 0.8 n_s V_{oc} - (m_s + l_s)\ V_d \tag{9}$$

(3) If the operating point is in *region* 2 and subassembly$_2$ works near to MPP, the array voltage will be:

$$V_{\max 2} = V_{sub1} + 0.8 m_s V_{oc} - l_s V_d \tag{10}$$

where V_{sub1} can be written as follows according to (Mutoh et al., 2006):

$$V_{sub1} = aV_t \ln\left(1 - 0.85\frac{G_{sub2}}{G_n}\right) + V_{oc,n} \tag{11}$$

where the current of subassembly$_2$ is equal to $0.85 n_{pi}(G_{sub2}/G_n) I_{sc,n}$.

(4) If the operating point is in *region* 3, it is derived:

$$V_{\max 3} = V_{sub1} + V_{sub2} + 0.8 l_s V_{oc} \tag{12}$$

where V_{sub1} and V_{sub2} are calculated as follows:

$$V_{sub1} = aV_t \ln\left(1 - 0.85\frac{G_{sub3}}{G_n}\right) + V_{oc,n} \tag{13}$$

$$V_{sub2} = aV_t \ln\left(\frac{G_{sub2}}{G_n} - 0.85\frac{G_{sub3}}{G_n}\right) + V_{oc,n} \tag{14}$$

According to Eqs. (9)–(14), it is concluded that the corresponding voltage of each peak point in the group *P–V* curve is approximately an integer multiple of $0.8V_{oc}$. This conclusion can be extended for a PV array by considering the number of groups and the subassemblies.

3. Derivation of partially shaded condition

To derive an analytic equation for determination of partially shaded conditions, it is necessary to calculate the amount of current variation around the peak point ($V_{MPP} = 0.8N_s V_{oc}$), in both normal and partially shaded conditions.

In normal conditions, two current samples are used which are the current of maximum power point, i.e. I_{MPP}, and the PV current at which the array voltage is a little perturbed around the MPP, i.e. I_C. I_{MPP} and I_C can be derived by Eqs. (15) and (16) as follows.

$$I_{MPP} = I_{PV} - I_0\left[\exp\left(\frac{V_{MPP}}{aN_s V_t}\right) - 1\right] \tag{15}$$

$$I_C = I_{PV} - I_0\left[\exp\left(\frac{V_{MPP} + \Delta V}{aN_s V_t}\right) - 1\right] \tag{16}$$

Hence, the amount of current variation around the peak point under uniform insolation conditions can be formulated as follows:

$$\Delta I_u = I_0 \exp\left(\frac{V_{MPP}}{aN_s V_t}\right)\left[\exp(\frac{\Delta V}{aN_s V_t}) - 1\right] \tag{17}$$

where subscript *u* stands for "uniform".

As it was stated in Section 2, the conventional characteristic equation of the PV array cannot be used in partially shaded conditions. So, to calculate the current variation in these conditions, it is assumed that there are at most two subassemblies in each shaded group. Therefore, the voltage of shaded module in the *i*th group can be derived as follows when the array operating point is close to $0.8N_s V_{oc}$:

$$0.8N_s V_{oc} \cong m_{s_i} V_{shaded_i} + (N_s - m_{s_i})V_{oc} \rightarrow\ V_{shaded_i} \cong \frac{m_{s_i} - 0.2N_s}{m_{s_i}} V_{oc} \tag{18}$$

where m_{s_i} is the number of shaded modules and V_{shaded_i} is the voltage of a single shaded module in the *i*th group.

Now, the current variation of the *i*th group can be derived with respect to Eq. (18) and considering a little perturbation around V_{shaded_i} as follows:

$$\Delta I_{ps_i} = n_{p_i} I_0 \exp\left(\frac{V_{shaded_i}}{aV_t}\right)\left[\exp(\frac{\Delta V}{a\ m_{s_i} V_t}) - 1\right] \tag{19}$$

where subscript *ps* stands for "Partial Shading". Extending Eq. (19) to the PV array, leads to:

$$\Delta I_{ps} = \sum_{i=1}^{n} I_{0_i} \exp\left(\frac{V_{shaded_i}}{aV_t}\right)\left[\exp(\frac{\Delta V}{a\ m_{s_i} V_t}) - 1\right] \quad (20)$$

Comparing both ΔI_{ps} and ΔI_u, results in:

$$\left(\frac{\Delta I}{I_C}\right)_u > \left(\frac{\Delta I}{I_C}\right)_{ps} \qquad \text{around } V_{Array} = 0.8 N_s V_{oc} \quad (21)$$

This inequality shows that the normalized current variation of an array which works in uniform insolation condition is higher than the condition in which the insolation condition is partially shaded (when the array voltage is close to V_{MPP}). To evaluate the validity of Eq. (21), the sample PV array in Fig. 3a is considered and the corresponding I–V curves at different insolation conditions are derived and demonstrated in Fig. 3b and c. The normalized current variation for both uniform and partially shaded conditions are calculated and listed in Table 1. As it is seen in Table 1, the minimum normalized current variation in uniform insolation condition correspond to the maximum irradiation level, i.e. 1 kW/m^2. Furthermore, the normalized current variation in partially shaded conditions is always lower than all scenarios in uniform insolation conditions; even the irradiation level is 1 kW/m^2.

The main result of this study is that the behavior of a partially shaded array at the operating points close to $0.8N_sV_{oc}$ is similar to an array which works in current source region. Therefore, the normalized current variation will be much smaller than the case in which the array works in uniform insolation conditions.

4. Proposed MPPT algorithm for both uniform and non-uniform insolation conditions

The flowchart of the proposed MPPT algorithm is shown in Fig. 4. The algorithm works based on Eq. (21) where it compares $\Delta I/I_C$ at the operating point $0.8N_sV_{oc}$ with the reference value $(\Delta I/I_C)_{ref}$ calculated at uniform insolation condition with $G = 1$ kW/m^2. According to the previous results, if the measured $\Delta I/I_C$ is higher than $(\Delta I/I_C)_{ref}$ it means that the insolation condition is uniform; otherwise it means that the insolation condition is partially shaded. If a partially shaded condition is recognized, the algorithm will immediately sample from the array voltage and current in the integer multiples of $0.8V_{oc}$ to find the location of global peak. Then, it tracks the global peak using the hill climbing algorithm.

A sudden change in the insolation level (or happening a partial shading condition) leads to variation of generated power. If the variation of power is higher than ΔP_{crit} (which has been described in Patel and Agarwal (2008)), it means that the insolation condition has changed and the algorithm must start its work again.

As it is seen from the flowchart, the principle operation of the proposed algorithm depends on two parameters: the module open circuit voltage V_{oc} and the number of series modules N_s. By knowing one of these two parameters, the other one can be determined. For example, if the value of open circuit voltage is known for a module, then the number of series modules can be obtained by dividing the array open circuit voltage into V_{oc}.

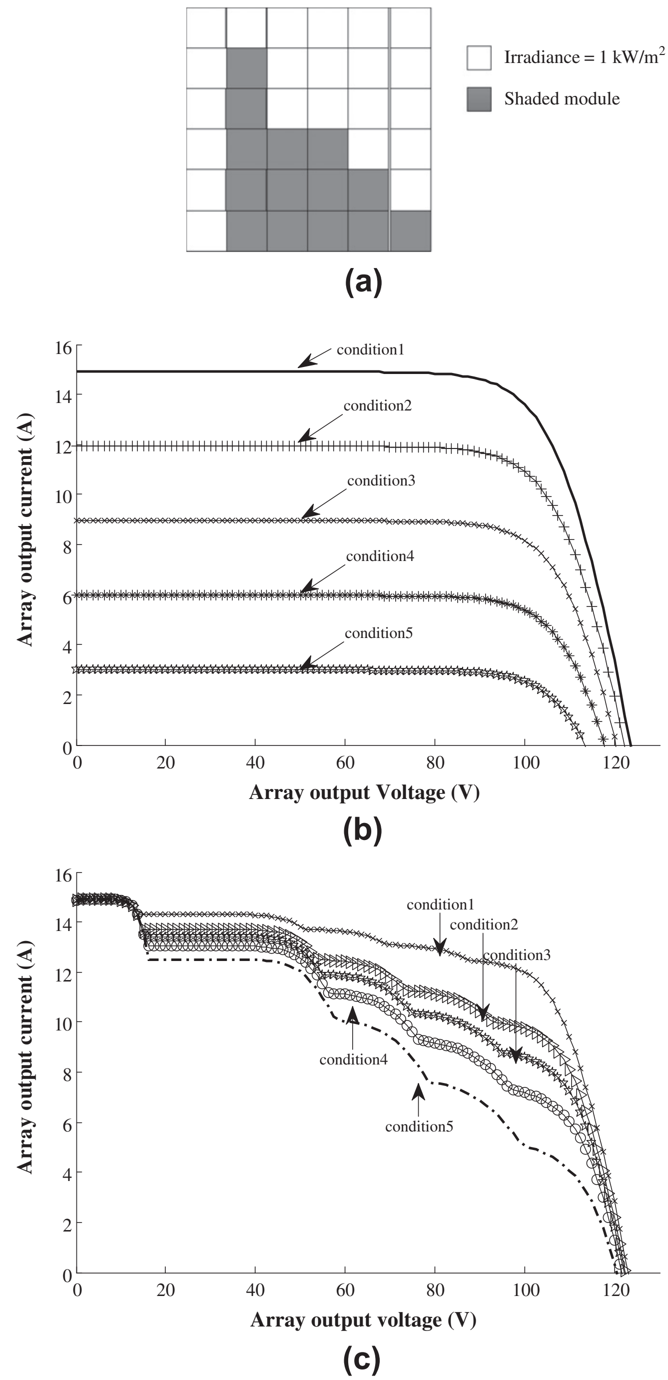


Fig. 3. Evaluating the validity of Eq. (21). (a) Sample PV array for the study. (b) Corresponding I–V curves under uniform insolation conditions. (c) Corresponding I–V curves under partially shaded conditions at five different insolation levels.

In order to consider the effect of temperature variations on the proposed algorithm, it is necessary to update the array open circuit voltage periodically. This is automatically done by sampling the array temperature each 10 min and updating V_{oc} by the following equation:

Table 1
Normalized PV array current for uniform and partially shaded conditions.

	Uniform insolation condition					Non-uniform insolation condition				
	Cond.1 (1 kW/m^2) = ΔI_u	Cond.2 (0.8 kW/m^2)	Cond.3 (0.6 kW/m^2)	Cond.4 (0.4 kW/m^2)	Cond.5 (0.2 kW/m^2)	Cond.1	Cond.2	Cond.3	Cond.4	Cond.5
$\Delta I/I_C$	0.265	0.27	0.3	0.4	0.88	0.21	0.15	0.14	0.15	0.23

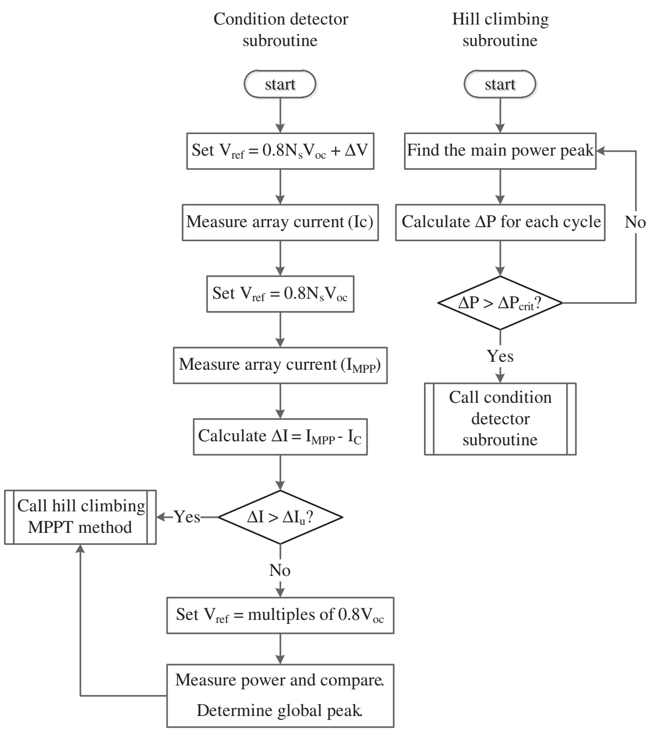


Fig. 4. Flowchart of the proposed algorithm.

$$V_{oc} = V_{oc,n} + K_V \Delta T \tag{22}$$

5. Simulation results

The validity of the proposed MPPT algorithm is verified by several simulations in MATLAB/Simulink environment. For these simulations, demonstrated structure in Fig. 2a with the TCT connection of PV modules is utilized. In addition, the series and shunt resistances of PV modules are considered to confirm the validity of Eq. (21). The utilized module parameters are listed in Table 2, where each PV module has only one bypass diode. The simulations first evaluate the performance of new method at different insolation conditions. Then, new method is compared with the hill climbing method and with the proposed method in Patel and Agarwal (2008).

In the first section of simulation, it is assumed that the insolation condition is uniform for all modules, and the irradiation level is 1 kW/m^2. Then at $t = 0.2$ s, the irradiation level reduces to 0.38 kW/m^2 in a stepwise manner. During the time interval of (0.35–0.5 s), a partially shaded condition similar to shading pattern in Fig. 2a happens for the PV array. The simulation results are shown in Fig. 5 which demonstrates the array power, the array voltage and the array current versus time, in the proposed approach. In addition, the corresponding $P–V$ curve of the array under pre-defined shading pattern is extracted and demonstrated in Fig. 7 as black curve.

Table 2
PV module parameters.

P_{MPP}	46 W
I_{MPP}	2.76 A
V_{MPP}	16.3 V
I_{SC}	2.98 A
V_{OC}	20.5 V
V_d [a]	0.8 V

[a] Voltage drop of bypass diode.

5.1. Investigation of the proposed method under various insolation conditions

From Fig. 5, it is seen that the proposed method quickly diagnoses any insolation change and finds the new MPP in less than 10 ms. The corresponding steady-state voltage and current of the MPP are 98 V, 13.7 A in the first state, 98 V, 5.36 A in the second state, and 81 V, 9.5 A in the third state. Comparing the maximum peak power in uniform insolation conditions with the predictable values from

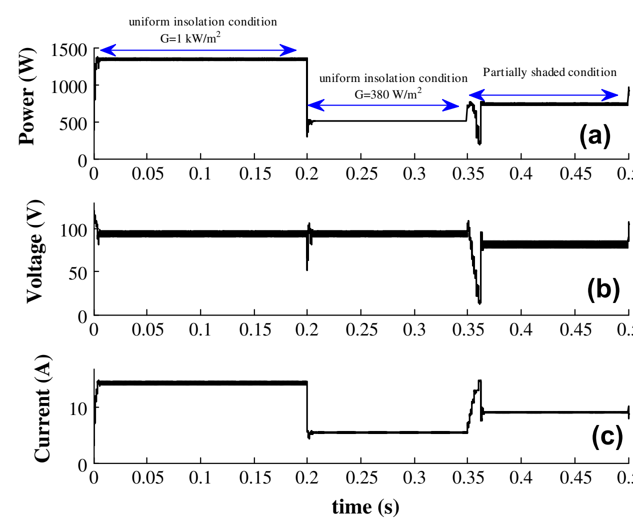


Fig. 5. Investigating the behavior of new MPPT algorithm at different insolation conditions. (a) Array output power, (b) array output voltage and (c) array output current, ($T = 25$ °C and sample time = 0.001 s).

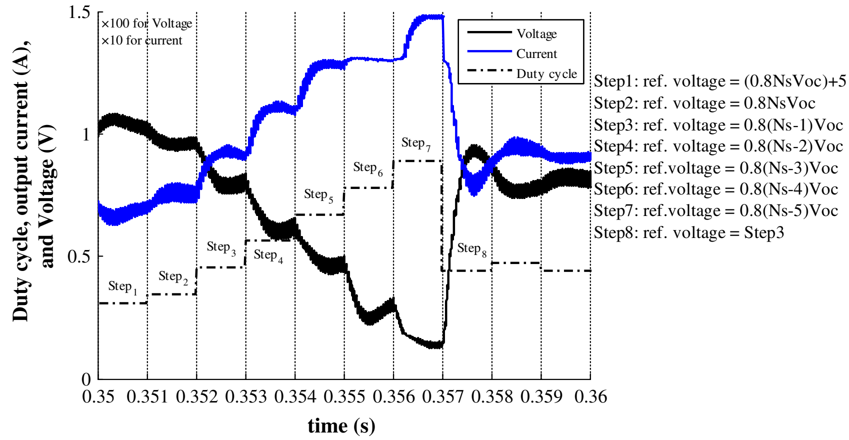


Fig. 6. Investigating the behavior of new MPPT algorithm when the insolation condition changes from uniform to partially shaded state at $t = 0.35$ s (corresponds to the time interval of 0.35 s → 0.36 s in Fig. 5).

Table 2 (which are 1355 W for the first state and 535 W for the second state) confirms a good agreement between the simulation and theoretical results. To verify the third state, one should compare the peak value in Fig. 5 with the peak point in Fig. 7 which demonstrates the $P–V$ curve of the partially shaded array. Comparing these values (766 W in Fig. 5a and 770 W in Fig. 7), confirms the correct behavior of new MPPT algorithm in partially shaded condition.

Fig. 6 investigates the behavior of new MPPT algorithm when the insolation condition changes from uniform to partially shaded state in the previous simulation (during 0.35 s → 0.36 s). As it can be seen from Fig. 6, the algorithm changes the converter duty cycle to bring the operating point into the right hand side of the $P–V$ curve while it has detected a partially shaded condition. Then, the duty cycle is updated by $1–0.8kV_{oc}/V_{out}$ (for $k = 1,2,\ldots,N_s$) to find the global peak point among the local peaks. In brief, steps 1 and 2 are used to determine the status of insolation condition and steps 2 to 8 are used to find the global peak point.

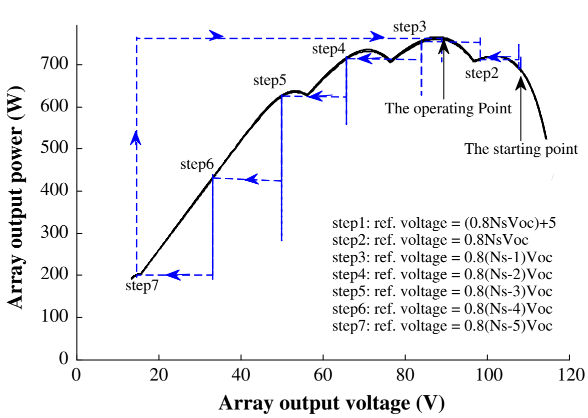


Fig. 7. Corresponding $P–V$ curve of the array under partially shaded condition (black curve) and the tracking path of new MPPT algorithm when the insolation condition changes at = 0.35 s (blue line shows the applied reference voltage to the converter). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Fig. 7 demonstrates the variation of operating points in the $P–V$ curve when the algorithm tries to find the global peak point under partially shaded condition (simulation time corresponds to the time interval of 0.35 s → 0.36 s in Fig. 5).

5.2. Comparison of the proposed method with other methods

The following investigations compare the behavior of new MPPT algorithm with the conventional hill climbing MPPT algorithm and the proposed method in Patel and Agarwal (2008) under uniform and non-uniform insolation conditions. In both comparisons, the case study is chosen similar to the demonstrated case in Fig. 5.

First comparison evaluates the behavior of hill climbing method and the proposed method in Fig. 8, where Fig. 8a shows the MPP tracking path of the conventional hill climbing algorithm and Fig. 8b shows the behavior of new MPPT algorithm. As it can be seen from Fig. 8, the proposed method not only operates correctly under uniform insolation conditions, but also it finds precisely the global peak under partially shaded conditions compared to the conventional method. The conventional method also fails to track MPP under non-uniform insolation condition and dissipates a lot of power (around 70 W).

In the second comparison, the transient response of the proposed method is compared with (Patel and Agarwal, 2008). In this simulation, two transient states are considered. First at $t = 0.2$ s, the insolation condition changes uniformly from 1 kW/m^2 to 0.38 kW/m^2. Second, at $t = 0.35$ s, a partially shaded condition happens. The simulation results are shown in Fig. 9a and b. As it can be seen from Fig. 9, the transient time of the proposed method is lower than the transient time of Patel and Agarwal (2008) in both cases.

Based on the simulation results at different insolation conditions, one can conclude that the proposed MPPT

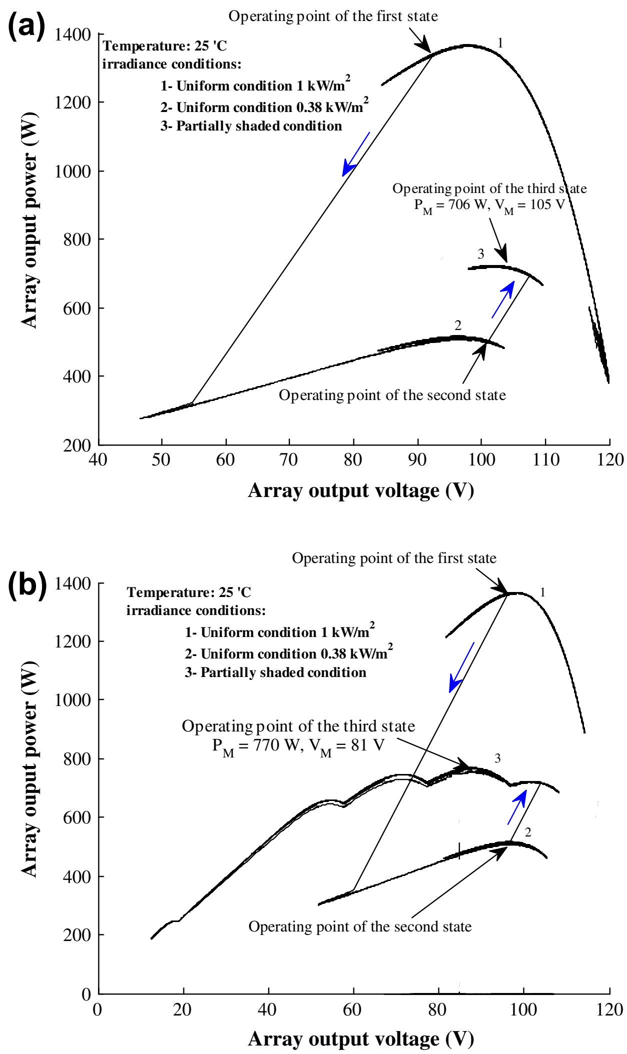


Fig. 8. Evaluating the performance of (a) conventional MPPT method and (b) proposed MPPT method under various insolation conditions. (Blue arrows demonstrate the tracking paths when the insolation condition changes). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

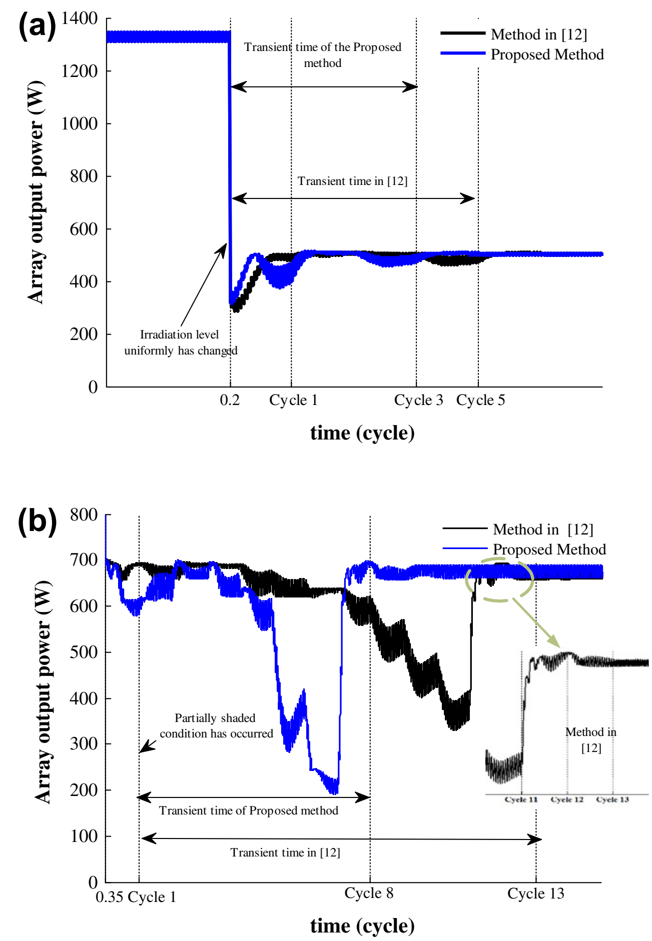


Fig. 9. Comparison of the transient response between new method and the proposed method in Patel and Agarwal (2008). (a) Uniform insolation change at $t = 0.2$ s and (b) partially shaded happening at $t = 0.35$ s.

method is capable to immediately diagnose the insolation conditions (uniform or non-uniform), as well as it does not need to scan the entire P–V curve to find the global peak among the local peaks. The speed of new algorithm is also high because it determines the status of insolation condition only by two sequential sampling around the operating point $V_{ref} = 0.8N_sV_{oc}$. In addition, after determining the partially shaded condition, the global peak point is searched by updating the converter duty cycle at integer multiples of $0.8V_{oc}$ and calculating the corresponding power.

6. Experimental results

The PV array which is considered for experimental setup is shown in Fig. 10a. It is composed of two strings and each string has two series modules. The module parameters are also listed in Table 2. It is worth noting that, before experimental tests, the recorded values for V_{oc} and I_{sc} of the PV array (under uniform insolation condition) were 37 V and 3.5 A which were taken at 10:00 A.M on July 2012.

For this study, a boost converter is used, with the following specifications: $C_i = 220$ μF, $C_o = 220$ μF, $L = 1$ mH, $f_s = 8$ kHz and $P_{nom} = 500$ W. Fig. 10b and c shows the experimental setup and the system block diagram. On the basis of the proposed algorithm in Section 3, the converter duty cycle will be calculated and controlled with a simple microcontroller.

To verify the performance of the new MPPT algorithm two tests were performed. In the first experiment, the PV array was under uniform insolation condition and the corresponding I–V curve was recorded and demonstrated in Fig. 11a. According to Fig. 11a, the corresponding voltage and current of MPP point were 29.2 V and 3.1 A. To confirm the validity of the proposed algorithm, the obtained results for the corresponding voltage and current waveforms of the PV array were demonstrated in Fig. 12. It is seen that the generated power in Fig. 12 is around 87 W and has good agreement with the result of Fig. 11a. This result confirms the correct operation of new MPPT algorithm under uniform insolation conditions.

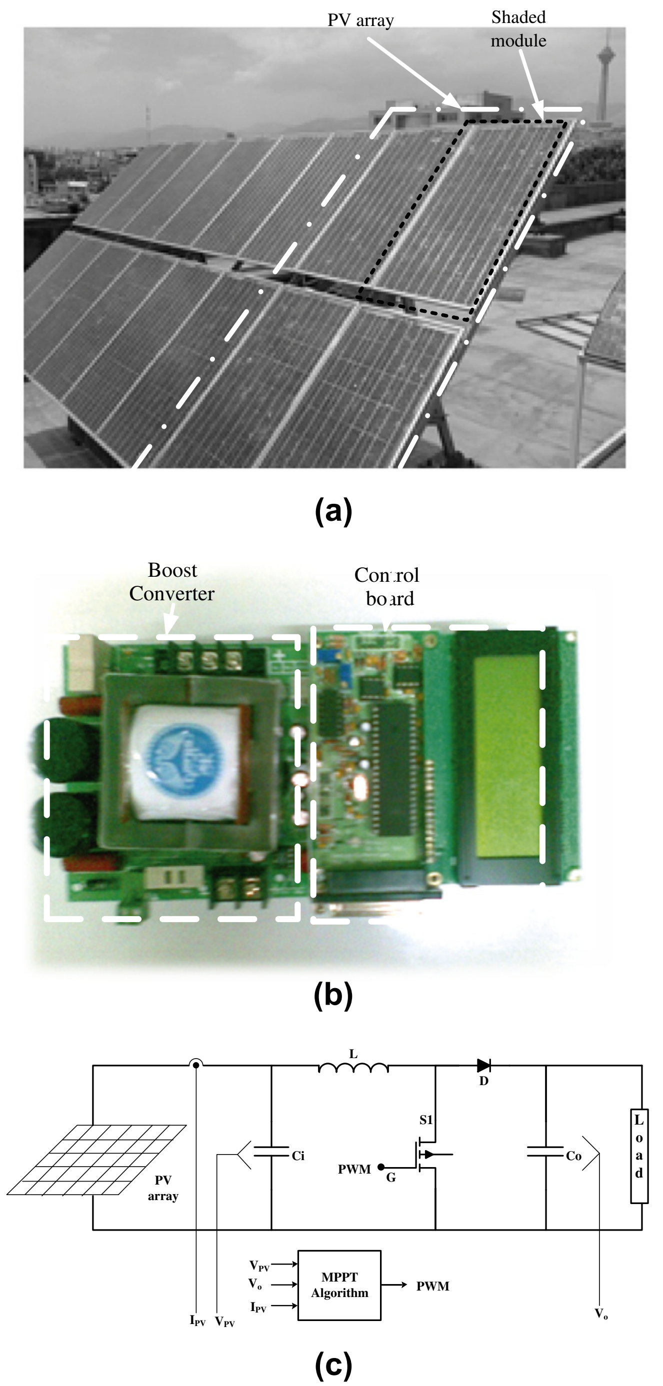


Fig. 10. Hardware prototype used in the experimental investigation. (a) Sample PV array, (b) boost converter and (c) system block diagram.

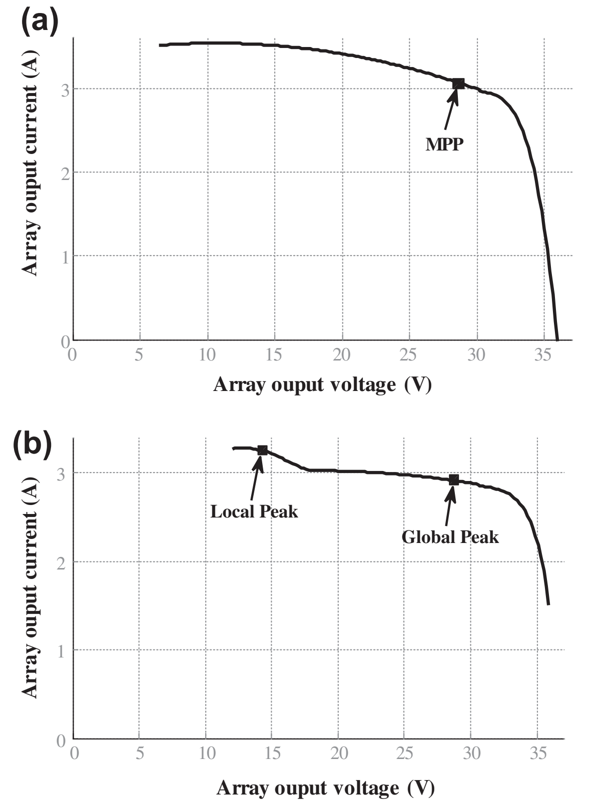


Fig. 11. *I–V* curve of the PV array under (a) uniform insolation condition and (b) partially shaded condition.

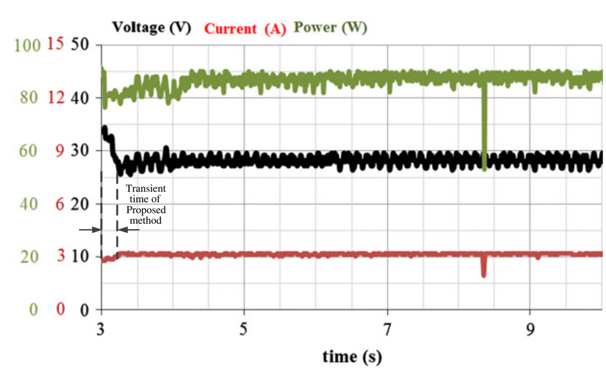


Fig. 12. Corresponding array power, voltage, and current waveforms under uniform insolation condition.

In the second experiment, the PV array was under uniform insolation condition for 23 s. Then, at $t = 23$ s, a partially shaded condition was made intentionally and the corresponding *I–V* curve was recorded and demonstrated in Fig. 11b. This condition was kept 20 s, and then it was restored to the initial condition. The behavior of MPPT algorithm before, during, and after the partially shaded condition is demonstrated in Fig. 13.

It is seen that the proposed MPPT algorithm well behaves in all conditions and quickly finds new MPP. For example, during partially shaded condition, the generated PV power is almost 75 W which is close to maximum achievable power, according to Fig. 11b. Furthermore, the new MPP is found in less than 0.21 s when a change occurs.

The last experiment compares the transient response of the new method with the proposed method in Patel and Agarwal (2008) when partial shading occurs. The obtained result in Fig. 14 confirms the better performance of new method. It is seen that the transient time of the proposed method is almost 0.21 s while the transient time of Patel and Agarwal (2008) is 0.5 s.

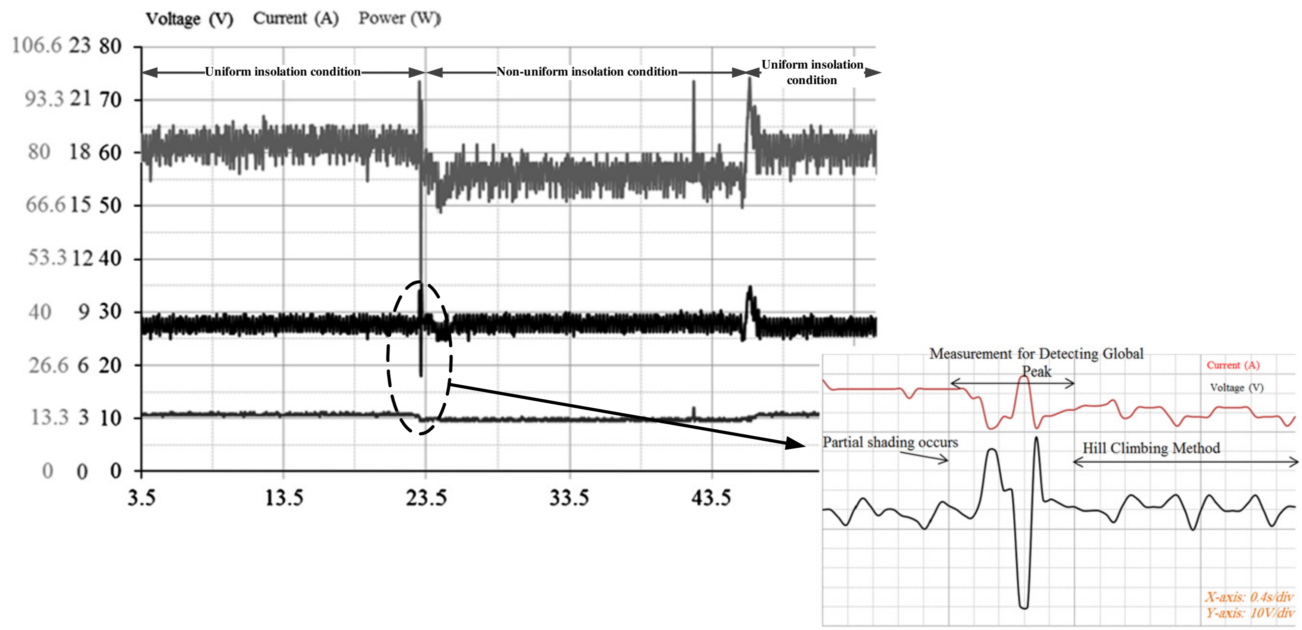


Fig. 13. Investigation the behavior of new MPPT algorithm before, during, and after happening of partially shaded condition.

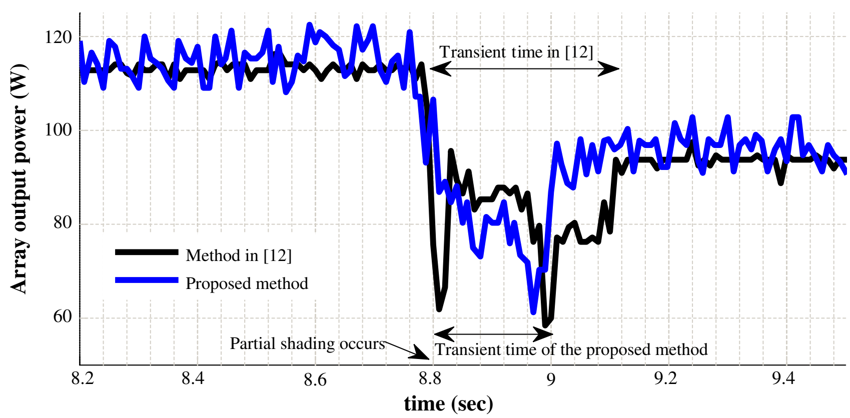


Fig. 14. Experimental comparison of new MPPT method and the proposed method in Patel and Agarwal (2008) when partial shading happens.

7. Conclusion

In this paper, a new MPPT method for tracking the global peak either in uniform or non-uniform insolation conditions was presented. The proposed method introduces an analytic condition for quick determination of partially shaded conditions from normal conditions. The analytical investigation shows some important results, which are useful for study of PV array under partially shaded conditions. These results are listed in the following.

(1) In partially shaded conditions, the group current is determined by the array voltage and insolation levels of the subassemblies (Eq. (5)). Moreover, the group current in the vicinity of array open circuit voltage is determined by the modules which have the lowest irradiation level.

(2) It is proved that the voltage difference between the peak points (in the P–V curve) is at least $0.8V_{OC}$.

(3) Normalized current variation of the PV array under uniform insolation conditions is higher than partially shaded conditions (Eq. (21)).

(4) Behavior of a partially shaded array is similar to an array which works in current source region when the operating voltage is close to $0.8N_sV_{oc}$

The above conclusions were confirmed by simulation and experimental results. The obtained results also confirm that: (1) the convergent speed of the proposed method is almost high; (2) it does not need to track the entire of a P–V curve to find MPP; and (3) the structure of new MPPT algorithms is so simple.

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