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Fuzzy Logic Based MPPT for Photovoltaic Modules Influenced by Solar Irradiation and Cell Temperature

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***Abstract*—This paper presents fuzzy based perturb and observe maximum power point tracking in solar panel. The solar system is modelled and analysed in MATLAB/SIMULINK. The photovoltaic panel has an optimal operating voltage where the PV panel can produce maximum power at this particular point. Due to the nonlinearity of the voltage-current characteristic in solar panel, it is difficult to determine analytically the maximum power operating voltage that varies with the change of solar irradiance and cell temperature. Maximum power point tracking (MPPT) is implemented to identify the maximum power operating point, subsequently regulate the solar panel to operate at that particular operating voltage for maximum power gaining. Perturb and observe (P&O) MPPT and fuzzy based optimized P&O MPPT are developed and the performances of both controllers are examined at variable solar irradiances at different temperatures. Simulation results show that fuzzy based P&O MPPT has better performance where it can facilitate the solar panel to produce a more stable power.**

Keywords-Solar photovoltaic; perturb and observe; MPPT; fuzzy logic control

I. INTRODUCTION

Solar photovoltaic is a phenomenon where the solar irradiance is converted directly into electricity through solar cell [1]. The process of conversion has no environmental impact since it does not occupy any material to be consumed or emitted. The operation of photovoltaic (PV) system is static, quite and free of moving parts since the solar cell is a semiconductor device [2].

The solar panel has an optimal operating point which can supply the maximum power to the load. The particular operating point is generally called maximum power point (MPP). The locus of MPP has a non-linear variation because the current-voltage characteristic of PV module is strongly influenced by the solar irradiance and cell temperature [3]. With the nonlinearity of PV module, maximum power point tracking (MPPT) should be developed for the PV system. MPPT can identify the PV panel MPP operating voltage at any solar irradiance and temperature. By regulating the voltage of PV module to the MPP operating voltage, the PV power can be drawn as much as possible. As a result, the efficiency of PV system can be improved.

There are several methods that have been widely implemented to track the MPP, e.g. perturb and observe (P&O), incremental conductance, parasitic capacitance and three-point weight comparison [4]. In this paper, P&O MPPT is discussed. P&O MPPT apply iterative method where the PV panel operating voltage is perturbed and subsequently, the effect on the PV output power is observed [5]. MPPT measures the power-voltage characteristic of PV module and determines the direction of the PV operating voltage. If the PV panel power at present state is larger than the previous state, the PV panel operating voltage shall be increased by a small increment of fixed voltage Δv or vice-versa. The iteration process will be continued even until the MPP has been identified due to the needs of continuous tracking for the next perturbation cycle. This however leads to the power fluctuation problem in the PV module due to the increment or decrement of voltage Δv by MPPT algorithm to the PV operating voltage.

In this paper, fuzzy logic is proposed to be implemented in the P&O MPPT. Fuzzy is relatively simple to design as fuzzy do not require any information about the exact model. The implementation of fuzzy is aimed to assist the P&O MPPT to minimize the PV power fluctuation. By obtaining the data change of power dp and change of power with respect to change of voltage dp/dv, the fuzzy can determine the suitable size of the perturbed voltage cv to P&O MPPT for further iteration. P&O MPPT will hence place an increment of decrement of voltage cv to the present PV operating voltage and continue to track the MPP.

II. FUZZY LOGIC BASED P&O MPPT PV SYSTEM

Solar PV system consists of a PV panel, a buck-boost converter, fuzzy based P&O MPPT control unit and a load which can be shown in Fig. 1. The power produced by PV panel is delivered to the load through the buck-boost converter. The output voltage and current of the PV panel are fed to the fuzzy based MPPT control unit for MPP tracking. Fuzzy logic is used to determine the size of the perturbed voltage based on the voltage and current signals from the PV module. Fuzzy logic P&O MPPT will decide the new operating voltage for PV panel by adjusting the duty cycle of the buck-boost converter.

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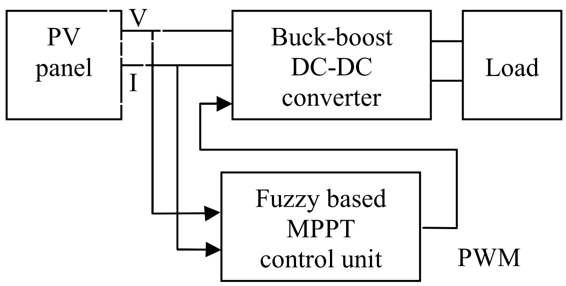


Figure 1. Fuzzy based MPPT solar PV panel.

A. Mathematical Modelof PV Module

The general model of solar cell can be derived from an equivalent circuit named one diode model or single diode model. One diode model consists of a photo current source, a diode, an equivalent parallel resistor and an equivalent series resistor which can be shown as in Fig. 2 [6].

The Schockley diode equation which describes the *I-V* characteristic of diode D_m is given as (1),

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

where I_{Dm} is the diode current, I_0 is the reverse bias saturation current of the diode, V_{Dm} is the voltage across the diode, n is the ideality factor of the diode and V_T is the thermal voltage. The thermal voltage, V_T has the function as shown in (2)

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

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).

Based on the equivalent circuit in Fig. 2, the *I-V* characteristic of PV module can be derived as in (3),

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

where I is the terminal current of PV module, I_{pv} is the PV module light-generated current, V_{pv} is the PV module terminal voltage, R_s is the equivalent series resistance and R_p is the equivalent parallel resistance.

The PV module presents hybrid behaviour of current source or voltage source. When the PV module operates at the voltage smaller than maximum power voltage point, it will act as a current source. Otherwise, PV module acts as voltage source. Fig. 3 shows the behaviour of PV module acts as current source and voltage source at different region.

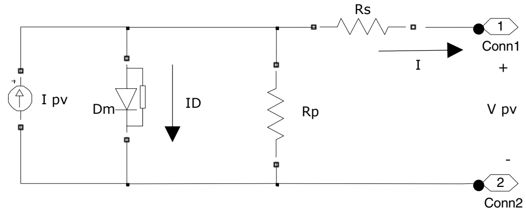


Figure 2. One diode model represents solar cell.

The *I-V* characteristic of the PV module depends on the internal characteristics of the PV module, R_s and R_p as well as the external influences such as solar irradiance level and the cell temperature. The series resistance, R_s which is the sum of structural resistance of PV module has great influence when the PV module acts as voltage source. The parallel resistance, R_p however has strong influence when PV module acts as current source where R_p exists due to the leakage current of *p-n* junction of the PV cell, depending on the fabrication method. In general, R_p is very high and R_s is very low. High resistance of R_p resists the PV cell being short-circuited and low resistance of R_s allows the current flow to the load without resistance. To simplify the PV module, the R_s and R_p are generally neglected [7].

The external influences (solar irradiance and cell temperature) influence the *I-V* characteristic of PV module. The amount of solar irradiance affects the generation of charge carrier in PV module and subsequently, affects the generated current. The PV module light-generated current, I_{pv} with the influence of the cell temperature can be described as (4),

$$I_{pv} = I_{pvn} + K_I \Delta T \quad (4)$$

where I_{pvn} is the PV module light-generated current in the nominal condition, K_I is the ratio of short-circuit current to temperature coefficient, ΔT is the difference of actual temperature to the nominal temperature. At nominal condition, the solar irradiance on the PV module surface is 1000 W/m^2 and the cell temperature is 25 ^{o}C [7].

B. Buck-boost DC-DC Converter

Buck-boost DC-DC converter is important in PV system since it has the ablility of regulating the output voltage. The output voltage can be controlled to be less or greater than the input voltage by varying the duty cycle D. Buck-boost converter allows more flexibility in modulating the energy transfer from the input source to the load [8]. Fig. 4 shows the circuit of buck-boost DC-DC converter.

The relationship among the load voltage, V_a input source voltage, V_s and duty cycle, D can be described as in (5).

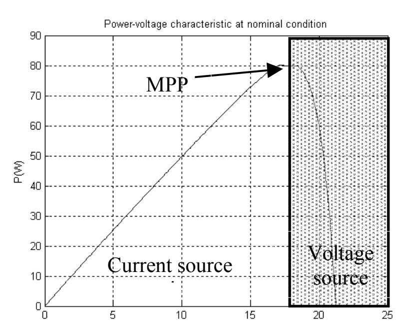


Figure 3. Hybrid behaviour of PV module.

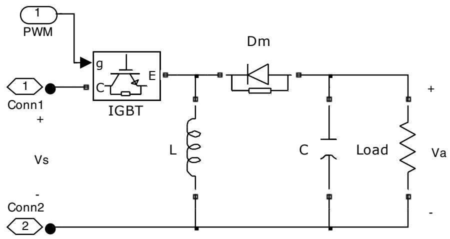


Figure 4. Circuit diagram of buck-boost converter.

$$D = \frac{V_a}{V_a - V_s} \tag{5}$$

C. Perturb and Observe MPPT

Perturb and observe (P&O) method is widely used to track the MPP of the PV module. The algorithm applies a small increment or decrement of perturbed voltage ΔV to the PV module operating voltage. The operation of the P&O MPPT can be shown as in Fig. 5.

The measurement of actual state k and previous state k-1 of parameters V and I are taken. Comparison has been made between the actual and previous state of the parameters power, P and voltage, V. Based on the conditions as stated in Fig. 5, increment or decrement of perturbed voltage, ΔV will be applied to the PV module operating voltage.

Fig. 6 shows the power-voltage characteristic of PV model which is used to discuss the principle of MPP tracking. There are four possible cases which will influence the direction of the tracking in P&O MPPT. Case I where $P_k > P_{k\text{-}1}$ *and* $V_k > V_{k\text{-}1}$, the situation can be described as path α in Fig. 6. When the operating voltage is increased, the PV power is increased also. Therefore, a small change of voltage ΔV need to be added to the present PV operating voltage followed by monitoring of the PV power. The process is continued until the MPP is identified.

Case II where $P_k > P_{k\text{-}1}$ *and* $V_k < V_{k\text{-}1}$ referred to path β in Fig. 6. It can be noticed that when the operating voltage is decreased, the PV power is increased. In order to identify the MPP operating point, reduction of ΔV should be made on the present PV operating voltage and the parameters P_k and $P_{k\text{-}1}$ are compared. If the condition $P_k > P_{k\text{-}1}$ is fulfilled, the decrement of ΔV will be continued until the MPP is successfully spotted.

Case III where $P_k < P_{k\text{-}1}$ and $V_k > V_{k\text{-}1}$ can be described as path β in Fig. 6. In this case, the PV power is decreasing as the increased of PV operating voltage. Thus, it should have a reduction of ΔV on the present PV operating voltage. Case IV where $P_k < P_{k\text{-}1}$ and $V_k < V_{k\text{-}1}$ is illustrated as path α in Fig. 6. The PV power is reducing as the decreasing of PV operating voltage. Thus the PV operating voltage should have an increment of ΔV to track the PV maximum power point.

The main weakness of P&O MPPT algorithm is the PV module's operating voltage is perturbed every cycle [11]. The algorithm will always perform an increment or decrement of ΔV to the PV operating voltage. The operation of maximum power tracking will be carried on even the MPP has been successfully tracked. This is due to the output power of PV module for the next perturbed cycle is unpredictable.

The continuous tracking of MPP is good for maximum power gaining from PV module. However it raises another problem. The increment and decrement of ΔV will lead to oscillation of the PV operating voltage and hence cause the power fluctuation which lead to the power loss in the PV system. Thus, fuzzy logic is implemented in the P&O MPPT to reduce the oscillation of the PV operating voltage and hence minimizing the power loss in the PV system.

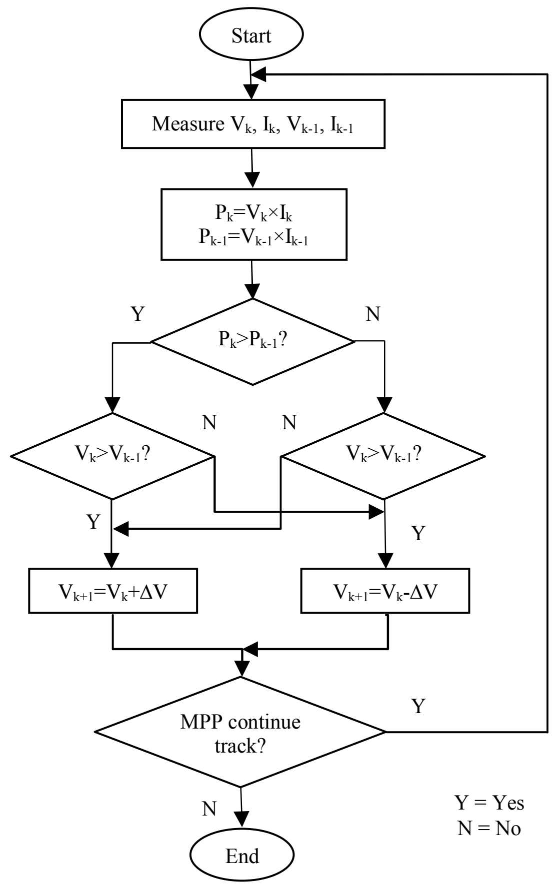


Figure 5. Flowchart shows the operation of P&O MPPT.

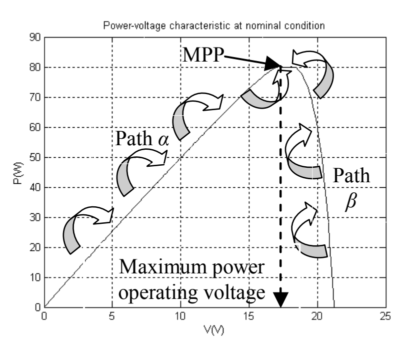


Figure 6. Principle for MPP tracking.

D. Fuzzy Logic

Fuzzy logic is a tool with their heuristic nature associated with simplicity and effectiveness for linear and non-linear systems. It is relatively easy to use since fuzzy do not require accurate mathematic model. In addition, fuzzy is able to function properly even with the imprecise inputs. Besides, fuzzy is more robust compared to the conventional non-linear controller [9].

The operation of fuzzy logic control can be classified into four basic elements. The four elements are fuzzification, rule base, inference engine and defuzzification. The operation of fuzzy logic control is shown in Fig. 7.

The fuzzification is the process of converting the system actual signal λ and δ into linguistic fuzzy sets using fuzzy membership function. The membership function is the curvature that presents each point of membership value. Fuzzy rule base is a collection of if-then rules which all the information is available for the controlled parameters. The fuzzy rule base is set according to professional experience and the operation of the system control. Fuzzy inference engine however has the function of formulating a logical decision based on the fuzzy rule setting. It will then transform the fuzzy rule base into fuzzy linguistic output. Defuzzifier is a manner to convert the linguistic fuzzy sets back into actual value γ.

III. Modelling and Simulation

A. PV Module

The SHARP NE-80E2EA multi-crystalline silicon PV module with 80W is modelled in MATLAB-SIMULINK. The author's previous paper in [10] has modelled the PV module at various solar irradiances. However, the PV model is only applicable at constant temperature of 25 ^{o}C. In this paper, the effect of solar cell temperature has been taken into consideration. To model the PV module in MATLAB-SIMULINK, the parameters which are obtained from SHARP NE-80E2EA datasheet are shown in Table 1.

The *P-V* characteristic of PV module at variable solar irradiance with constant cell temperature 25 ^{o}C is shown in Fig. 8. It can be noticed that the MPP operating voltage point of PV module is varying at different solar irradiance. The MPP voltage point is higher as the solar irradiance increased. Fig. 8 shows that the MPP voltage operating point of PV module at 1000 W/m^2 is greater than the MPP voltage operating point at 600 W/m^2.

Fig. 9 shows the *P-V* characteristic of the variable temperature of the PV module at constant 1000 W/m^2 solar irradiance. It shows that the MPP operating voltage point of PV module is decreasing with higher value of cell temperature.

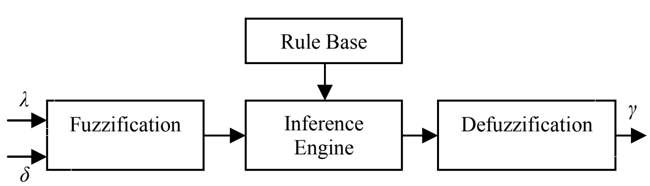


Figure 7. Four basic elements in fuzzy logic controller.

TABLE I. Parameters of SHARP NE-80E2EA PV Array at 1000W/m^2 Solar Irradiance.

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

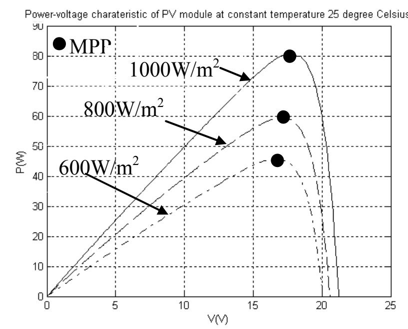


Figure 8. *P-V* characteristic of PV module at constant temperature 25 ^{o}C.

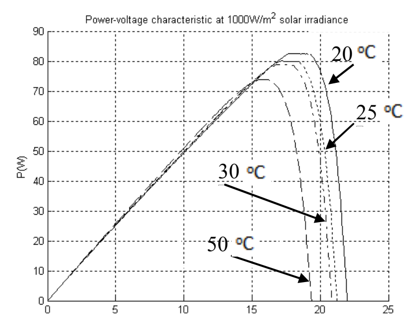


Figure 9. *P-V* characteristic of PV module at constant 1000 W/m^2 solar irradiance.

The PV module which is modelled in MATLAB-SIMULINK has been examined and the results show that the simulated PV module has similar characteristics that described in SHARP NE-80E2EA datasheet.

B. Fuzzy Logic Based MPPT

The change of power d*p* and change of power with respect to change of voltage d*p*/d*v* are selected as the inputs of the fuzzy logic controllers. The two inputs can be described as in (6) and (7) where *k* is the current state and *k*-1 is the previous state.

$$dp = P_k - P_{k-1} \tag{6}$$

$$\frac{dp}{dv} = \frac{P_k - P_{k-1}}{V_k - V_{k-1}} \tag{7}$$

Fuzzy logic is implemented in P&O MPPT to reduce the oscillation around the MPP operating voltage point. Fuzzy logic is designed to decide the magnitude of perturbed voltage c*v* for P&O MPPT. The conventional P&O MPPT perturbs the PV operating voltage with constant value ΔV, whereas fuzzy can decide a range of perturbed voltage where it will select a proper perturbed voltage c*v* according to different circumstances (variation of solar irradiance and cell temperature) by comparing actual state *k* and previous state *k*-1 of the magnitude inputs d*p* and d*p*/d*v*. Subsequently, the P&O MPPT perform the MPP tracking operation with an increment or decrement of the fuzzy output c*v*. The range of universal discourse perturbed voltage c*v* can be controlled by fuzzy logic to limit the PV module from performing large operating voltage oscillation.

Fig. 10 shows the fuzzy viewer of optimized P&O MPPT. Fuzzy viewer is used to verify if the rules are set correctly. Fuzzy rule base is an important element as it collects all the data for the fuzzy inference engine. Fuzzy inference engine will then process and determine a logical conclusion with the condition that the rules are set correctly.

There are total of seven rules set in the rule base. From Fig. 10, it can be seen that the fuzzy viewer shows seven rows of plot. This is because one row of plot represents one rule.

In the first row of plot, the rule has been set as when the d*p* is high, then the c*v* is set to be the highest, regardless any changes of d*p*/d*v*. If the change of power is large, it is predicted that the current state of PV operating voltage point is far from the actual MPP operating voltage point. Therefore, a large perturbed voltage should be applied in order to track the MPP faster.

The output decision of fuzzy inference engine can be checked via adjusting the index line of inputs d*p* and d*p*/d*v*. Refer to Fig. 10, the index line of d*p* and d*p*/d*v* is adjusted to 2.8 and 3 respectively. Through the process of fuzzy inference engine, the perturbed voltage c*v* can be calculated. The defuzzification method used in fuzzy logic which is implemented in P&O MPPT is centroid. Centroid computes the centre of arc under curve as shown in Fig. 10. The areas of the first, second and third row of plot are accumulated and the centre of area under curve is calculated as 0.532.

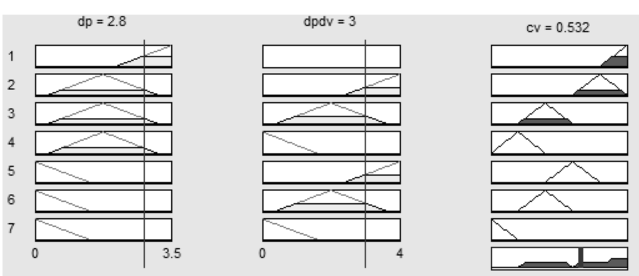


Figure 10. Fuzzy rule viewer for parameters verification.

IV. RESULTS

Fig. 11 shows the data of solar irradiance and cell temperature collected for 8 hours (480 minutes) are fed into the PV module for P&O MPPT and fuzzy logic based P&O MPPT investigation. The simulation results of P&O MPPT and fuzzy logic based P&O MPPT involving the PV operating voltage and PV maximum power are shown in Fig. 12 and Fig. 13 respectively.

V. DISCUSSION

The author has investigated the controllers' performance at variable changes of solar irradiance but only at constant temperature of 25 ^{o}C in [10]. In this paper, both controllers are investigated with variable changes of solar irradiance and in addition with the changes of cell temperature which is also affecting the PV maximum power gaining.

The *x*-axis in Fig. 11 represents the time in minute. The total examination time for both controllers is eight hours or 480 minutes. Based on the observation of the simulation results in Fig. 12 and Fig. 13, both controllers can track the maximum power. However, fuzzy based P&O MPPT has better performance as compared to the conventional P&O MPPT. The operating voltage in conventional P&O MPPT has frequent large oscillation between 13.5V to 16V. Compared to fuzzy based P&O MPPT, the oscillation of PV operating voltage is only varies in the range of 14V to 15.5V. The simulation results verify that fuzzy logic has selected proper perturbed voltage c*v* for the MPPT based on the information extracted from inputs d*p* and d*p*/d*v*.

Large oscillation of operating voltage will cause large power fluctuation which will eventually lead to power loss problem in PV module. The PV system using P&O MPPT without fuzzy logic control optimization has larger oscillation of operating voltage around the MPP. Therefore, the output power has larger fluctuation. By implementing fuzzy logic control to optimize P&O MPPT, the oscillation around the MPP point is reduced as shown in Fig. 13. Hence, the power fluctuation in PV module is minimized.

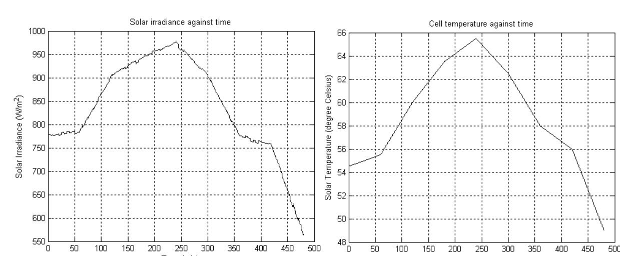
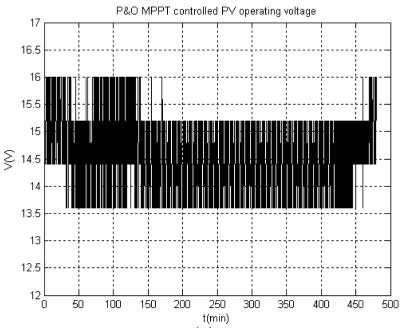
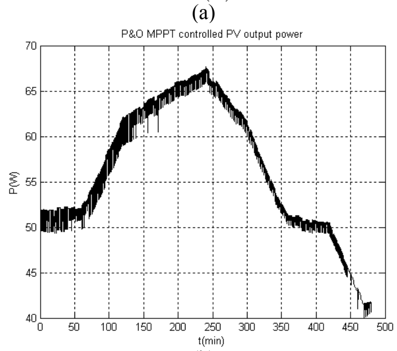


Figure 11. Solar irradiance and cell temperature for controllers examination.

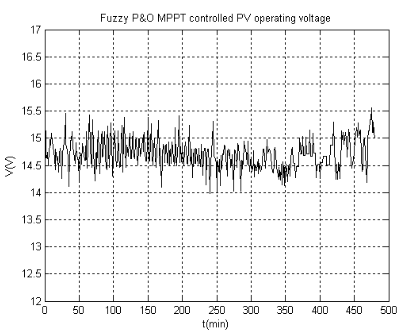


(a)



(b)

Figure 12. Results of P&O MPPT which include (a) PV operating voltage and (b) PV output power



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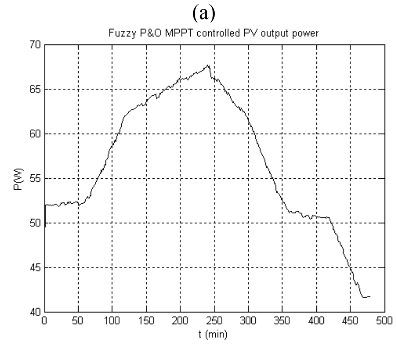

(b)

Figure 13. Results of fuzzy based P&O MPPT which include (a) PV operating voltage and (b) PV output power.

VI. CONCLUSION

The *P-V* characteristic and *I-V* characteristic of PV module SHARP NE-80E2EA has been modelled in MATLAB-SIMULINK with various change of solar irradiance and cell temperature. The P&O MPPT is developed to track the MPP of PV module. Fuzzy logic is implemented to the conventional P&O MPPT to optimize the perturbed voltage of conventional MPPT to obtain less power fluctuation. Based on the simulations results, it can be observed that both controllers can be used to track the MPP under variable changes of solar irradiance and cell temperature. PV module can produce maximum power which both controllers regulate the PV module to operate at MPP operating voltage. However, it can be concluded that fuzzy logic based P&O MPPT perform better with less oscillation around the MPP operating voltage point. This improvement minimizes the power fluctuation of the PV module and thus, prevents power loss in PV module.

REFERENCES

[1] Noppadol Khaehintung, Phaophak Sirisuk, and Anatawat Kunakorn, “Grid-connected photovoltaic system with maximum power point tracking using self-organizing fuzzy logic controller”, IEEE Power Electronics and Drives Systems, PEDS, Kuala Lumpur, 2005, pp. 517-521.

[2] Huan-Liang Tsai, “Insolation-oriented model of photovoltaic module using MATLAB/SIMULINK”, Solar Energy 84, 2010, pp. 1318-1326.

[3] S.Lalouni, D. Rekioua, T. Rekioua, and E. Matagne, “Fuzzy logic control of stand-alone photovoltaic system with battery storage”, Journal of Power Sources, Volume 193, Issue2, 5 September 2009, pp. 899-907.

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

[5] M.S. Ait Cheikh, C. Larbes, G. F. Tchoketch Kebir, and A. Zerguerras, “Maximum power point tracking using a fuzzy logic control scheme”, Revue des energies Renouvelables, Vol. 10, 2007, pp. 387-395.

[6] Wang Chang-Chun, Wu Ming-Chuan, and Ou Sheng-Yuan, “Analysis and research on maximum power point tracking of photovoltaic array with fuzzy logic control and three point weight comparison method”, Science China Press and Springer-Verlag Berlin Heidelberg, Vol. 53, August 2010, pp.2183-2189.

[7] Marcelo Gradella Villalve, Jonas Rafael Gazoli, and Ernesto Ruppert Filho, “Comprehensive approach to modeling and simulation of photvoltaic arrays”, IEEE Transactions on Power Electronics, vol. 24, no.5, pp. 1198-2009.

[8] Dimosthenis Peftitsis, Georgios Adamidis, Panagiotis Bakas, and Anastasios Balouktsis, “Photovoltaic system MPPTracker Investigation and implementation using DSP engine and buck-boost DC-DC converter”, IEEE Power Electronics and Motion Control Conference, 13th EPE-PEMC, 2008, pp. 1840-1846.

[9] Mummadi Veerachary, Tomonobu Senjyu, and Katsumi Uezato, “Feedforward maximum power point tracking of PV systems using fuzzy controller”, IEEE transactions on Aerospace and Electronics Systems, Vol. 38, Issue 3, 2002, pp. 969-981.

[10] C. S. Chin, P. Neelakantan, H. P. Yoong, and K. T. K. Teo, “Control and optimization of fuzzy based maximum power point tracking in solar photovoltaic system”, Global Conference on Power Control and Optimization, 2010.

[11] Roberto Faranda, and Sonia Leva, “Energy comparison of MPPT techniques for PV systems”, WSEA transactions on Power Systems, 2008, pp. 446-455.