Fuzzy Logic Based MPPT for PV Array under Partially Shaded Conditions

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***Abstract*— This paper presents the fuzzy logic based maximum power point tracking for the optimization of the solar photovoltaic (PV) array under partially shaded conditions. The PV system is modelled in MATLAB/SIMULINK where the PV array is formed by five PV modules connected in series. The *P V* characteristic of PV module and PV array under uniform solar irradiance are nonlinear but there are one maximum power point (MPP) can be identified. Nevertheless, the *P V* characteristic becomes more complex with multiple MPP when the PV array under partially shaded conditions (PSC). In this paper, maximum power point tracking (MPPT) approach based on perturb and observe algorithm has been investigated. Fuzzy logic is adopted into the conventional MPPT to enhance the overall performance of the PV system. The performances of MPPT and FMPPT are investigated particularly on the transient response and the steady state response when the PV array is exposed under different partially shaded conditions. The simulation results show that FMPPT has better performance where it can facilitate the PV array to reach the MPP faster and provide more stable output power.**

Keywords-photovoltaic; partially shaded conditions; fuzzy logic; MPPT

I. INTRODUCTION

The solar photovoltaic (PV) power system becomes popular in this new era because the solar energy is renewable and environmental friendly. Although research and development on solar cell design and fabrication is carried out continuously to reduce the high capital cost, the improvement of overall PV system performance is equally important [1]. One of the interesting areas is by implementing maximum power point tracking (MPPT) technique to control the operating condition of the PV system. This approach is to track the maximum available output power of the PV system and hence to ensure the maximum power can be extracted regardless changes of environmental conditions such as solar irradiance level and ambient temperature.

Various MPPT schemes have been introduced by different authors. Among the popular tracking methods are short circuit current, open circuit voltage, perturb and observe (P&O) and incremental conductance. Short circuit current and open circuit voltage methods appeared in the early stage to detect the optimal operation of the PV system [2]. These methods assume that the relationship between maximum power point (MPP) voltage and short circuit current or open circuit voltage is constant. Hence the optimal voltage can be tracked based on the linear relationship. However, these techniques are not reliable as the relationship between the MPP voltage and short circuit current or open circuit voltage might not be the same for different PV cell technology. These methods might fail in determining the optimal operating condition of the PV system especially when the system is under rapidly changing environmental conditions [3]. Due to this reason, P&O method is proposed to replace the short circuit current and open circuit voltage methods. P&O method is popular and widely applied because of the ease of implementation. However, many modified techniques are still proposed with the aiming to reduce the hardware costing or to improve the performance of the controller [4]. Incremental conductance method for instance is an extensive technique of P&O method. It is developed to improve the tracking accuracy.

To track the optimum operating condition of PV system, the characteristics of the PV system should be recognized. Solar cell is common known as the basic element that converts solar energy into electrical energy. The electricity generation is affected by the incident light where the amount of the illuminated solar irradiance determines the generation of the charge carrier in solar cell [5]. Under uniform illuminated conditions, PV system presents nonlinear characteristics where a unique maximum point can be identified in the *P V* characteristic. The point is commonly known as maximum power point. If the PV system is operated under MPP, maximum power can be extracted from the PV system. However, PV system presents different characteristics when it is exposed under partially shaded conditions. Multiple MPPs will appear in the *P V* characteristic. The complication of the characteristics is depending on the orientation of the PV array and the shading patterns [6, 7]. The occurrence of multiple MPPs decreases the effectiveness of tracking algorithm where the PV array might be operated at the trapped local MPP [8]. Ji et al. has proposed a real MPP tracking (RMPPT) method to allocate the global maximum power point [9] and consequently optimizing the generation of PV system.

In this paper, optimization of PV system under partially shaded conditions will be discussed. PV array will be formed by five PV modules connected in series. The P&O algorithm will be developed to track the optimal condition of the PV system. In general, the efficiency of P&O algorithm is strongly affected by the iteration perturbation size [10].

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Large perturbation size can speed up the tracking speed but the accuracy will be reduced. On the other hand, the small perturbation size can improve the accuracy but the PV system will be suffered from slow response in locating the MPP. Therefore, fuzzy logic is adopted into the conventional P&O algorithm forming fuzzy logic based MPPT (FMPPT). The PV system will implement RMPPT as proposed by Ji et al. to reset the operating condition of PV system when PSC is detected. The transient and steady state response of MPPT and FMPPT for PV system will be evaluated. Results show that FMPPT has better performance in tracking the MPP faster and control the PV system to have more stable output power.

A. Modelling of PV Array

The equivalent circuit in Fig. 1 is known as one diode model and it represents the schematic model of a basic PV cell. A PV cell 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 R_p in the solar cell is caused by the usual p n junction leakage current in the cell and the R_s is caused by the contact resistance of the metal base within the semiconductor layer [5].

Diode's I V characteristic can be described by the Schockley diode equation. The mathematical modelling of I V characteristic of the solar PV cell can be derived as in (1),

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

where I is the solar cell terminal current, I_{pv} is the solar cell light-generated current, I_0 is the diode D_m reverse biased saturation current, V 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.

PV module is formed by a number of identical solar cells connected in series or in parallel to provide larger operating voltage or larger current to the connected load. The further series or parallel connection of several PV modules can form PV array. The basic configuration of five identical PV modules connected in series to form a PV array can be shown in Fig. 2.

B. MPPT Algorithm

The P&O method has been selected to perform maximum power point tracking for PV array due to its simplicity and

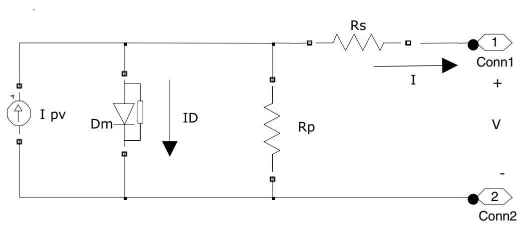

Fig. 1. One diode model.

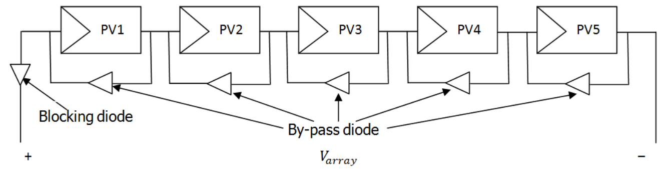

Fig. 2. PV array consists of five identical PV modules.

ease of implementation. P&O is initiated by applying a perturbed voltage, ΔV to alter the operating condition of the PV array. The change of output power at the present and the previous sampling interval is subsequently compared. Based on the instantaneous output power of the two sampling intervals, the MPPT control system can decide to regulate the PV array to be operated either at larger or lower operating voltage. The PV array will pursue numerous of iteration process but eventually the PV system will be operated at a particular optimum power point. At this stage, PV array will be generating maximum output power.

The tracking principal of P&O algorithm is illustrated in the flowchart as in Fig. 3. The operation of P&O algorithm is begun by measuring the voltage and current at two sampling intervals. As the power is the product of voltage and current, the power at two sampling intervals can be compared. By evaluating the operating voltage and output power of the PV array at two sampling intervals, P&O algorithm decides the direction of the tracking process, shifting the operating

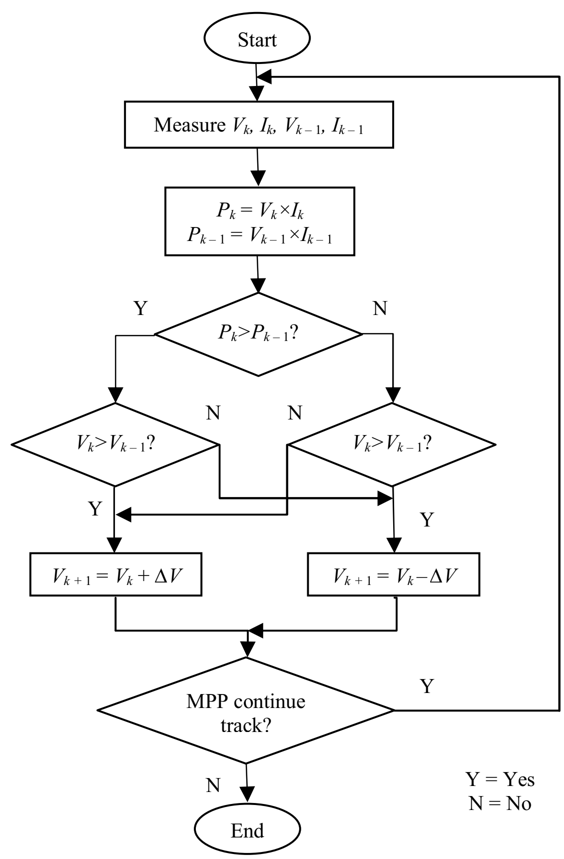

Fig. 3. Flowchart of P&O operation.

voltage either to a larger value or to a smaller value. The operation of P&O algorithm to change the operating voltage of PV array is based on four conditions. The four conditions and action to be taken by the P&O algorithm can be summarized as in Table 1.

The basic operation of P&O algorithm is by implementing the iterative process to track the optimal operating conditions of the PV array. Even though the optimal operating voltage is successfully identified, P&O algorithm will continuously iterate the PV array's operating voltage, aiming to track the next MPP. As a result, the increment and decrement process will lead to the voltage and power fluctuation problem. The fluctuation is obvious when a large perturbation size is applied. Therefore, fuzzy logic is proposed to be adopted into the conventional P&O algorithm. By varying the perturbation size of ΔV, the oscillation of the PV operating voltage is anticipated to be minimum hence reducing power loss in the PV system.

C. Fuzzy Logic

Fuzzy logic is well known as a logical system that does not require accurate mathematic model. Fuzzy logic implements linguistic variable computing method rather than the precise numerical digit numbers. In other words, fuzzy is able to function properly even without precise inputs. Fuzzy logic is relatively more robust compared to the conventional nonlinear controller.

There are four basic elements in the operation of fuzzy logic control, known as the fuzzification, the rule base, the inference engine and the defuzzification. The operation of fuzzy logic control is shown in Fig. 4 where the fuzzy logic control has two inputs, λ and δ and one output, γ.

The operation of fuzzy logic control is initiated by the fuzzification. Fuzzification is the progression of converting the inputs into linguistic variable. Referring to Fig. 4, the PV system actual signal λ and δ will be converted into

TABLE I. CONDITIONS FOR THE OPERATION OF P&O ALGORITHM

Case	Condition	Action on PV array
Case I	$P_k > P_{k-1}$ and $V_k > V_{k-1}$	Operating voltage is increased by ΔV
Case II	$P_k > P_{k-1}$ and $V_k < V_{k-1}$	Operating voltage is decreased by ΔV
Case III	$P_k < P_{k-1}$ and $V_k > V_{k-1}$	Operating voltage is decreased by ΔV
Case IV	$P_k < P_{k-1}$ and $V_k < V_{k-1}$	Operating voltage is increased by ΔV

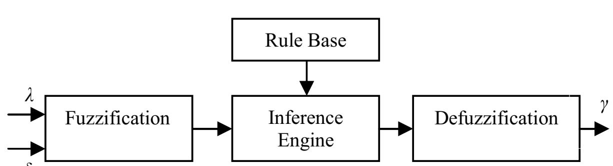

Fig. 4. Operation of fuzzy logic control.

linguistic fuzzy sets via fuzzification. The linguistic fuzzy sets will be represented by fuzzy membership function which it is a curvature presenting each and every point of the membership value. The fuzzy rule base is a compilation of every if-then rules. The rule base contains all information for the controlled parameters and judges all the possible outcomes. The rules are defined according to the professional knowledge and experience on the operation of the system control. The fuzzy inference engine has the capability on decision making where the judgment is based on the defined fuzzy rules. The inference engine is therefore transforming the fuzzy rule base into fuzzy linguistic output. Subsequently, the defuzzifier transferred the linguistic fuzzy sets back into the actual value of γ.

Fuzzy logic is adopted in the P&O algorithm to increase the flexibility of the algorithm in varying the size of the perturbed voltage, ΔV. When the fixed perturbation size ΔV is small, the PV array will suffer from slow tracking of MPP. Increasing perturbation size of ΔV will cause large oscillation on the PV array's operating voltage and subsequently causing power fluctuation problem in the system. With the assistance of fuzzy logic, FMPPT is able to adjust the perturbation size of ΔV based on the collected data at instantaneous circumstances. FMPPT can control the PV array to have fast transient response hence the maximum power operating condition can be tracked faster. In addition, FMPPT is able to reduce the oscillation of the operating voltage thus maintaining the power stability of the PV array when the MPP has been successfully identified.

D. 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 experiences PSC [9]. When the PV array is under PSC, the P V characteristic will become more complex with the occurrence of multiple MPPs. PV array which is operated at the trapped local MPP will generate limited power but in fact the PV array is capable to generate higher output power. For a PV array that generates less power, the efficiency of the system is reduced.

The idea of RMPPT is to compute a new and resettable voltage point within the vicinity of operating voltage when the PSC is detected. If the evidence showing that the PSC is occurred, RMPPT will instruct the PV array to operate at the computed voltage point for a new cycle of MPP tracking. The rearrangement of operating voltage point can facilitate the PV array from being trapped at the local MPPs.

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

$$V_{reset} = \frac{V_{mp}}{I_{mp}} \times I \tag{2}$$

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. At STC, the PV array is receiving 1000W/m^2 solar irradiance and operated at 25^{0}C cell temperature.

II. Modelling and Simulation

The SHARP NE 80E2EA multi-crystalline silicon PV module with rated power 80W is selected as the reference model for PV array modelling in MATLAB SIMULINK. It has 36 series connected solar cell with open circuited voltage of 21.3V and short circuited current of 5.16A. Several PV modules can be connected in series to form PV array in order to have larger output power. The *I V* of PV module and PV arrays under STC are shown in Fig. 5 and the respective *P V* characteristics are shown in Fig. 6. The operating voltage of PV array is greater for larger numbers of series connected PV modules. Referring to Fig. 6, three series connected PV modules can generate output power of 240W which is equal to three times the rated power of a PV module. On the other hand, five series connected PV modules is able to generate output power of 400W, equivalent to five times of the rated power of a PV module. However, series connected PV module is not able to generate larger current as shown in Fig. 5.

The character of PV array under PSC is modelled and the simulation of *I V* and *P V* characteristics of PV array under STC and PSC are shown in Fig. 7 and Fig. 8 respectively. These characteristics are referring to five PV modules connected in series.

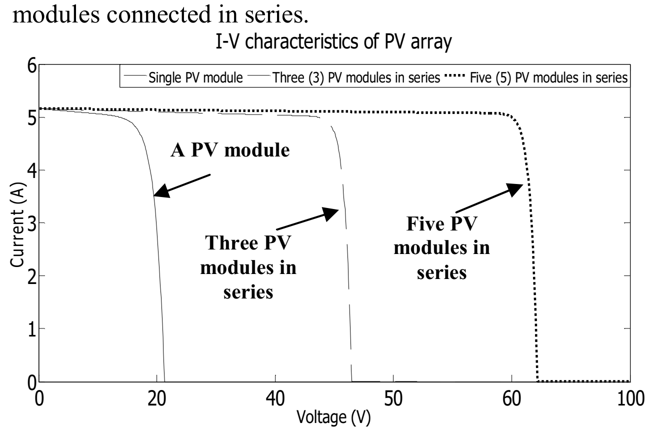

Fig. 5. *I V* characteristic of PV array under STC.

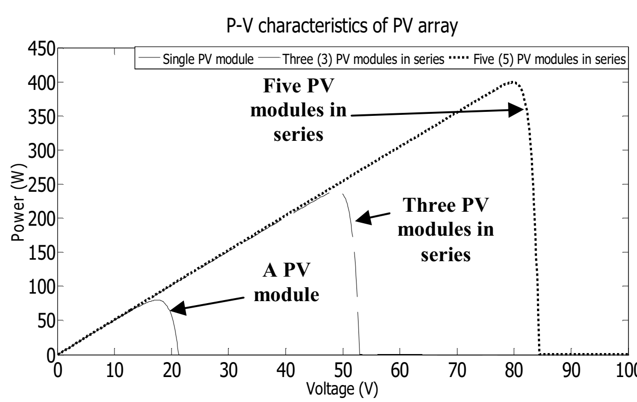

Fig. 6. *I V* characteristic of PV array under STC.

The current generated by PV array under PSC is not the same as the PV array under STC. At STC, 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 generating current is not able to be sustained at a constant value.

When 80% of PV array being shaded 60%, the PV array is generating constant current of approximate 5.2A for the first 13V operating voltage. The current starts to decrease after 13V and settling at a constant current approximately 2.1A along the remaining operating voltage until it reaches 74V.

The PV array at STC has only one MPP as shown in the *P V* characteristic in Fig. 8. However, if the PV array is under PSC, the PV array shows multiple MPPs. When 80% of PV array is shaded 60%, a local MPP located at approximate 17V and a global MPP located at 74V are spotted in the *P V* characteristic. When the condition is changed to 80% shaded on 40% of the entire PV array, a local MPP located at approximate 73V and a global MPP located at 48V are identified in the *P V* characteristic.

Fuzzy logic is developed to assist the P&O algorithm for faster response in tracking the MPP while controlling the PV array to have less fluctuation around the MPP. Fuzzy logic will make decision on the size of the perturbed voltage, ΔV based on the change of power, *dp* and change of power with respect to change of voltage, *dp/dv*. Fig. 9 shows the

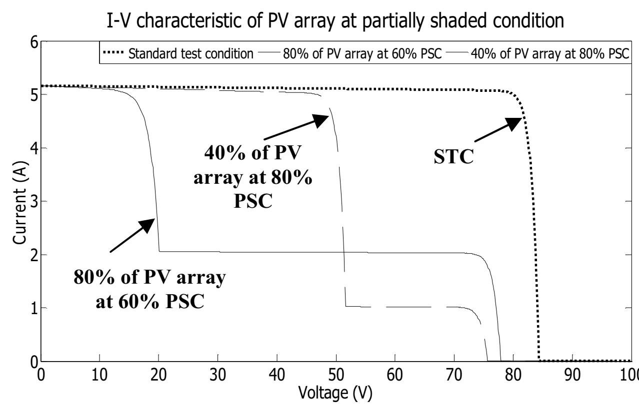

Fig. 7. *I V* characteristic of PV array under PSC.

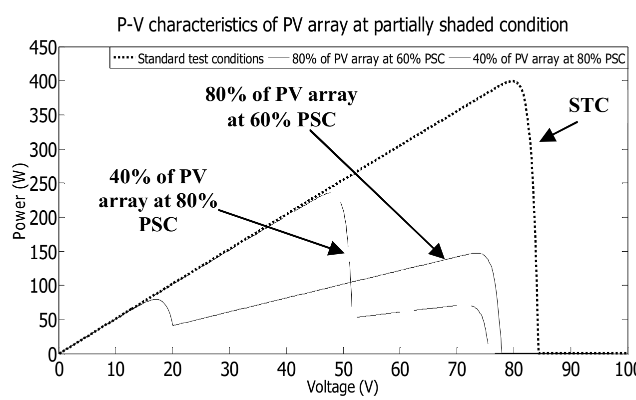

Fig. 8. *P V* characteristic of PV array under PSC.

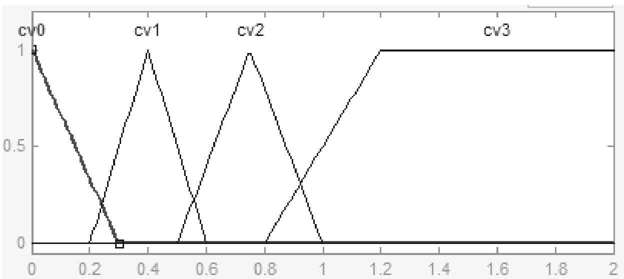

Fig. 9. Membership function of the fuzzy output variable ΔV.

arrangement of membership function in the fuzzy output variable, ΔV.

The configuration of membership function is not set to be distributed evenly along the universe of discourse. As shown in Fig. 9, the output variable has three membership functions in the range of [0 1] whereas only one membership functions is defined in the range of [0.8 2]. This is because fuzzy logic has been placed to work more sensitive in the range of [0 1], where fuzzy logic will decide a smaller but precise size of perturbed voltage when the PV array is approaching MPP.

The membership functions of the input variables are matched with the membership functions of the output variable forming fuzzy rule base system. The rules are validated through fuzzy viewer by adjusting the index line. This process is to verify the fuzzy computed ΔV to be same as the desired value.

A. Results

The performance of FMPPT is compared with the MPPT with perturbation size 0.5V and 1.0V particularly when the PV array is under PSC. The PV system is predefined at STC for the first 50s and subsequently the system is changed to 60% PSC on 80% of PV array (stage 1) until the time equal to 150s. The shaded condition is then changed to 80% PSC on 40% PV array (stage 2) from 150s to 200s. Although RMPPT is implemented in the PV system, this paper will focus on the performance of FMPPT and MPPT.

The simulation results on the PV output power generation can be shown in Fig. 10. The simulation results on the operating voltage of the PV system which are limited from 160s to 200s are shown in Fig. 11. Fig. 12 is the computed perturbation size of FMPPT.

B. Discussion

The RMPPT proposed by Ji et al. is able to allocate new resettable operating voltage for global MPP tracking in the PV system. In Fig. 10, the PV system at stage 1 is operated at global MPP and able to generate maximum power of 150W. When the PV system is shift to another shading effect at stage 2, the PV system is allocated to resettable operating voltage for a new cycle of MPP tracking. Finally in the stage 2, the PV system generates maximum power of 240W.

The transient response of the MPPT and FMPPT can be observed in Fig. 10. Results show that FMPPT can track the MPP faster than MPPT with perturbation size of 0.5V and 1.0V. At stage 1, FMPPT tracks the MPP within 15s and

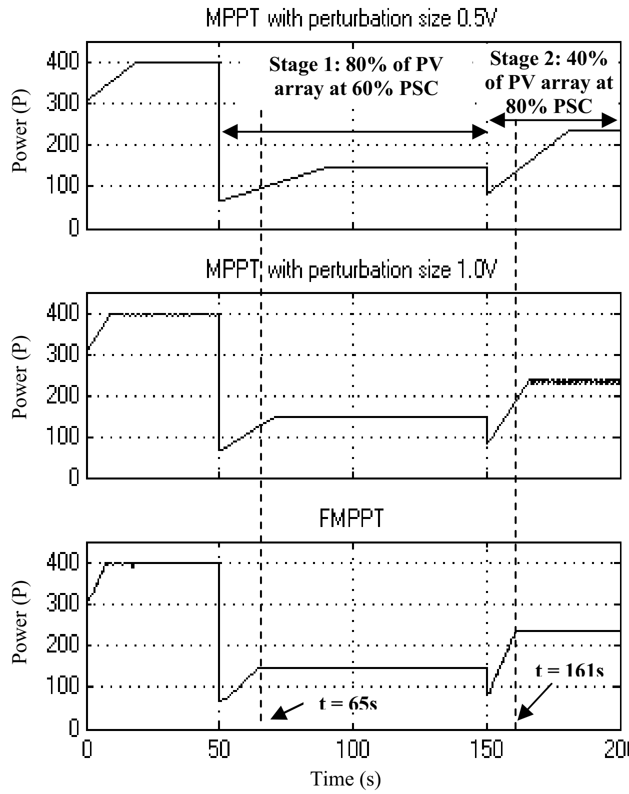

Fig. 10. The output power controlled by MPPT and FMPPT.

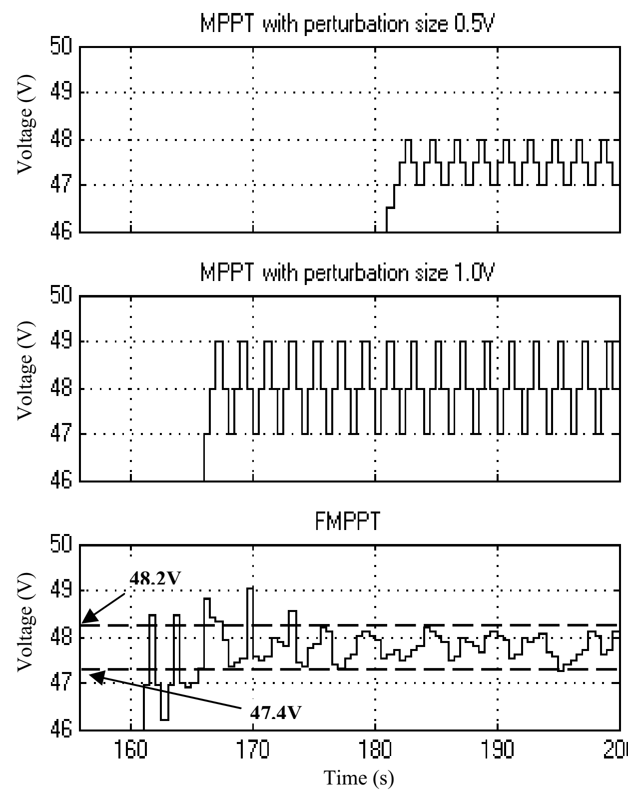

Fig. 11. Comparison of voltage fluctuation.

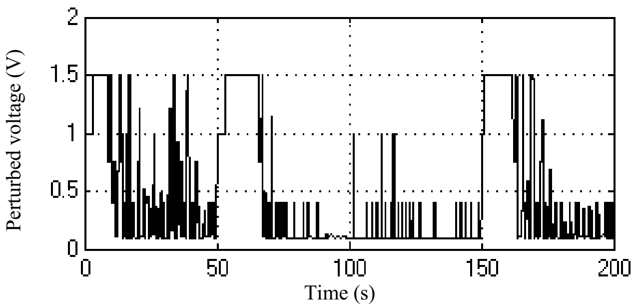

Fig. 12. Various sizes of perturbed voltage by FMPPT.

started to settle down at t = 65s. The tracking periods for MPPT with 1.0V and 0.5V perturbation size however are 20s and 39s respectively. Therefore, FMPPT is able to save 25% of tracking time compared to MPPT with 1.0V perturbation size while saving 61.5% of tacking time compared to MPPT with 0.5V perturbation size.

At stage 2, the MPPT with perturbation size 0.5V, 1.0V and FMPPT settling down at global MPP at simulation time of 181s, 166s and 161s respectively. Under this shading effect, FMPPT has the fastest transient response and manage to save the tracking time of 31.3% and 64.5% compared to MPPT with perturbation size of 1.0V and 0.5V.

The steady state response of the controllers can be observed through the fluctuation of the operating voltage in the PV system at stage 2 as shown in Fig. 11. Results show that MPPT with smaller perturbation size having less fluctuation. At steady state condition, MPPT with perturbation size of 0.5V, 1.0V and FMPPT are settling down within the voltage ranges of 47V to 48V, 47V to 49V and 47.4V to 48.2V respectively. FMPPT has minimum voltage fluctuation and being calculated fluctuated within 0.8V as compared to 1.0V and 2.0V voltage fluctuation by MPPT with 0.5V and 1.0V perturbation size. FMPPT has improved 20% and 60% of the steady state response compared to MPPT with 0.5V and 1.0V perturbation size.

In addition, Fig. 11 shows that FMPPT can control the PV system to be operated at a more precise MPP. The MPP is to be controlled within the upper and lower boundaries of voltage fluctuation. Referring to Fig.11, based on the average between upper and lower boundaries, it is calculated that the MPP operating voltage is 47.8V. This operating voltage is within the fluctuation boundaries of the MPPT with 0.5V and 1.0V perturbation size and it is more precise compared to MPPT with perturbation size of 0.5V and 1.0V.

FMPPT decides various size of ΔV according to the instantaneous environmental circumstances. Referring to Fig. 12, it shows that large perturbation size as high as 1.5V is selected when the change of environmental conditions appeared at 50s and 150s. Large perturbation size is chosen to reduce the iteration process and hence having a minimum tracking time. When the PV system approaches MPP, FMPPT selects a small perturbation size of ΔV as low as 0.09V. The small perturbation size is selected to minimize the voltage fluctuation around MPP.

III. Conclusion

The performance of the proposed fuzzy logic based MPPT is investigated when the PV array is under partially shaded conditions. In this work, PV array is modelled based on five series connected PV modules. FMPPT is able to optimize the generation of PV system by tracking the MPP faster when the environmental condition is changed. When the PV system is approaching MPP, FMPPT will select small perturbation size of voltage to minimize the fluctuation around MPP. In addition, FMPPT can control the PV system to be operated at a more precise operating voltage. Based on the simulation results, FMPPT can reduce tracking time and voltage fluctuation as high as 31.3% and 60% respectively compared to MPPT with 1.0V perturbation size. On the other hand, FMPPT can improve the tracking time and voltage fluctuation as high as 64.5% and 20% correspondingly compared to MPPT with 0.5V perturbation size.

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