A Study of Maximum Power Point Tracking Algorithms for Stand-alone Photovoltaic Systems

Mei Shan Ngan, Chee Wei Tan
Department of Energy Conversion, Faculty of Electrical Engineering
Universiti Teknologi Malaysia, 81300, Skudai, Johor, Malaysia.

Abstract- **The Photovoltaic (PV) energy is one of the renewable energies that attracts attention of researchers in the recent decades. Since the conversion efficiency of PV arrays is very low, it requires maximum power point tracking (MPPT) control techniques to extract the maximum available power from PV arrays. In this paper, two categories of MPPT algorithms, namely indirect and direct methods are discussed. In addition to that, the advantages and disadvantages of each MPPT algorithm are reviewed. Simulations of PV modules were also performed using Perturb and Observe algorithm and Fuzzy Logic controller. The simulation results produced by the two algorithms are compared with the expected results generated by Solarex MSX60 PV modules. Besides that, the P-V characteristics of PV arrays under partial shaded conditions are discussed in the last section.**

I. INTRODUCTION

In recent decades, the continuous growth of energy demand from all around the world has urged the society to seek for alternative energies due to the depletion of conventional energy resources. Among the available alternative energies, photovoltaic (PV) energy is one of the most promising renewable energy, PV energy is clean, inexhaustible and free to harvest [1]. However, there are two main drawbacks of PV system, namely the high installation cost and the low conversion efficiency of PV modules which is only in the range of 9-17% [1]. Besides that, PV characteristics are non linear and it is very much weather dependent. Fig. 1Fig. **2** show the I-V and P-V characteristics of a typical PV module for a series of temperatures and solar irradiance levels [2,3]. It can be noticed that PV output voltage greatly governed by temperature while PV output current has approximate linear relationship with solar irradiances. It can be seen from the P-V characteristic curve that there is only one peak operating point which is named as the maximum power point (MPP). Due to the high capital cost of PV array, maximum power point tracking (MPPT) control techniques are essential in order to extract the maximum available power from PV array in order to maximize the utilization efficiency of PV array. Therefore, a DC-DC converter is inserted between PV generator and load or battery storage. MPPT algorithms are used to control the switching of DC-DC converter by applying pulse-width modulation (PWM) technique [1,2].

This paper reviews and simulates the existing MPPT algorithms, namely MPPT under fully illuminated and MPPT for partial shaded conditions. The advantages and disadvantages of five different MPPT algorithms are discussed and simulations of PV system using Perturb and Observe (P&O) and Fuzzly Logic controller (FLC) algorithms are described. Then, results and discussions of the simulations will be analyzed. The development of the PV system under partial shaded conditions will also be discussed. Finally, the last section concludes the review and the simulations of the studied MPPT algorithms.

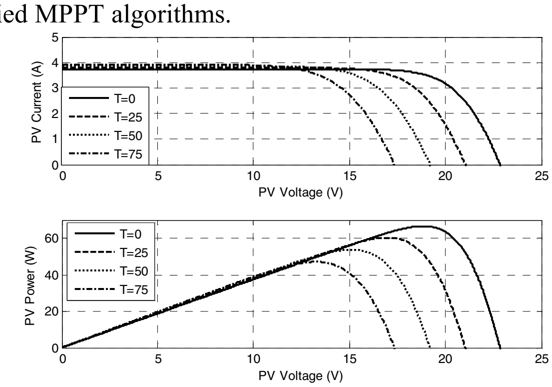


Fig. 1. I-V and P-V characteristics of a typical PV module for varied temperatures [2-4].

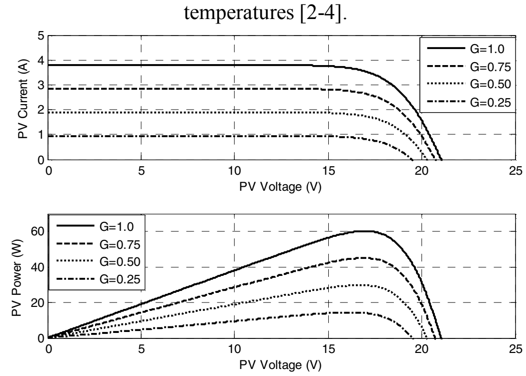


Fig. 2**.** I-V and P-V characteristics of a typical PV module for varied solar irradiances [2-4].

II. MPPT ALGORITHMS

There are many MPPT algorithms have been developed and implemented by researchers [1-3]. In general, MPPT techniques can be divided into two categories, namely direct and indirect methods [2]. Direct method of MPPT algorithms is independent from prior knowledge of PV modules' characteristics. The MPPT algorithms that include in this category are Perturb and Observe method (P&O), incremental conductance method (INCond.), feedback voltage or current, fuzzy logic method and neural network method. Indirect method requires prior evaluation of PV generator; it is based on mathematical relationship obtained from empirical data. Methods like look-up table, open-circuit PV voltage, short circuits PV current and other MPPT algorithms are included in indirect method.

A. Perturb and Observe (P&O) Method

The P&O method is most widely used in MPPT because of its simple structure and it requires only few parameters. Fig. 3 shows the flow chart of P&O method. It perturbs the PV array's terminal voltage periodically, and then it compares the PV output power with that of the previous cycle of perturbation [5-8].

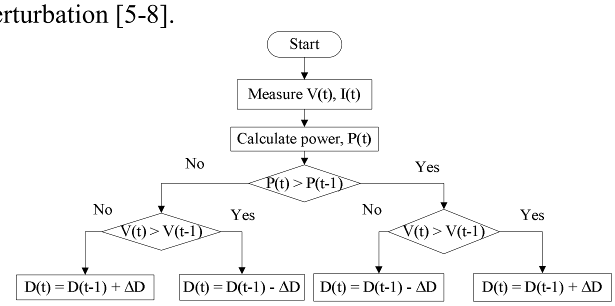


Fig. 3. Flow chart of perturb and observe method (P&O) [5].

Based on Fig. 3, when PV power and PV voltage increase at the same time and vice versa, a perturbation step size, ΔD will be added to the duty cycle, D to generate the next cycle of perturbation in order to force the operating point moving towards the MPP. When PV power increases and PV voltage decreases and vice versa, the perturbation step will be subtracted for the next cycle of perturbation [9]. This process will be carried on continuously until MPP is reached. However, the system will oscillate around the MPP throughout this process, and this will result in loss of energy. These oscillations can be minimized by reducing the perturbation step size but it slows down the MPP tracking system [7,8].

Neil S. D'Souza, *et al.* [10] employed a peak current control and instantaneous value to calculate the direction of next cycle of perturbation of the conventional P&O method. It increased the speed of response of the system and reduced the amplitude of power oscillations around the MPP. Youngseok.J, *et al.* [5] proposed an improved perturbation and observation method (iP&O). It satisfied the good dynamic response and steady-state performances. References [4,11] optimized the choice of ΔD for experiment and analysis. Literature [6] designed iP&O method with a current-mode controlled DC-DC step-up converter. It proved that MPP can be tracked accurately under both rapid and gradual changes of solar irradiance.

B. Incremental Conductance Method (INCond.)

The incremental conductance method is based on **(1)** with the derivative of PV output power with respect to the PV voltage. The derivation is zero at MPP, positive on the left side of MPP and negative on the right side of MPP (2) to (4) [8,12].

$$dP/dV = d(IV)/dV = I + V(dI/dV) = I + V(\Delta I/\Delta V) \qquad (1)$$

By setting the result equals to zero,

$$\Delta I/\Delta V = -I/V \ (dP/dV = 0) \quad \text{at MPP} \qquad (2)$$

$$\Delta I/\Delta V > -I/V \ (dP/dV > 0) \quad \text{left side of MPP} \qquad (3)$$

$$\Delta I/\Delta V < -I/V \ (dP/dV < 0) \quad \text{right side of MPP} \qquad (4)$$

The MPP is tracked by comparing the instantaneous conductance (I/V) to the incremental conductance ($\Delta I/\Delta V$). Based on the flow chart in Fig. 4, V(*k*) and I(*k*) are the PV array output voltage and current at time *k*. The duty cycle, D of boost converter at which PV array is forced to operate at MPP. When the PV output voltage is constant but the output current increases, the duty cycle will increase. If the current decreases with the constant voltage, the duty cycle decreases [13,14]. The duty of the algorithm is to search a suitable duty cycle at which the incremental conductance equals to instantaneous conductance so that the PV system always operate at the MPP [12].

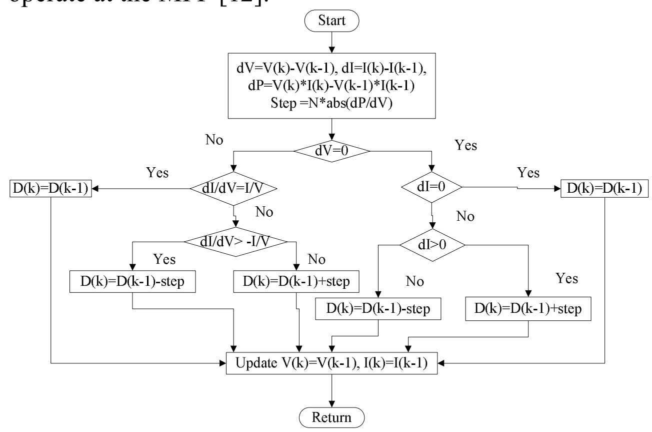


Fig. 4. Flow chart of Incremental Conductance method (INCond.) [8].

The incremental size, ΔD, determines how fast the MPP is being tracked. Fast tracking can be reached by greater incremental size, but it will make the system oscillates about its MPP. The main advantage of INCond method is that it can produce good results under rapidly changing environment. INCond. algorithm is able to achiev lower oscillation around MPP than P&O method. However, it requires two sensors to measure the instantaneous PV output voltage and current, which results in high cost and complex circuit of the system [13].

Jiyong.L, *et al.* [15] proposed a variable step size incremental conductance method and a space vector pulse width modulation (SVPWM) control scheme for three-phase voltage source PWM inverter. Fangrui. L, *et al.* [8] also designed a modified variable step size incremental conductance method with a simple constant voltage tracking (CVT) start program which may enable the smooth start process. Bangyin. L, *et al.* [13] has implemented the same method for experimentation and analysis. All these methods can improve the dynamic and steady-state performance of PV system simultaneously.

C. Open-Circuit Voltage Method

This is a method based on the linear relationship between output voltage of the PV array at the MPP, V_{MPP} and the PV array's open circuit voltage, V_{OC} in (5) under varying temperature and solar irradiance [2,16].

$$V_{MPP} \approx k_1 V_{OC} \qquad (5)$$

Constant value of k_1 is dependent on the characteristics of PV array. Generally, it has to be computed empirically in order to determine the V_{MPP} and V_{OC} for varied temperatures and solar irradiances. The value of k_1 ranges from 0.73 to 0.80 for polycrystalline PV module over a temperature range of 0 to 60^oC and solar irradiance range of 200 to $1000W/m^2$ [2,16].

In Fig. 5, the PV array is temporarily isolated from MPPT, then the open circuit voltage, V_{OC} is measured periodically by shutting down the power converter momentarily. The MPPT calculates V_{MPP} from the pre-set value of k_1 and the calculated value of V_{OC}. Then, the array's voltage is varied until V_{MPP} is reached [3]. The shutdown of power converter periodically will incur temporary loss of power which results in power extracted will not be the maxima. Since (5) is an approximation, the PV array will never reach the MPP. Even though this technique is very easy and cheap for implementation, yet the constant value of k_1 is not valid in the presence of partial shading of the PV array [2,16].

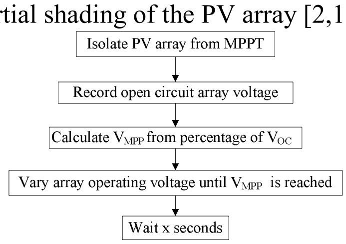


Fig. 5. Flow chart of constant voltage method [3].

D. Short-Circuit Current Method

This method is quite similar to the open circuit voltage method. It is based on the linear relationship between PV array output current at MPP, I_{MPP} and PV array short-circuit current, I_{SC} as shown (6) [2,16].

$$I_{MPP} \approx k_2 I_{SC} \tag{6}$$

where k_2 is the proportionality constant.

The constant value of k_2 also depends on characteristics of PV array. Generally, it ranges from 0.78 to 0.92 for polycrystalline PV modules under the same conditions like the one mentioned previously [2,16]. The way of determining k_2 is more complicated than a fixed value. After k_2 is obtained, the PV system remains with the approximation in **(6)**, until the next calculation of k_2.

The procedure of short-circuit current method is the same as that of open-circuit voltage method, the flow chart of this method can be referred to the same flow chart as shown in Fig. 5. An additional switch is added to the power converter and it is switched on momentarily to measure the short-circuit current, I_{SC} by using a current sensor, then the MPP current is calculated [3]. The output current of PV array is adjusted until the MPP current is reached. This process is repeated periodically. Like open-circuit voltage method, the MPP is never reached since (6) is an approximation, hence the output power produced will not be the maximum.

E. Fuzzy Logic Controller

Fuzzy Logic controller (FLC) works with imprecise inputs, it does not need an accurate mathematical model and it can handle nonlinearity well. It relies on the user's knowledge and experience rather than the technical understanding of the system. FLC is divided into four categories, which include fuzzification, inference, rule based and defuzzification as shown in
Fig. 6 [17,18].

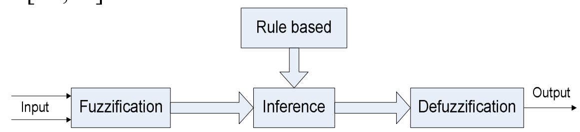


Fig. 6. Block diagram of fuzzy logic controller [17].

In this study, the inputs of FLC are error, E and change in error, CE at sample time k, which are defined by (7) and (8), while the output of FLC is the duty cycle, D [18,20].

$$E(k) = [P_{PV}(k) - P_{PV}(k-1)] / [V_{PV}(k) - V_{PV}(k-1)] \tag{7}$$

$$CE(k) = E(k) - E(k-1) \tag{8}$$

During fuzzification, the numerical input variables are converted into linguistic variables based on the membership functions as shown in Fig. 7 [18]. Five fuzzy levels are used for all the inputs and outputs variables: NB (negative big), NS (negative small), ZE (zero), PS (positive small), and PB (positive big). References [17,19,21] designed seven fuzzy levels to improve the control surface and to allow a smooth transition from transient to steady state. The user has the flexibility of choosing values of numerical variables of the inputs.

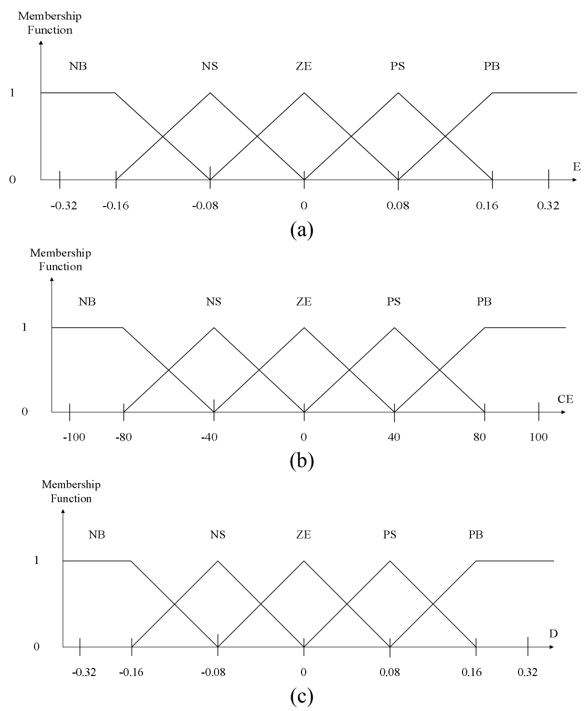


Fig. 7. Membership function for (a) input of error, E, (b) input of change of error, CE and (c) output of duty cycle, D.

Once E and CE are calculated, they are converted into linguistic variables and then the output, D is generated by looking up in a rule base table as shown in Table I, which consists of 25 rules. The FLC tracks the MPP based on master rule of "If X and Y, Then Z" [10,17]. Usually, weights are added to the rules to improve reasoning accuracy and to reduce undesirable consequent.

The inference method used to determine the output of fuzzy logic controller. Mamdani's inference method is the most common method used in engineering application [18,20]. It is employed in this study. Other inference methods include Compositional Rule of Inference (CRI), Generalized Modus Ponens (GMP) and Sugeno inference method [17].

TABLE I. Rule Base for Fuzzy Logic Controller.

E ↓ \ CE →	NB	NS	ZE	PS	PB
NB	ZE	ZE	PB	PB	PB
NS	ZE	ZE	PS	PS	PS
ZE	PS	ZE	ZE	ZE	NS
PS	NS	NS	NS	ZE	ZE
PB	NB	NB	NB	ZE	ZE

During the process of defuzzification, FLC output is converted back to a numerical variable. This in turn, provides an analog signal to control the power converter. The centroid method is the most commonly used defuzzification methods because it has good averaging properties and it produces good results. Other defuzzification methods include bisector and Middle of Maxima (MOM) [17].

References [18-20] compared the results of fuzzy logic controller and P&O controller. It shows that FLC exhibits a better behavior than P&O method, which provides faster tracking of MPP and it presents smoother signal with less fluctuation in steady-state. Neil S. *et al.* [10] applied fuzzy logic for P&O method with peak current control and sampling of instantaneous values. It achieves very fast transient response and reduces the oscillations around MPP in steady-state. Kottas,T.L, *et al.* [22] proposed a method of fuzzy cognitive network by using fuzzy logic controller, which results in very good maximum power operation of PV array under varying change of conditions.

F. Other MPPT algorithms

B. Amrouche, *et al.* [23] proposed artificial neural network, (ANN) based modified P&O method to predict the power value during the next perturbation cycle so that the value of perturbation step can be adjusted for next perturbation cycle. Zhang. L, *et al.* [24] built a Genetic Algorithm trained Radial Basis Function Neural Network (GA-RBFNN) model to predict the reference DC bus voltage of the control system to maximize the output power. Veerachary. M, *et al.* [25] implemented a feed-forward MPPT scheme for coupled-inductor interleaved boost converter fed PV system by using fuzzy logic controller, while ANN is trained offline to estimate the voltage reference. Joe-Air Jiang, *et al.* [26] designed a three-point weight comparison method to avoid rapidly moving of the operating points of PV when it is under varying atmosphere conditions which could overcome the drawback of P&O method. References [27,28] proposed neural fuzzy network for MPPT control scheme. The neural network used to train sets of data off-line for inputs of fuzzy logic controller, while the fuzzy logic controller used to control the duty cycle effectively and hence the MPP can be tracked effectively.

III. SIMULATION

The Solarex MSX60, 60W PV module was chosen for modeling and simulation using MATLAB/SimuLink. The module has 36 polycrystalline cells which are connected in series. The electrical specifications are shown in Table II.

TABLE II. Specifications of Solarex MSX60.

At temperature	25 °C
Open circuit voltage, V_{OC}	21.0 V
Short circuit current, I_{SC}	3.74 A
Voltage at maximum power, V_{MPP}	17.1 V
Current at maximum power, I_{MPP}	3.5 A
Maximum power, MPP	59.9 W

Fig. 8 shows the configuration of PV system built in Simulink. It consists of a PV module model, a boost converter, MPPT algorithm and PWM generator. The inputs of the PV module are the solar irradiance and the ambient temperature. The output produced by the PV module is the PV current, which acts as a controlled current source for the input of the boost converter. The input capacitance of the converter, C_{in} is 500 μF, the inductance, L is 25 μH and the output capacitance, C_{out} is set to be 5 μF. The load resistance, R is 20 Ω. The MPPT block consists of two MPPT algorithms, namely perturb and observe algorithm and fuzzy logic controller algorithm. The PWM generator provides a triangle waveform for pulse width modulation. The switching frequency, f_s was set to be 25 kHz in this simulation. The sampling time of the simulations is assumed to be 10 μs. Fig. 9(a) and Fig. 9(b) show the configurations of MPPT algorithms in Simulink according to the flow chart of P&O method explained in Fig. 3 and block diagram of FLC in Fig. 6.

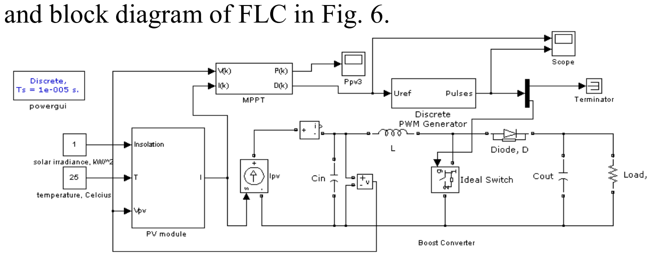
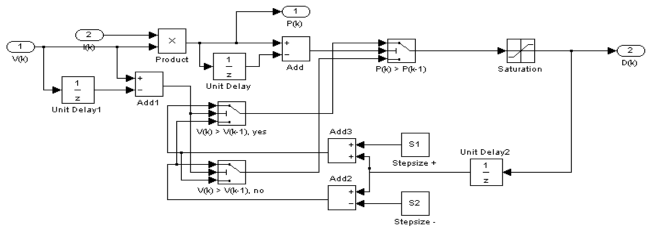


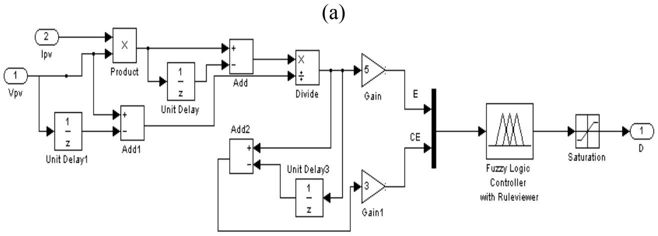
Fig. 8. Configuration of PV system in Simulink.

IV. RESULTS AND DISCUSSION

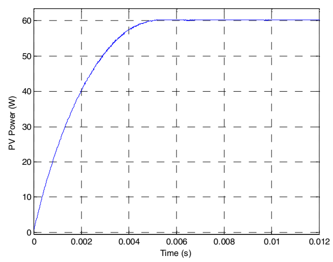
Fig. 10 shows the PV power waveforms simulated using the Perturb and Observe (P&O) algorithm and the fuzzy logic control, respectively. The incremental and the decremental perturbation step size of P&O algorithm are 0.00001 and 0.01, respectively. Both algorithms were tested at temperature of 25 ^{o}C and solar irradiance of 1 kW/m^2. The maximum PV power generated by both algorithms is 60 W, which is the expected maximum power, MPP of Solarex MSX60 as shown in TABLE II. Based on Fig. 10, it can be noticed that time for the PV power curve to reach at steady state for both algorithms is slightly different, it is about 0.005 s for P&O algorithm and 0.006 s for FLC algorithm. Meanwhile, the PV power curve generated by FLC algorithm has a lot of ripples during transient time as compared to that of P&O algorithm.

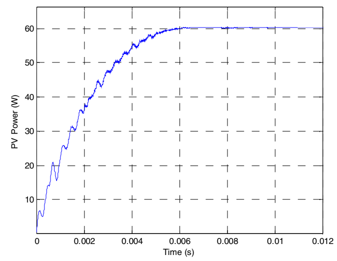


(a)



(b) Fig. 9. Configurations of MPPT algorithms in Simulink. (a) Perturb and Observe (P&O) MPPT algorithm and (b) Fuzzy Logic Controller (FLC) algorithm.

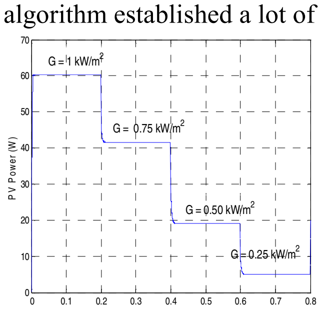


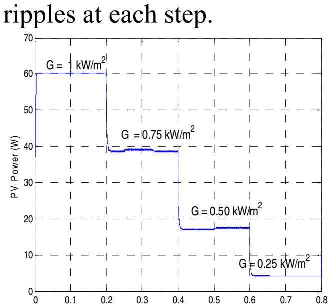


(a) (b)

Fig. 10. PV power curves generated by (a) Perturb and Observe algorithm and (b) Fuzzy Logic controller at temperature 25 °C and solar irradiance 1 kW/m^2.

Besides that, the P&O and the FLC algorithms were tested under varying solar irradiance and at a constant temperature of 25°C, The solar irradiance changes from 1 to 0.25 kW/m^2 with every decremental of 0.25 kW/m^2. The PV power waveforms generated by the testing are shown in Fig. 11. It can be noticed that the PV power waveforms generated by P&O algorithm are smooth, while the PV power waveforms generated by FLC algorithm established a lot of ripples at each step.



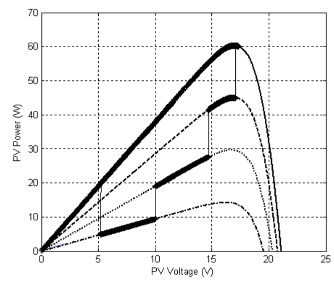


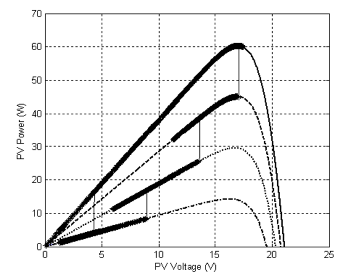
(a) (b)

Fig. 11. PV power curves generated by (a) Perturb and Observe algorithm and (b) Fuzzy Logic controller at temperature 25 °C and solar irradiance change from 1 kW/m^2 to 0.25 kW/m^2.

The P-V characteristic curves of both algorithms are shown in Fig. 12. The bolded curves show the maximum power that can be reached by using the algorithms under varied solar irradiance. It can be noticed the power curves of both algorithms failed to reach to the maximum when the solar irradiance start to drop from 0.50 to 0.25 kW/m^2. The PV power values generated by these two algorithms are compared to the expected result as shown in Table III. The PV powers generated by P&O algorithm during low solar irradiance are very much less than the expected MPP, they are about 27% and 53% less than the expected MPP for solar irradiance of 0.5 kW/m^2 and 0.25 kW/m^2, respectively. Meanwhile, for the FLC algorithm even worst, the PV powers generated are 30% and 60% less than the expected MPP for solar irradiance of 0.5 kW/m^2 and 0.25 kW/m^2 respectively. This indicated that the P&O and the FLC algorithms are not able to perform well under low solar irradiance.

The simulations show that all these conventional algorithms are not able to perform well under varying solar irradiances. It is because of there is no modification or changes made on both of the P&O and FLC MPPT algorithms. Nevertheless, the comparison of the simulation results provides very useful information on the MPP.





(a) (b)

Fig. 12. The P-V characteristics curves generated by (a) Perturb and Observe algorithm and (b) Fuzzy Logic Controller when the solar irradiance changes from 1 to 0.25 kW/m^2.

TABLE III. Comparison results of PV power generated under Varied Solar irradiance and Constant temperature.

Solar irradiance (kW/m^2)	PV Power (W)		
	Perturb and Observe algorithm	Fuzzy Logic Controller	Expected result
1.00	60.35	60.35	60.35
0.75	41.59	38.93	45.07
0.50	19.07	17.08	26.29
0.25	4.96	4.09	10.70

V. PV Arrays Under Partial Shaded Conditiions

In reality, PV arrays do not receive uniform insolations at all the time. Some part of the PV arrays might be shaded by heavy cloud, trees or nearby buildings. The shaded PV cells absorb a large amount of electric power generated by other PV cells that receive high insolation and convert it into heat. This situation is called the hot spot problem which may damage the PV cells with low insolation [29]. In order to relieve the stress on the shaded PV cells, bypass diodes are connected in parallel with each PV modules [30]. The inserted bypass diodes may cause multiple peaks are established in the P-V characteristic curves under non-uniform insolation as shown in Fig. 13. In general, most of the conventional MPPT algorithms that were mentioned previously cannot detect the global maximum peak effectively [31]. Therefore, further researches should be made on this situation so that the PV systems under partial shaded conditions can perform at the optimum condition.

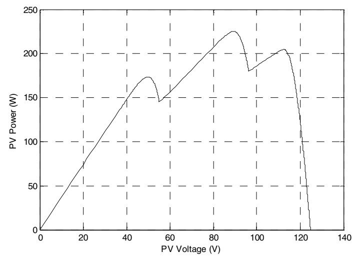


Fig. 13. P-V characteristic curve of three PV modules connected in series under non-uniform insolation.

VI. Conclusion

Two groups of MPPT control algorithms, namely direct and indirect methods were discussed and reviewed. The study presents a simulation comparison of the maximum power produced for P&O algorithm and FLC method. The P&O algorithm is the simplest method, which results in low cost of installation and it may be competitive with other MPPT algorithms. Hence, it should be further modified and improved to provide a good result. On the other hand, the FLC method provides a simpler way to arrive at a definite conclusion, but it highly depends on the user's knowledge of the process operation for the FLC parameter setting. It could also be further improved according to its flexibility of choosing numerical variables of input and output. The conventional MPPT algorithms are not capable of solving the problems of multiple peaks that established in the P-V characteristic curves of the PV systems due to partial shaded conditions. Therefore, further research should be done to extract maximum power effectively from the PV systems under non-uniform insolation.

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