Effect of Partially Shaded Conditions on Photovoltaic Array's Maximum Power Point Tracking

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Abstract **- Maximum power point tracking algorithm is widely implemented in photovoltaic system to maximize the PV array output power. In general, Perturb and Observe (P&O) is simple thus being selected to continuously track the array maximum power point (MPP). Under uniform solar irradiance, PV array characteristic is non-linear and consisting only one MPP along the functional operating voltage. However, when the PV array is partially shaded, the P-V characteristic becomes more complex with multiple MPPs. The occurrence of multiple MPP might cause the PV array to be trapped at the local MPP. At this operating condition of local MPP, PV array will generate lesser output power. In this study, the performance of PV array is explored especially when each PV module is at 30% and 70% shaded conditions. Simulation results show that PV array at absolute MPP can generate greater output power with the largest increased by 74.6% hence achieving higher power efficiency.**

Keywords - PV array, partially shaded conditions, maximum power point, perturb and observe

I. INTRDUCTION

The world primary energy demand is expected to increase 1.7% per year from the year 2002 and expending more than 50% at 2030 [1]. It is projected the main global energy consumption will be continuously dominated by fossil fuel. Due to the awareness of global warming and climate change, nations are concerned of the planet's carbon emissions and fossil fuel used. Therefore, renewable energy resources such as solar energy will play a significant role in the world energy in the upcoming future [2].

Solar energy is the sun's radiant energy where the radiate amount is enormous. Solar energy can be converted directly into electrical energy via solar cell and the phenomenon is commonly described as photovoltaic (PV) effect [3]. Solar energy has gained the world's interest as it is a promising option of renewable energy. The conversion of solar energy to electrical energy is static, quite, free of moving object and does not have any negative impact to the environment. Therefore, the annual growth of the world PV industry has reached an average of 30% during the past decade [4].

Commercial PV module is configured from series, parallel or combination of series and parallel connection of PV cells. Solar irradiance, cell temperature, tilt angle shaded condition and the operating condition are among the factors that will influence the output current and power characteristics of the PV module. However, the electricity generation is mainly affected by the level of solar irradiance. The amount of incident light to the PV module will determine the total generation charge carrier hence the generated current in the PV module [5, 6]. In general, PV array is formed by a couple of PV modules to obtain larger output power.

II. LITERATURE REVIEW

In [2], [3] and [4], the authors presented the non-linearity of the *I-V* and *P-V* characteristics when the PV system is under uniform illumination of sunlight. Generally, PV system has a unique operating point named as maximum power point (MPP) which will produce maximum power at the optimum voltage and current. The authors in [4] proved that the MPP is varied according to the amount of solar irradiance as the PV characteristics diverse as the changing of the atmospheric conditions. Cell temperature is one of the factors discussed in [3] which will influence the position of MPP. However, [3] and [4] did not discuss the effect of partially shaded condition on the PV system.

In [3] and [7], the authors proposed maximum power point tracking (MPPT) algorithm to identify the MPP in the uniform illuminated PV system. According to [7], Perturb and Observe (P&O) method is commonly used for its simplicity and low cost implementation. P&O is able to maximize the power generation of the PV system by continuously tracking the MPP regardless of the changing of the atmospheric conditions. However, the research is only limited to the uniform illuminated conditions.

The studies in [8], [9] and [10] show that when the PV array is under partially shaded conditions (PSC), the array characteristics become more complex with multiple MPPs. PSC is defined as the circumstance where one or more of the PV modules in the array received less amount of solar irradiance. The existence of multiple MPPs reduces the effectiveness of MPPT algorithm since the power losses of

PV system under partially shaded conditions can reach as high as 70% [8].

In this paper, the effect of the partially shaded conditions on PV array's MPPT will be studied. The occurrence of multiple MPPs generally might cause the PV array to be trapped at the local MPP. At this operating condition, PV array will generate lesser output power. On the other hand, if the PV array is operated at the absolute MPP, the array can generate greater output power. Therefore, PV array which is operated at the absolute MPP can achieve higher power efficiency compared to the trapped local MPP.

III. MODELLING OF PV SYSTEM AND COMPUTATIONAL OF MPPT

This section described the mathematical model of the basic element solar cell. The mathematical model of solar cell can be further implemented for the PV module and PV array modelling. In addition, the computational of Perturb and Observe (P&O) will be discussed.

A. Mathematical Model of PV Module

Solar cell is the basic element in PV module and it can be represented by one-diode model as shown in Fig. 1. The equivalent circuit of ideal PV cell consists of a photo current source and a diode [11]. In order to model the PV characteristics more practically, additional parameters such as equivalent parallel resistor, R_p and equivalent series resistor, R_s should be considered. R_p existed in the solar cell mainly due to the p-n junction leakage current whereas the occurrence of R_s is caused by the contact resistance within the semiconductor layer of the metal base [12].

The *I-V* characteristic of diode D_m can be described by the Schockley diode equation as shown in (1) where I_{Dm} is the current that flow through diode D_m, I_0 is the diode D_m reverse bias saturation current, V_{Dm} is the voltage across the diode D_m, n is the ideality factor of the diode D_m and V_T is the thermal voltage.

$$I_{D_m} = I_0\left[\exp\left(\frac{V_{D_m}}{nV_T}\right) - 1\right] \quad (1)$$

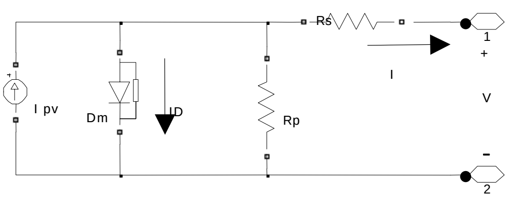

Figure 1. One-diode model.

The thermal voltage, V_T is shown in (2) where k is the Boltzman constant ($1.3806503 \times 10^{-23}$ J/K), T is cell's operating temperature in degree Kelvin and q is the electron charge ($1.60217646 \times 10^{-19}$ C).

$$V_T = \frac{kT}{q} \quad (2)$$

Based on the general model of the solar cell as in Fig. 1, the *I-V* characteristic of the solar cell can be further described as in (3), where I is the terminal current of the solar cell, I_{pv} is the light-generated current of the solar cell, V is the solar cell terminal voltage, R_s is the equivalent series resistance and R_p is the equivalent parallel resistance.

$$I = I_{pv} - I_0\left[\exp\left(\frac{V + IR_S}{nV_T}\right) - 1\right] - \left(\frac{V + IR_S}{R_p}\right) \quad (3)$$

In general, PV module consists of several identical solar cell connected in series to provide higher operating voltage for the PV module [11]. PV module which consists of n series connected solar cell can be modelled with modification in (2). The thermal voltage in (2) will be multiplied by the number of series solar cell, n.

B. PV Array with By-Pass Diode

PV array is formed to have larger output power generation. PV array which is formed by series connected PV module has larger functional operating voltage [13]. Fig. 2 shows the forming of PV array by three identical PV modules connected in series.

The modelling of the characteristic of PV array is based on superposition of each individual PV module characteristic. Theoretically, PV array will produce same amount of generating current as the PV module which is operated under the same environmental conditions on the other hand, the PV array provides greater output voltage. Referring to Fig. 2, the array will gain three times operating voltage compared to the PV module.

By-pass diode is externally coupled to each PV module to prevent hot spot formation in the PV array. During

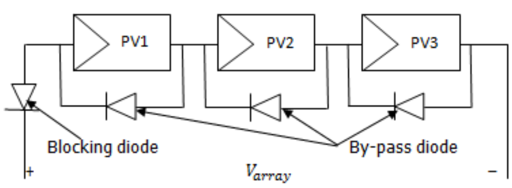

Figure 2. PV array consists of three identical PV modules.

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uniform solar illumination, the entire PV modules will generate same amount of current. However, the shaded module will generate less current during PSC. The shaded module will cause the overall current generation by the entire PV array being limited. The solar cells will be reverse biased due to the mismatched effect and dissipate power in form of heat. When the hot spots exceed the maximum power which can be sustained by the PV cells, it will cause permanent damage to the PV module and the array will be open circuited causing power interruption to the users [14]. With by-pass diode, the excess current by the un-shaded PV module is allowed to flow through the external diode, preventing the PV module from being limited by shaded module and avoiding the destructive effect caused by hot spot formation in the PV array.

Blocking diode is externally connected to the string of series connected PV modules. The function of blocking diode is to prevent the reverse flow of current particularly from the secondary power sources such as the lead-acid battery during the absence of sun light.

C. Perturb and Observe

Perturb and Observe (P&O) is implemented to control the PV array and optimize the power generation under varying atmospheric conditions. P&O has simple control structure where it needs a few measured parameters to perform maximum power tracking [15]. P&O operates periodically for perturbing the control variable and comparing the instantaneous PV output power at each sampling interval.

P&O is initiated by applying perturbed voltage to change the operating voltage of the PV array. Subsequently, module parameters V and I at the present state, k and previous state, $k-1$ are measured. The module output power, P can be calculated by multiplying the parameters V and I. Based on the comparison of present and previous state of the operating voltage and output power, P&O will make decision either to shift the PV array for larger or lower operating voltage. Eventually, the PV array will be operated at MPP where PV array generates maximum power. Fig. 3 shows the operation of P&O.

Fig. 4 shows the P-V characteristic of the PV module under 600W/m^2 solar irradiance with the MPP tracking process of P&O. The shifting of the instantaneous operating voltage to approach the MPP in Fig. 4 is based on the P&O operation as in the flowchart in Fig. 3. There are total of four possible circumstances which will affect the direction of the MPP tracking.

Case I where $P_k>P_{k-1}$ and $V_k>V_{k-1}$ is illustrated as tracking path α in Fig. 4. Increasing of PV module operating voltage will lead to larger PV power. Hence, P&O will apply an increment of perturbed voltage, ΔV to the present PV module operating voltage until the MPP is successfully determined.

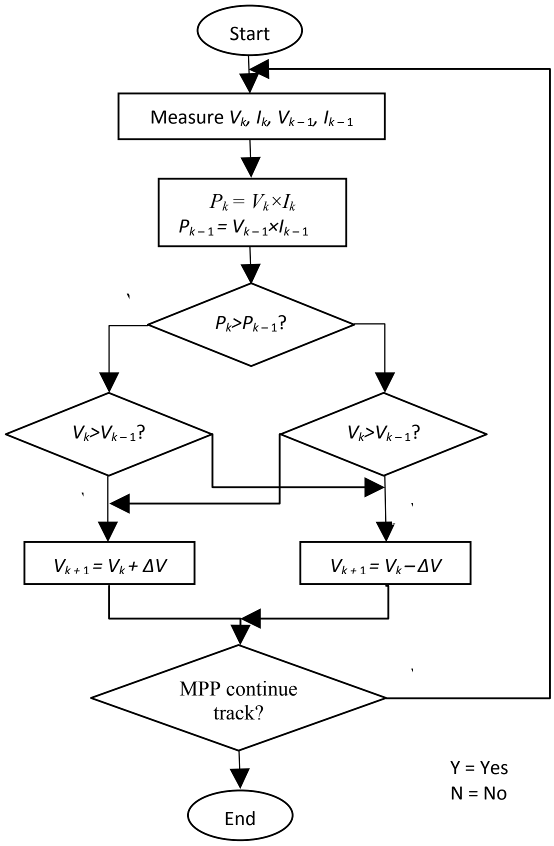


Figure 3. Flowchart of P&O operation.

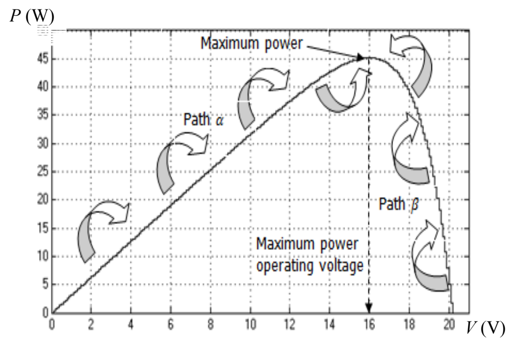


Figure 4. P&O tracking path.

Case II where $P_k>P_{k-1}$ and $V_k<V_{k-1}$ is described as tracking path β in Fig. 4. At this condition, the PV module output power will increase as the decreasing of PV operating voltage. Thus, P&O will take action to reduce the perturbed voltage, ΔV to the present PV module operating voltage. While the condition is unchanged, the decrement of ΔV will be continued until the MPP is identified.

Case III involves $P_k<P_{k-1}$ and $V_k>V_{k-1}$ which is represented by the tracking path β in Fig. 4. In this case, the PV power decreases as the PV operating voltage increases.

Thus, P&O applies perturbed voltage, ΔV to shift the PV module's operating voltage to lower value.

Case IV is illustrated as $P_k<P_{k-1}$ and $V_k<V_{k-1}$ and it is described by tracking path α in Fig. 4. It can be observed that when the PV operating voltage is reduced, the output power will be decreased. Thus, P&O will apply perturbed voltage, ΔV to the PV module and operate at larger voltage.

P&O will continue to track MPP even the optimal voltage point has been successfully achieved. The continuous MPP tracking is vital to discover the next MPP for maximum power gaining especially when the PV system is under rapid changes of environmental conditions.

IV. SIMULATION OF PV SYSTEM

Modelling and simulation of PV system has been carried out in MATLAB-SIMULINK. The commercial PV module, SHARP NE-80E2EA multi-crystalline silicon with 80W is selected as the reference model for the modelling. SHARP NE-80E2EA consists of 36 series connected solar cell with 21.3V open circuited voltage and 5.16A short circuit current.

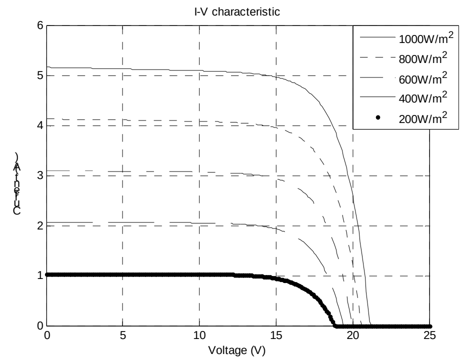
A. Uniform Illuminated Conditions

Fig. 5 shows the *I-V* and *P-V* characteristics of PV modules at various solar irradiances. The characteristics describe the output current and power of the PV module within the functional operating voltage. The amount of the illuminated solar irradiance affects the output current generation. As the solar irradiance increased, PV cells in the module are able to release more electrons thus generating larger current. Hence, the output power is increased as the growing of solar irradiance. The *P-V* characteristic illustrates non-linearity behaviour with appearance of one MPP. At 1000W/m^2 solar irradiance, the MPP is located at 17.1V with the power generation of 80W while at 200W/m^2 solar irradiance, the MPP is relocated to 15.1V with the power generation of 16W.

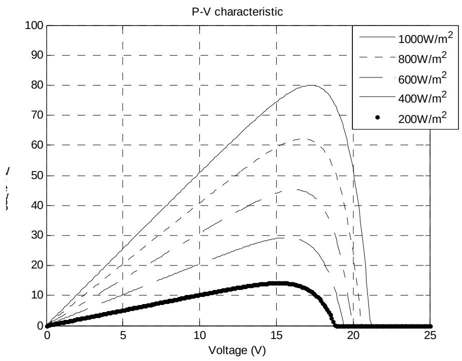
Fig. 6 shows the *I-V* and *P-V* characteristics of the PV array. In this study, PV array is formed by three identical PV module connected in series. Therefore, PV array has three times larger operating voltage compared to the single PV module where in Fig. 6, the functional operating voltage range of PV array has three times of the voltage magnitude of PV module in Fig. 5. However, the series connected PV modules will not amplify the current generation. The current generated by thePV array is the same as PV module. Nevertheless, the array power generation will be three times greater than the output power produced by single PV module.

B. Partially Shaded Conditions

PV array under uniform illuminated conditions has non-linear characteristic with the occurrence of one MPP in the

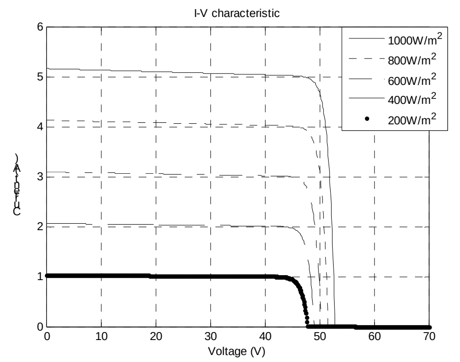


(a)

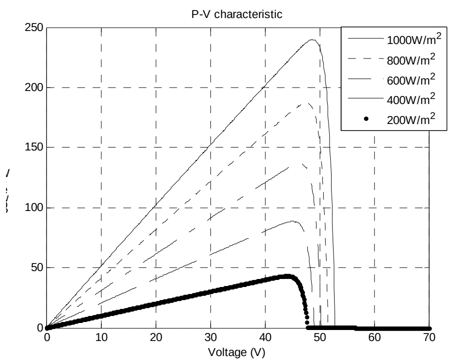


(b)

Figure 5. The (a) *I-V* and (b) *P-V* characteristics of PV module.



(a)



(b)

Figure 6. The (a) *I-V* and (b) *P-V* characteristics of PV array.

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P-V curve. However, when the PV array is under partially shaded conditions, the *P-V* characteristic becomes more complex. Multiple MPPs occur in the *P-V* characteristic due to the mismatched current generation by the PV array. Fig. 7 and Fig. 8 illustrate the characteristics of PV array when one of the PV modules in the PV array is under shaded condition of 20% and 50% respectively. There are two MPPs in the *P-V* characteristic as shown in Fig. 7. It can be observed that PV array which is exposed to 20% partial shading has a local MPP of 34V and an absolute MPP of 48V. At local MPP, PV array will have approximately 170W power generation. However, if the PV array is operated at the absolute MPP, the power generation can be boost up to approximately 190W, 11.8% more than the local MPP.

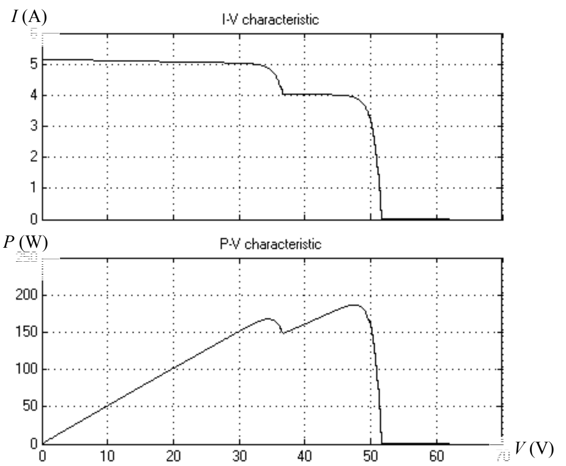

Figure 7. Characteristics of PV array where one of PV module shaded 20%.

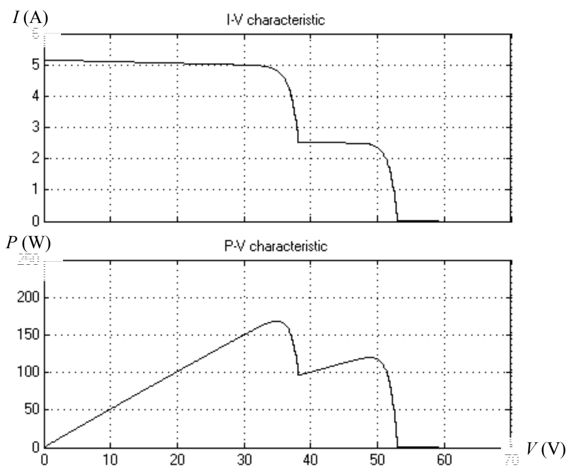

Figure 8. Characteristics of PV array where one of PV module shaded 50%.

Considering Fig. 8, where PV array is exposed to 50% partially shaded condition, the array presents a local MPP at operating voltage of 50V and an absolute MPP at 34V. PV array can generate output power of 120W in the local MPP operating condition. However, the efficiency of PV array will be enhanced if the PV array shifted the operation to the absolute MPP, where PV array can generate 41.7% larger power than the local MPP.

Fig. 9 shows the characteristics of PV array when two of the PV modules are shaded 50%. It can be observed that there are two MPPs in the *P-V* curve which are located at the operating voltage of 17V and 50V respectively. In this situation, PV array which is operated at 17V is considered trapped at the local MPP. PV array at the trapped local MPP is only able to generate output power of approximately 80W. On the other hand, if the PV array is able to shift the operating voltage beyond the trapped local MPP and operated at 50V, the output power will be increased to 130W, 160% larger than the local MPP.

Table I summarizes the location of both local and absolute MPP when the PV array is under various partially shaded conditions. The effect of PV array power generation at absolute MPP compared to local MPP is also included in the table.

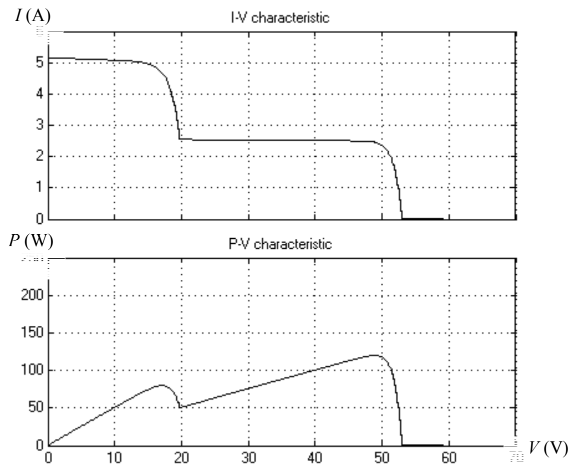

Figure 9. Characteristics of PV array where two of PV modules shaded 50%.

Table I. MPPs and the effect to the PV array power generation.

Number of PV modules shaded (% shaded)	**MPPs operating voltage (V)**		**Effect of power generation (Absolute MPP operating condition)**
	Local	**Absolute**	
One (20%)	34	48	Increased of 11.8%
One (50%)	34	50	Increased of 41.7%
Two (50%)	17	50	Increased of 160%

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When the PV array is exposed to various partial shading, multiple local MPPs might be occurred in the *P-V* characteristic. Fig. 10 shows the PV characteristics when each PV modules in PV array is under 30% and 40% shaded conditions, whereas Fig. 11 shows the PV characteristics when each PV modules in the array is under 30% and 70% shaded conditions.

It can be noticed from Fig. 10, there are two local MPPs and one absolute MPP. The absolute MPP is located at the operating voltage of 47V. At local MPP of 17V, PV array generates output power of approximately 80W. There is another local MPP beyond the local MPP of 17V, which is situated at the operating voltage of 32V. The PV array generates greater output power, 110W if it is operated at local MPP of 32V. However, at absolute MPP operating condition, the PV array produce the highest output power generation, which is 140W.

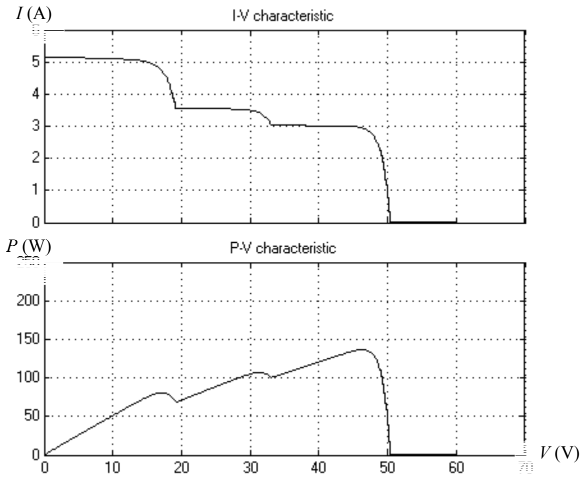

Figure 10. Characteristics of PV array where PV modules shaded 30% and 40%.

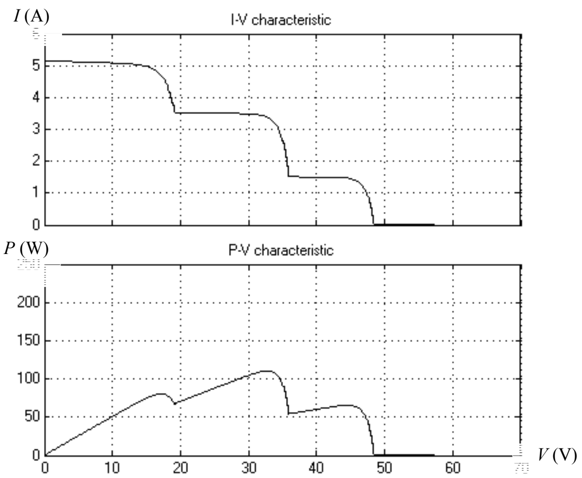

Figure 11. Characteristics of PV array where PV modules shaded 30% and 70%.

There are three MPPs being detected in Fig. 11. The MPPs are situated at the operating voltage of 17V, 32V and 47V respectively. Unlike Fig. 10, Fig. 11 shows that the absolute MPP located at the operating voltage of 32V. At this operating condition, the PV array is able to generate maximum power of 110W. PV array will have smaller power generation if it is operated at the local MPPs of 17V and 32V. Thus, the efficiency of PV array operated at the local MPPs will be reduced.

V. RESULTS

Fig. 12, Fig. 13 and Fig. 14 shows the tracking operation of MPPT on partially shaded PV array in order to maximize the output power generation. The PV array is under partially shaded condition where one of module is shaded 30% while another PV module is shaded 70%. Those corresponding characteristics can be referred in Fig. 11.

VI. DISCUSSION

P&O is one of the most common MPPT methods used to track the MPP of PV array for maximum power gaining purpose. In general, P&O performs well when the PV module or PV array is under uniform illuminated solar irradiance. However, partially shaded conditions can significantly affect the operation of the P&O.

Referring to Fig. 12, PV array is initially operated at 10V. At this condition, PV array is able to generate output power of 50W. P&O is implemented in the PV system to regulate the operating voltage of the PV array for greater output power. By comparing the operating voltage and the measured power at two sampling instants, P&O decides to

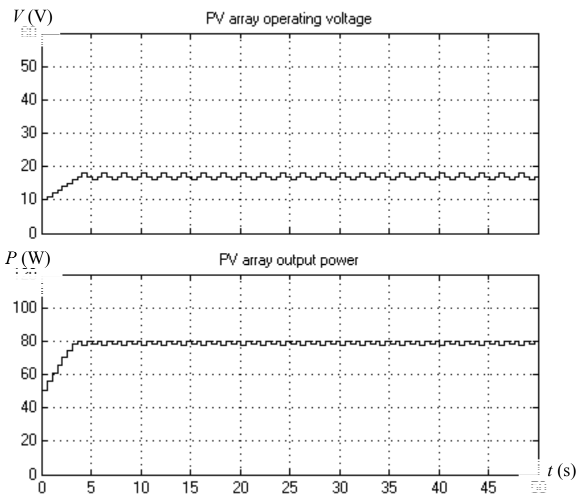

Figure 12. PV array trapped at local MPP of 17V.

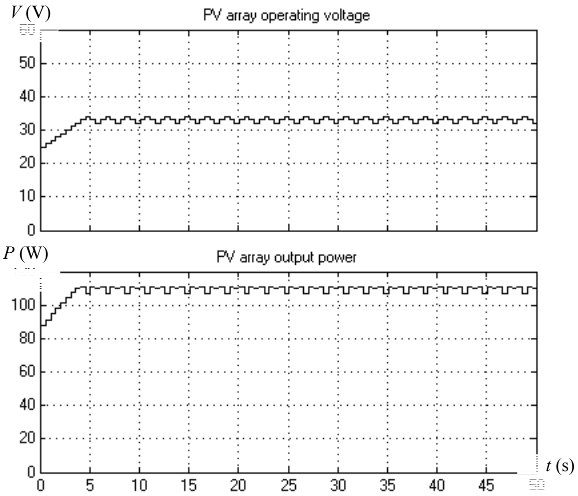

Figure 13. PV array operated at absolute MPP of 34V.

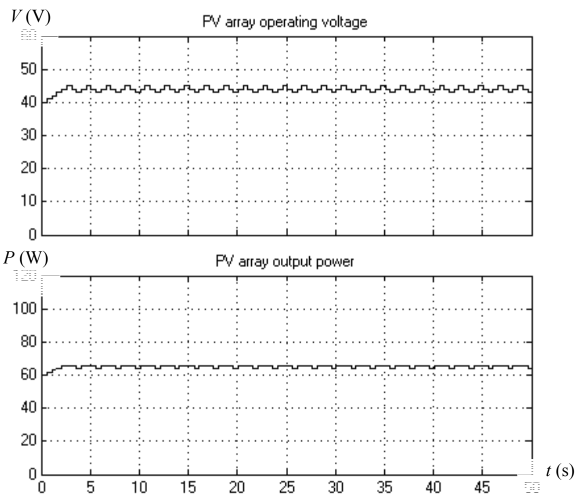

Figure 14. PV array trapped at local MPP of 47V.

shift the array for larger operating voltage. Thus, the PV array operating voltage is increased until it reached MPP at 17V. At this operating condition, the PV array is able to generate output power of 80W. The output power has been increased by 60% compared to the initial operating condition.

The operation of P&O is based on comparison of parameters at two sampling interval. Thus, P&O instructs the array to maintain the operating voltage at around 17V. Result in Fig. 12 shows that voltage fluctuation has occurred. This is because P&O attempts to track another MPP during the next perturbation cycle.

The MPPT might be able to initiate the tracking process from another initial voltage point. Referring to Fig. 13, the initial operating voltage of PV array is 25V. At this situation, PV array has the power generation of approximately 82W. To obtain maximum power, P&O increase the operating voltage of PV array, hence achieving higher power generation. The voltage increment process is continued until it reaches MPP at 32V. PV array is able to generate output power of approximately 110W. Compared to the initial voltage, the power generation has been increased by 34.1%.

In Fig. 14, P&O start the tracking process from 40V. At 40V, PV array is able to generate output power of 60W. However, P&O performs tracking process and shifts the PV array to a larger operating voltage. At the MPP of 42V, the PV array is able to generate higher output power of approximately 63W, an increase of 5% compared to the initial operating voltage.

During partially shaded conditions, PV array presents a more complex *P-V* characteristic with multiple MPPs. The occurrence of multiple MPP can cause the PV array to be trapped at the local MPP. Fig. 12 and Fig. 14 are the simulation results which show that the PV array has been trapped at the local MPP. Although P&O has successfully track the MPP, the output power generation at the trapped local MPP of 17V and 47V is less than the absolute MPP of 32V. At absolute MPP operating condition, PV array can generate output power of 110W, which is 37.5% and 74.6% greater that the power generation of the PV array at local MPP of 17V and 47V respectively. Hence, PV array which is operated at absolute MPP can achieve higher efficiency of PV system than the trapped local MPP. Table II summarises the power improvement of PV array operated at absolute MPP compared to the trapped local MPPs.

VII. CONCLUSION

The power efficiency of PV system can be improved by implementing MPPT algorithm to the system to track the optimal MPP. P&O is selected to perform the tracking because of its ease and low cost implementation. PV array at uniform solar irradiance presents non-linear characteristic. However, the characteristic is simple with only one MPP in the *P-V* curvature. Partially shaded conditions cause the *P-V* characteristic become more complex with multiple MPPs. This situation might lead the PV array to be trapped at the local MPP and reduce the power generation. Results show that PV array which is

Table II. Effect of different shaded conditions to the PV array power generation.

PV array where each module under 30% and 70% shaded conditions		
MPPs operating voltage (V)		**Effect of power generation (Absolute MPP operating condition)**
Local	**Absolute**	
17	32	Increased of 37.5%
47	32	Increased of 74.6%

operated at the absolute MPP can achieve the largest power generation as high as 74.6% improvement than the trapped local MPP. Therefore, it can be concluded that PV array at the absolute MPP operating condition will achieve higher efficiency compared to the trapped local MPP.

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