ISSN: 2229-6956(ONLINE)
DOI: 10.21917/ijsc.2013.0069



# MODELLING AND CONTROL OF PARTIALLY SHADED PHOTOVOLTAIC ARRAYS

**Chia Seet Chin[1], Bih Lii Chua[1], Pei Yi Lim[1], Hui Hwang Goh[1] and Kenneth Tze Kin Teo[2]**

*Modeling, Simulation & Computing Laboratory, Material & Mineral Research Unit*
*School of Engineering and Information Technology, Universiti Malaysia Sabah, Malaysia*
E-mail: [1]msclab@ums.edu.my and [2]ktkteo@ieee.org

***Abstract***
***The photovoltaic (PV) array controlled by Maximum Power Point Tracking (MPPT) method for optimum PV power generation, particularly when the PV array is under partially shaded condition is presented in this paper. The system modelling is carried out in MATLAB-SIMULINK where the PV array is formed by five series connected identical PV modules. Under uniform solar irradiance conditions, the PV module and the PV array present nonlinear P-V characteristic but the maximum power point (MPP) can be easily identified. However, when the PV array is under shaded conditions, the P-V characteristic becomes more complex with the present of multiple MPP. While the PV array operated at local MPP, the generated power is limited. Thus, the investigation on MPPT approach is carried out to maximize the PV generated power even when the PV array is under partially shaded conditions (PSC). Fuzzy logic is adopted into the conventional MPPT to form fuzzy logic based MPPT (FMPPT) for better performance. The developed MPPT and FMPPT are compared, particularly the performances on the transient response and the steady state response when the array is under various shaded conditions. FMPPT shows better performance where the simulation results demonstrate FMPPT is able to facilitate the PV array to reach the MPP faster while it helps the PV array to produce a more stable output power.***

***Keywords:***
***Photovoltaic, Partially Shaded Conditions, MPPT, Fuzzy Logic, Perturb and Observe***

## 1. INTRODUCTION

Solar energy is the most inexhaustible and environmental friendly among all the renewable energy resources. This is the major reason where the photovoltaic (PV) technology has gained the world interest for the last few decades. Research and development has been carried out continuously on the light absorbing material which is used for solar cell fabrication, to reduce the high capital cost on solar cell manufacturing [1]. However, the improvement on the overall PV system performance is equally important. One of the interesting but challenging area is to track the maximum available output power of the PV system. This can be done by implementing maximum power point tracking (MPPT) method to control the internal operating condition of the PV system. The function of MPPT is to ensure that the PV system is always generating maximum power regardless any changes of environmental conditions such as solar irradiance level and ambient temperature [2]-[3].

Various MPPT methods have been introduced by different researchers. Among the popular and common MPPT schemes are short circuit current, open circuit voltage, perturb and observe (P&O) and incremental conductance.

In the early stage, short circuit current and open circuit voltage methods were introduced to detect the optimal operation of the PV system. The short circuit current method assumed that the relationship of the maximum power point (MPP) voltage and short circuit current is constant, whereas the open circuit voltage methods assumed that the relationship of the maximum power point (MPP) voltage and open circuit voltage is constant. Based on this assumption, the optimal voltage of PV system can be identified [4]. These methods however are not reliable as the relationship between the MPP voltage and short circuit current or open circuit voltage might change for different PV cell technology. Short circuit current and open circuit voltage methods might also fail especially when the system is under rapidly changing environmental conditions [5].

P&O method is introduced later to replace the short circuit current and open circuit voltage methods. P&O implements iterative technique to track the optimum condition of the PV system. P&O is the most popular and widely applied method among all the MPPT schemes because of ease of implementation. However, researchers are still investigating on various modified techniques, aiming to reduce the hardware costing or to improve the performance of the controller [6]. One of the examples is the incremental conductance method. The incremental conductance method is an extensive technique of P&O which is developed to improve the tracking accuracy.

The characteristic recognition of the PV system is essential for the MPPT to track the optimum condition of the PV system. Solar cell is the basic element that converts solar energy into electrical energy. Solar energy on striking the solar cell imparts enough energy to some negatively charge electron to raise their energy level and thus release them. Therefore, the amount of the illuminated solar irradiance is the main factor to determine the generation of the charge carrier in the solar cell [7]. PV system presents nonlinear characteristics under uniformly illuminated condition. However, a unique maximum point can be easily identified in the P-V characteristic, which commonly known as the maximum power point (MPP). PV system which is operated at the MPP can generate maximum power. Nevertheless, the characteristics are different and complex when the PV array is partially shaded by cloud, tree branches or other obstacles. Multiple MPPs are spotted in the P-V characteristic and the complication of the characteristics is very much depending on the orientation of the PV array and the shading patterns [8]-[10]. This shading effect will decrease the effectiveness of the tracking algorithm where the controller might lead the PV array operated at the trapped local MPP [11]. The generated power of PV system at the trapped local MPP might drop drastically and limited power can only be generated. Due to this consequence, Ji et al. has proposed a real MPP tracking (RMPPT) method to re-locate the voltage tracking point thus avoid the PV system being trapped at the local MPP. RMPPT resets the operating voltage of the PV system and lead the conventional MPPT to track the global maximum power point [12]. As a result, PV array can operate at the global MPP and hence optimize the power generation.

In this paper, modelling and control of the PV system under partially shaded conditions will be discussed. Throughout the discussion, the PV array is structured by five identical PV modules connected in series. The P&O algorithm is developed to track the optimal condition of the PV system and fuzzy logic is adopted in the P&O algorithm to vary the iterative perturbation size for better performance.

## 2. REVIEWS OF PV SYSTEM

The PV system consists of a PV array, a fuzzy logic based MPPT control unit and a load. While the PV array generates power for the load, the voltage and current signals are fed to the fuzzy logic based MPPT control unit to perform iterative tracking on the maximum power condition of the PV array. The modelling of the PV array, the operation of the MPPT algorithm, the concept of the fuzzy logic and the Real Maximum Power Point Tracking (RMPPT) proposed by Ji et al. [12] are discussed in the following sections.

### 2.1 MODELLING OF PV ARRAY

PV cell is the basic element that converts solar energy into electrical energy. The equivalent circuit of the PV cell known as one diode model is shown in Fig.1. The PV cell equivalent circuit consists of a photo current source, $I_{pv}$, a diode, $D_m$, the equivalent parallel resistor, $R_p$, and the equivalent series resistor, $R_s$. The equivalent parallel resistor, $R_p$ is generally influenced by the typical *p-n* junction leakage current in the solar cell but the equivalent series resistor, $R_s$ is usually caused by the contact resistance among the metal base and the semiconductor layer [7]. In practice, several identical PV cells connected in series or parallel can form a PV module or a PV panel whereas several identical PV modules can be connected in series or parallel to form the PV array.

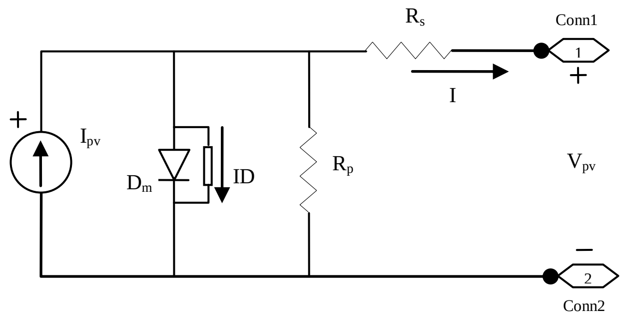


Fig.1. One Diode Model

The diode's I-V characteristic described by the Schockley diode equation is used for the mathematical modelling of the I-V characteristic of the solar PV cell [13]. The mathematical modelling can be derived as in Eq.(1), where $I$ is the solar cell terminal current, $I_{pv}$ is the solar cell light-generated current, $I_0$ is the diode reverse biased saturation current, $V_{pv}$ is the solar cell terminal voltage, $n$ is the ideality factor of the diode $D_m$, $V_T$ is the thermal voltage, $R_s$ and $R_p$ are the equivalent series and parallel resistance respectively.

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

A number of identical solar cells are connected in series or in parallel to form a PV module or PV panel. PV module is constructed to provide larger operating voltage or larger current to the connected load [14]. The further connection of several identical PV modules in series or parallel can form a large PV array. The basic configuration of PV array which consists of *n* series connected PV modules can be shown in Fig.2.

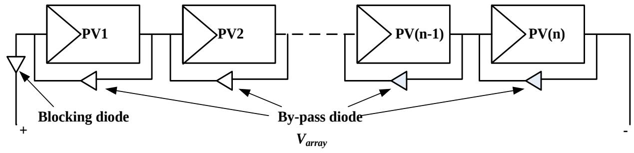


Fig.2. PV Array Formed by *n* Series Connected PV Modules

### 2.2 MPPT ALGORITHM

Among all the MPPT methods, P&O technique is selected to track the maximum condition of the PV array due to its simplicity and ease of implementation. The operation of the P&O is initiated by applying a small perturbed voltage, $\Delta V$ to alter the operating condition of the PV array [15]. As the operating voltage changing, the PV generated current will slightly change and the generated power will be different. The change of output power at two sampling interval, i.e. at the present and at the previous sampling interval is subsequently compared. Based on the instantaneous output power at two intervals, the MPPT control unit can decide to regulate the PV array to be operated either at larger or lower operating voltage. MPPT will perform several iteration processes and eventually the PV system will reach a particular optimum power point where it can generate maximum output power.

The flowchart shown in Fig.3 is the basic operation of the P&O algorithm. By measuring the voltage and current signal at two sampling intervals, the output power of the two intervals can be calculated and compared. P&O algorithm is developed to be able to decide the direction of the tracking process, shifting the operating voltage of the PV system either to a larger value or to a smaller value. The decision is made by evaluating the feed in voltage signal and the calculated output power of the PV array at two sampling intervals.

It is predicted that there are total of four possible cases which will influence the operation of P&O algorithm. The four cases are presented in Table.1 and the responded action taken by the P&O algorithm is summarized in the same table.

The principal of P&O algorithm is to implement a perturbation to the PV operating voltage and carry on with the iterative process until the optimal operating conditions of the PV array is successfully identified. However, even though the PV array is operated at the optimal operating voltage, P&O algorithm will continuously perturb and iterate the PV array's operating voltage, intending to track the subsequent MPP. As a consequence, the iterative process will cause voltage and power fluctuation problem. The fluctuation is more obvious when the P&O algorithm applies larger perturbation size to the PV system.

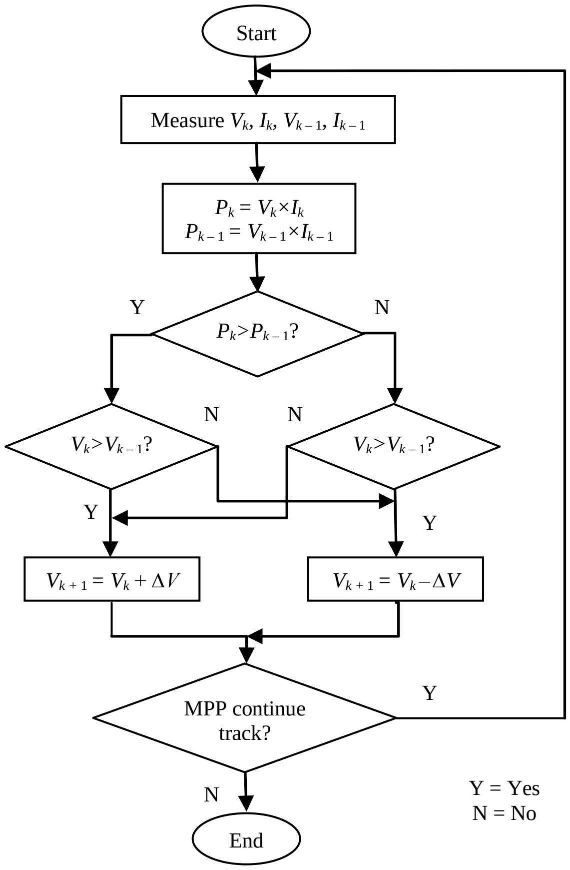


Fig.3. Flowchart of P&O Control Algorithm

Table.1. Four Possible Conditions and the Responded Action

| Case | Condition | | Action to PV array by P&O algorithm |
|---|---|---|---|
| Case I | $P_k > P_{k-1}$ | $V_k > V_{k-1}$ | Operating voltage is increased by ΔV |
| Case II | $P_k > P_{k-1}$ | $V_k < V_{k-1}$ | Operating voltage is decreased by ΔV |
| Case III | $P_k < P_{k-1}$ | $V_k > V_{k-1}$ | Operating voltage is decreased by ΔV |
| Case IV | $Pk < P_{k-1}$ | $V_k < V_{k-1}$ | Operating voltage is increased by ΔV |

The response of P&O depends on the perturbation size of the perturbed voltage. Large perturbation size can boost the tracking speed but the tracking accuracy is low. On the other hand, small perturbation size can improve the accuracy but the PV system will have slow response in locating the MPP. Hence, fuzzy logic is proposed to be adopted into the conventional P&O algorithm for faster MPP tracking as well as minimizing the fluctuation.

## 2.3 FUZZY LOGIC

Fuzzy logic is well known for dealing with reasoning that is approximate rather than precise numerical digit numbers. It is a logical system that does not require accurate mathematic model but it implements linguistic variable computing method. In the traditional logic, the binary sets have two valued logic, true or false but fuzzy logic may have true value that ranges in between true and false. Fuzzy logic is able to function properly even without precise inputs and it is relatively more robust compared to the conventional controller.

The four basic elements in the operation of fuzzy logic control are known as fuzzification, rule base, inference engine and defuzzification. Fig.4 shows the basic element of fuzzy logic control for further discussion where the fuzzy logic has two inputs, λ and δ and one output, $\gamma$.

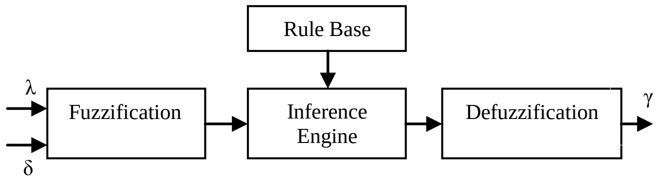


Fig.4. Basic Elements in Fuzzy Logic Control

Fuzzification is the primary operation of fuzzy logic control. Fuzzification is the progressions of converting the inputs into linguistic variable where these non-numeric linguistic variables are usually facilitate the expression of fuzzy rules and facts. Referring to Fig.4, the PV system actual signals $\lambda$ and $\delta$ will be converted into the linguistic fuzzy sets via fuzzification. The linguistic fuzzy sets will be corresponded by the fuzzy membership function where the fuzzy membership function describes each and every point of the membership value.

The fuzzy rule base is a collection of every if-then rule. It contains all data for the controlled parameters and makes judgement for all the possible outcomes. The rules are described based on the expert understanding and experience on the system control. Decision making will be handling by the fuzzy inference engine where the judgment is depending on the defined fuzzy rules. Then, the inference engine transforming the fuzzy rule base into fuzzy linguistic output and finally, the defuzzifier transferred the linguistic fuzzy sets back into the actual value of γ.

Fuzzy logic is adopted into the conventional P&O algorithm to form fuzzy logic based MPPT (FMPPT) and to enhance the flexibility of the algorithm in varying the size of the perturbed voltage, ΔV. The conventional P&O algorithm applies a fixed perturbation size of perturbed voltage for iterative tracking. PV array will suffer from slow tracking of MPP when the perturbation size ΔV is small. On the other hand, increasing the perturbation size of ΔV will cause large oscillation and fluctuation on the array operating voltage and power. With the use of fuzzy logic, FMPPT is able to adjust the perturbation size of ΔV based on the instantaneous conditions and hence the PV array will have faster transient response and minimum power fluctuation. In other words, FMPPT is expected to direct the PV system to operate at the maximum power condition with minimum tracking time while minimizing the oscillation of the operating voltage when the PV array has reached the maximum power condition.

## 2.4 REAL MAXIMUM POWER POINT TRACKING

The real maximum power point tracking method (RMPPT) proposed by Ji et al. is to allocate the global MPP when the PV array is under PSC [12]. Since the P-V characteristic becomes more complex with the occurrence of multiple MPPs, PV array might be trapped at the local MPP. At the local MPP, PV system will only generate limited power although the PV array is capable to generate greater output power at global MPP. Consequently, the efficiency of the system is not fully maximized.

The RMPPT will be triggered when PSC is detected. Under uniform illuminated conditions, the conventional MPPT method is adequate to track the MPP. However, when the PV array is under PSC, the conventional MPPT might fail to track the global MPP. The general concept of RMPPT is to compute a resettable voltage point within the range of operating voltage when the evidence shows that the PV array is under a change of PSC. RMPPT will therefore instruct the PV array to operate at a new voltage point for new cycle of MPP tracking. This process can facilitate the PV array to avoid being trapped at the local MPPs.

The computation of the new and resettable voltage reference, $V_{reset}$ is described as in Eq.(2),

$$V_{reset} = \frac{V_{mp}}{I_{mp}} \times I \quad (2)$$

where, $V_{mp}$ is the maximum power operating voltage of PV array at standard test condition (STC), $I_{mp}$ is the maximum power operating current of PV array at STC and $I$ is the instantaneous current when the PSC is identified. PV array at STC will be receiving 1000W/m$^2$ solar irradiance and operated at 25$^0$C cell temperature.

## 3. MODELLING AND SIMULATION

The SHARP NE-80E2EA multi-crystalline silicon PV module with data shown in Table.2 is selected as the reference model for PV array modelling in MATLAB-SIMULINK.

Table.2. Data of SHARP NE-80E2EA PV Module

| Parameters | Symbol | Typical Value |
|---|---|---|
| Open circuit voltage (OCV) | $V_{oc}$ | 21.3V |
| Maximum power voltage | $V_{pm}$ | 17.1V |
| Short circuit current (SCC) | $I_{sc}$ | 5.16A |
| Maximum power current | $I_{pm}$ | 4.68A |
| Maximum power | $P_m$ | 80W |
| SCC / Temperature coefficient | $K_I$ | 0.053 % / °C |
| OCV / Temperature coefficient | $K_V$ | -0.36 % / °C |
| No. of cells | - | 36 |

In order to have larger output power, several PV modules are connected in series to form the PV array. The I-V and P-V characteristics of PV module and PV arrays (three series connected PV modules and five series connected PV modules) under STC are shown in Fig.5 and Fig.6 respectively. Due to the larger numbers of series connected PV modules, the operating voltage of PV array is greater and therefore the generated power is larger. Fig.6 shows that three series connected PV modules can generate output power of 240W which is equal to three times of the rated power of a single PV module. However, five series connected PV modules is able to generate output power of 400W which is equivalent to five times of the rated power of a single PV module. As shown in Fig.5, series connected PV module is not able to amplify the generated current.

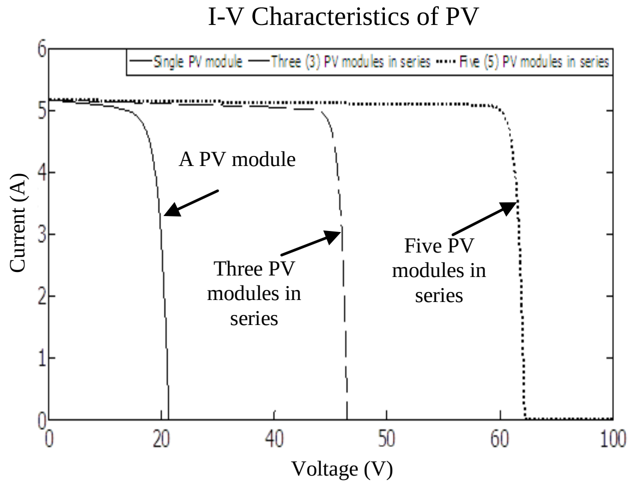


Fig.5. I-V Characteristics of PV Arrays under STC

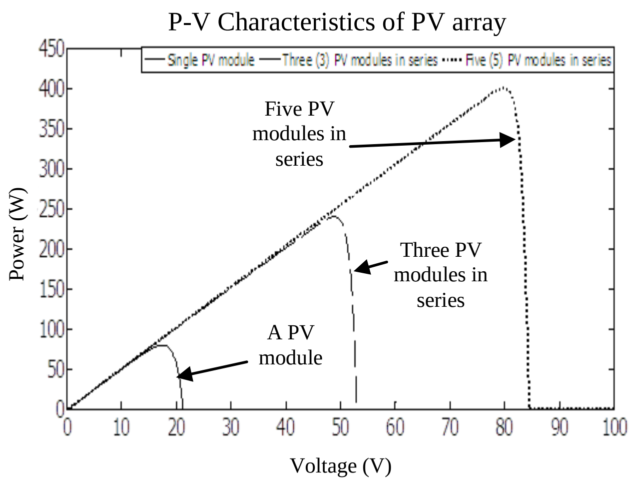


Fig.6. P-V Characteristics of PV Arrays under STC

Five series connected PV modules are selected as the PV array reference model for the PV array modelling under PSC. The simulation characteristics of PV arrays i.e. I-V and P-V characteristics under STC and PSC are shown in Fig.7 and Fig.8 respectively.

The current generation of PV array under PSC is not the same as the current generation under STC. At STC, a constant current of approximate 5.2A is generated along the functional operating voltage from 0V to 80V. However, when the PV array is under PSC, the current would not be sustained at a fixed value for the particular operating voltage. The amount of current generated will vary based on the size of the shaded area on the PV array and the level of the shaded condition. In this study, two cases of PSC are selected based on 60% of PV array shaded by 40% solar irradiance and 40% of PV array shaded by 70% solar irradiance.

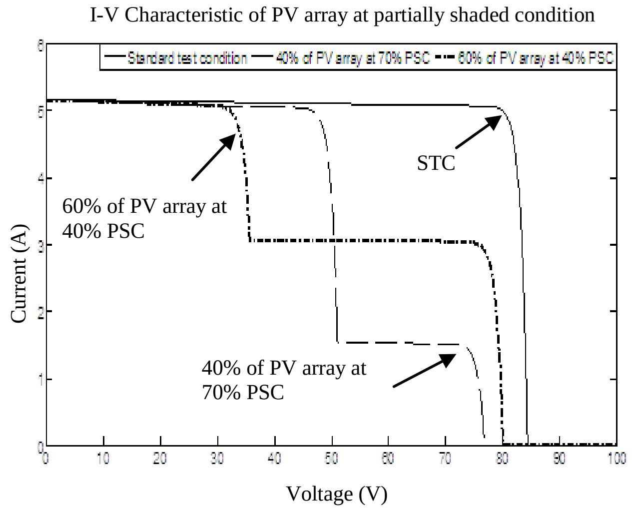


Fig.7. I-V Characteristics of PV Arrays under PSC

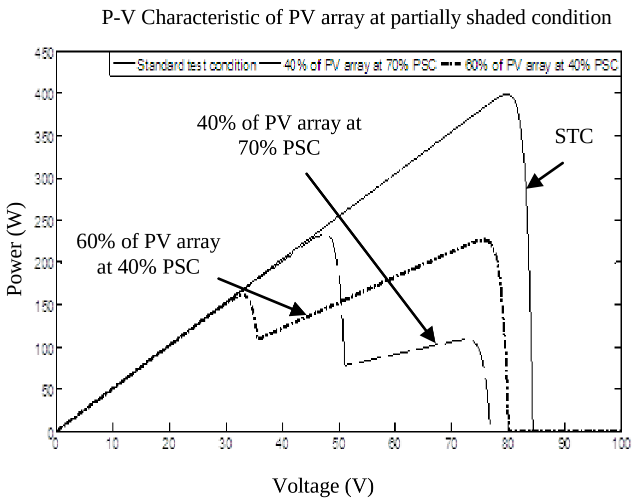


Fig.8. P-V Characteristics of PV Arrays under PSC

When the 60% of PV array is shaded by 40% of irradiance, the PV array will generate constant current of approximate 5.2A for the first 32V operating voltage as shown in Fig.7. The current is then started to decrease after 32V and settling at a constant current approximately 3.1A along the remaining operating voltage. At this shaded condition, a local MPP at approximate 33V and a global MPP at 77V are spotted in the P-V characteristic as shown in Fig.8. It is noticed that at this shaded condition, there are two MPPs in the P-V characteristic, compared to the only one MPP in the P-V characteristic for the PV array at STC.

When the 40% of PV array is shaded by 70% of irradiance, the PV array generates constant current of approximate 5.2A for the first 47V of the operating voltage (Refer Fig.7). The current is then started to decrease after 47V and settling with a constant current approximately 1.5A along the remaining operating voltage. Differs to the previous shaded condition, a local MPP at approximate 74V and a global MPP at 48V are spotted in the P-V characteristic.

Fuzzy logic is developed to assist the P&O algorithm for faster response during the tracking of the MPP. Besides, fuzzy logic is expected to be able to control the PV array to have minimum fluctuation when the PV array is approaching the MPP. Fuzzy logic will determine the most suitable size of the perturbed voltage, $\Delta V$ based on the feed in signals of the change of power, *dp* and change of power with respect to change of voltage, *dp/dv*.

The configuration of membership function at the inputs *dp* and *dp/dv* as well as the output $\Delta V$ are set accordingly. The membership functions of the *dp* and *dp/dv* are matched with the membership functions of the $\Delta V$ forming a fuzzy rule base system. The rules are validated through fuzzy viewer by adjusting the index line to verify that the fuzzy inference system is able to compute the required $\Delta V$.

## 3.1 RESULTS

The investigation of the developed FMPPT and the MPPT with fixed perturbation size of 0.5V and 1.0V is done when PV array under PSC. The PV array which consists of five series connected PV modules is predefined under STC for the first 39s. Subsequently, 60% of PV array is exposed to 40% PSC (stage 1) until the simulation time equal to 99s followed by 40% of PV array is exposed to 80% PSC (stage 2) from simulation time ranged 100s to 150s. The RMPPT is implemented in the PV system to reset the PV operating voltage when the shaded condition is detected. However, this paper discusses mainly the transient response and the steady state response of the developed FMPPT and MPPT.

The simulation results of the PV output power generation are shown in Fig.9. Fig.10 shows the operating voltage of the PV system but the voltage is limited from 110s to 150s for voltage fluctuation discussion. Fig.11 shows the perturbation size computed by the fuzzy logic in the FMPPT.

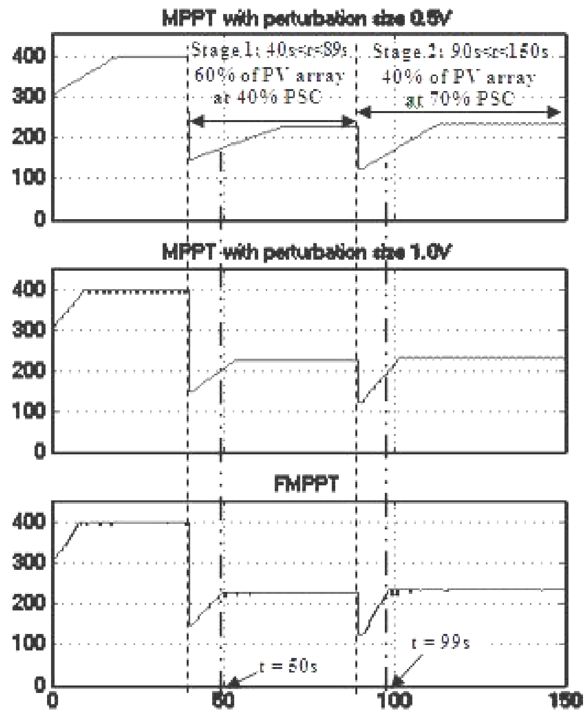


Fig.9. The Output Power Controlled by MPPT and FMPPT

## 3.2 DISCUSSION

The RMPPT resets and allocates the PV array at a new operating voltage when it detects the PV array is under PSC. As shown in Fig.9, the PV system at stage 1 is operated at the global MPP during the steady state condition and generates maximum power of 225W (Refer Fig.8). When the PV system is switched to another shading effect at stage 2, the PV system is allocated at another new operating voltage for a new cycle of MPP tracking. Finally at the stage 2, the PV system is also able to operate at the global MPP and generates maximum power of 233W (Refer Fig.8).

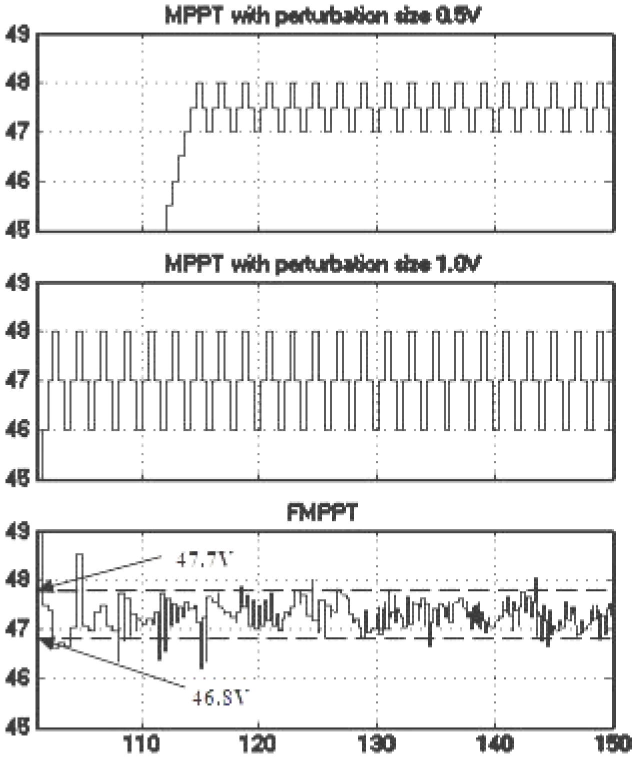


Fig.10. Comparison of Voltage Fluctuation

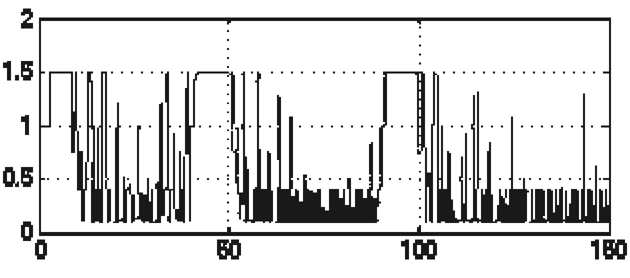


Fig.11. Various perturbed voltage sizes by FMPPT

The transient response of the MPPT and FMPPT can be observed in Fig.9. The simulation results show that FMPPT is the fastest controller in tracking the MPP comparing to MPPT with perturbation size of 0.5V and 1.0V. The simulation result for the first 39s is negligible since the PV system is operated under STC. At simulation time of 40s (stage 1), FMPPT able to track the MPP successfully within 10s and start to settling down at $t$ = 50s. Compared to the conventional MPPT, the tracking time for MPPT with 1.0V and 0.5V perturbation size is recorded as 14s and 27s respectively. Thus, the developed FMPPT utilized a minimum tracking time to lead the PV system to the maximum power generation. Based on the calculation, FMPPT is able to save 28.6% of tracking time comparing to MPPT with 1.0V perturbation size while FMPPT can save 63.0% of tracking time compared to MPPT with 0.5V perturbation size.

The PV system is assigned to face another shading effect at stage 2 when $t$ = 90s. At this stage, 40% of PV array experienced 70% shading. Via RMPPT, the PV system is reset to a new operating voltage point. By observing the result in Fig.9, the MPPT with perturbation size 0.5V, 1.0V and FMPPT are settling down at simulation time of 113s, 102s and 99s respectively. On the other hand, FMPPT has taken 9s to track the global MPP while the tracking time of MPPT with perturbation size 0.5V and 1.0V are 23s and 12s correspondingly. Once again it is verified that FMPPT has better transient response than MPPT where it can save the tracking time by 25.0% and 60.9% comparing to MPPT with perturbation size of 1.0V and 0.5V. The transient response of the controllers can be summarized as in Table.3.

Table.3. Tracking Time of the Controllers

| **Stage** | **Tracking time (s)** | | |
|---|---|---|---|
| | **FMPPT** | **MPPT (fixed Δ*V*, 0.5V)** | **MPPT (fixed Δ*V*, 1.0V)** |
| 1 | 10 | 27 | 14 |
| 2 | 9 | 23 | 12 |

The analysis on the steady state response of the controllers can be done based on the fluctuation of the PV operating voltage. Fig.11 shows the enlarged signal of the PV operating voltage at stage 2. The simulation results show that MPPT with smaller perturbation size tend to generate minimum voltage fluctuation. At steady state condition, MPPT with perturbation size of 0.5V, 1.0V and FMPPT are settling down within the voltage ranges from 47V to 48V, 47V to 49V and 46.8V to 47.7V respectively. Result shows that FMPPT can regulate the PV system to have a minimum voltage fluctuation within 0.9V. Compared to MPPT with 0.5V and 1.0V perturbation size, the voltage fluctuations are recorded as 1.0V and 2.0V respectively. Therefore, FMPPT is able to minimize 10.0% of voltage fluctuation compared to MPPT with 0.5V perturbation size while FMPPT minimize 55.0% of voltage fluctuation comparing to MPPT with 1.0V perturbation size.

FMPPT can vary the perturbation size of the perturbed voltage while the conventional MPPT applies fixed size of perturbed voltage. Referring to Fig.11, FMPPT can control the perturbation size ranges from 0.09V to 1.50V. Since the produced perturbation size can be a very small value, FMPPT generally has higher sensitivity. As a result, FMPPT can control the PV system to be operated at a more precise voltage point or control the PV system converges to the exact MPP voltage point. Assuming the controlled MPP voltage point is the average of upper and lower boundaries of the voltage fluctuation, it can be calculated that the controlled operating voltage by FMPPT is 47.25V while the operating voltage controlled by MPPT with perturbation size of 0.5V and 1.0V is calculated as 47.50V and 48.00V respectively.

The simulation results in Fig.9 and Fig.10 show that FMPPT can control the PV system to reach MPP faster while minimizing the voltage fluctuation when the system approaches the steady state voltage point. This is because FMPPT is able to decide various size of $\Delta V$ according to the instantaneous environmental circumstances. Referring to Fig.11, it shows that large perturbation size as high as 1.5V is selected at simulation time 40s and 90s. At this interval, the fuzzy logic in FMPPT has sensed that there is a relative large change of power, *dp* and large change of power with respect to change of voltage, *dp/dv*. Therefore, a large perturbation size is chosen to reduce the iteration process, hence minimizing the tracking time. However, when the PV system approaches MPP, FMPPT will select a small perturbation size of $\Delta V$. It is recorded in Fig.11 that FMPPT has selected the perturbation size as low as 0.09V when the MPP has been successfully tracked. The small perturbation size is selected to reduce the voltage fluctuation around MPP and hence minimizing the power loss.

FMPPT has better performance comparing to MPPT with perturbation size of 0.5V and 1.0V. The performance of FMPPT can be summarized in Table.4.

Table.4. FMPPT performance compare to MPPT

| **Stage, Type of Response** | **MPPT (fixed $\Delta V$, 0.5V)** | **MPPT (fixed $\Delta V$, 1.0V)** |
|---|---|---|
| **Stage 1, Transient response** | FMPPT saves 63.0% tracking time | FMPPT saves 28.6% tracking time |
| **Stage 2, Transient response** | FMPPT saves 60.9% tracking time | FMPPT saves 25.0% tracking time |
| **Stage 2, Steady state response** | FMPPT minimize 10.0% of voltage fluctuation | FMPPT minimize 55.0% of voltage fluctuation |

## 4. CONCLUSION

The performance of the proposed fuzzy logic based MPPT is investigated particularly when the PV array is under partially shaded conditions. PV module is modelled in MATLAB-SIMULINK based on the commercial SHARP NE-80E2EA PV module. PV array is formed by connecting five identical PV modules in series for larger output power. Under uniformly illuminated conditions, PV system presents nonlinear characteristics but a unique maximum point can be identified in the P-V characteristic. However, as the PV array is under partially shaded conditions, the PV system presents a more complex P-V characteristic with the present of multiple MPPs. To optimize the PV power generation, RMPPT has been implemented to reset the operating voltage point of PV system for a new cycle of global MPP tracking.

The transient response and steady state response of the developed FMPPT and MPPT with perturbation size of 0.5V and 1.0V have been analyzed. It is noticed that FMPPT is able to optimize the power generation of PV system by tracking the MPP in the faster way when there is an immediate change of environmental condition. When the PV system is approaching MPP, FMPPT can select a small perturbation size of voltage to minimize the voltage fluctuation around MPP. Furthermore, FMPPT can control the PV system to be operated at a more precise MPP operating voltage. Based on Table.4, FMPPT can reduce the tracking time as high as 28.6% and voltage fluctuation by 55.0% comparing to MPPT with 1.0V perturbation size. On the other hand, FMPPT can improve the tracking time as high as 63.0% and voltage fluctuation by 10.0% comparing to MPPT with 0.5V perturbation size.

## ACKNOWLEDGEMENT

The authors would like to acknowledge the financial assistance of the Ministry of Higher Education of Malaysia (MoHE) under Fundamental Research Grant Schemes (FRGS) no. FRG0311-TK-1/2012 and the Research Acculturation Grant Scheme (RAGS), grant no. RAG0010-TK-1/2012.

## REFERENCES

[1] B. Parida, S. Iniyan and R. Goic, “A review of solar photovoltaic technologies”, *Renewable and Sustainable Energy Reviews- Elsevier*, Vol. 15, No. 3, pp. 1625-1636, 2011.

[2] K. Ishaque, Z. Salam, A. Shamsudin and M. Amjad, “A direct control based maximum power point tracking method for photovoltaic system under partial shading conditions using particle swarm optimization algorithm”, *Applied Energy-Elsevier*, Vol. 99, pp. 414-422, 2012.

[3] C.S. Chin, P. Neelakantan, H.P. Yoong and K.T.K. Teo, “Optimisation of fuzzy based maximum power point tracking in pv system for rapidly changing solar irradiance”, *Global Journal of Technology and Optimisation, Transaction on Solar Energy and Planning*, Vol. 2, No. 2, pp.130-137, 2011.

[4] V. Salas, E. Olias, A. Barrado and A. Lazaro, “Review of the maximum power point tracking algorithm for stand-alone photovoltaic systems”, *Solar Energy Materials and Solar Cells*, Vol. 90, pp. 1555-1578, 2006.

[5] Syafaruddin, E. Karatepe and T. Hiyama, “Polar coordinate fuzzy controller based real-time maximum-power point control of photovoltaic system”, *Renewable Energy-Elsevier*, Vol. 34, No. 12, pp. 2597-2606, 2009.

[6] R. Ramaprabha, M. Balaji and B.L. Mathur, “Maximum power point tracking of partially shaded solar PV system using modified Fibonacci search method with fuzzy controller”, *International Journal of Electrical Power and Energy Systems*, Vol. 43, No. 1, pp. 754-765, 2012.

[7] M.G. Villalva, J.R. Gazoli and F.E. Ruppert, “Modeling and circuit-based simulation of photovoltaic arrays”, *IEEE Conference on Brazillian Journal of Power Electronics*, pp. 1244-1254, 2009.

[8] Y.J. Wang and P.C. Hsu, “Analytical modelling of partial shading and different orientation of photovoltaic modules”, *IET Renewable Power Generation*, Vol. 4, No. 3, pp. 272-282, 2010.

[9] R. Ramaprabha and B. Mathur, “Effect of shading on series and parallel connected solar PV modules”, *Journal of Modern Applied Science*, Vol. 3, No. 10, pp. 32-41, 2009.

[10] S.R. Chowdhury, and S. Hiranmay, “Maximum power point tracking of partially shaded solar photovoltaic arrays”, *Solar Energy Materials and Solar Cells*, Vol. 94, No. 9, pp. 1441-1447, 2010.

[11] C.S. Chin, P. Neelakantan, S.S. Yang, B.L. Chua and K.T.K. Teo, “Effect of partially shaded conditions on photovoltaic array’s maximum power point tracking”,

*International Journal of Simulation Systems, Science and Technology*, Vol. 12, No. 3, pp. 52-59, 2011.

[12] Y.H. Ji, D.Y, Jung, J.G. Kim, J.H. Kim, T.W. Lee and C.Y. Won, “A real maximum power point tracking method for mismatching compensation in PV array under partially shaded conditions”, *IEEE Transaction on Power Electronics*, Vol. 26, No. 4, pp. 1001-1009, 2011.

[13] C.S. Chin, P. Neelakantan, H.P. Yoong and K.T.K. Teo, “Fuzzy logic based MPPT for photovotaic modules influenced by solar irradiance and cell temperature”, *13th International Conference on Computer Modeling and Simulation,* pp. 376-381, 2011.

[14] M.T. Benmessaoud, F.Z. Zerhouni, M.Zegrar, A. Boudghene and M. Tioursi, “New approach modeling and a maximum power point tracker method for solar cells”, Journal of *Computers and Mathematics with Applications*, Vol. 60, No. 4, pp. 1124-1134, 2010.

[15] N. Femia, G. Petrone, G. Spagnuolo and M. Vitelli, “Optimization of perturb and observe maximum power point tracking method”, *IEEE Transaction on Power Electronics*, Vol. 20, No. 4, pp. 963-973, 2005.