Improved Efficiency of photovoltaic Module Based on Fuzzy Logic MPPT Technique

H M Abd Alhussain¹, Dr. N M Yasin²
¹,² Electrical Power Engineering Techniques, Department of Electrical Engineering Technical College, Middle Technical University, Baghdad, Iraq
¹ hayder_moayad@yahoo.com, ² naseeryasin@yahoo.com

Abstract. In photovoltaic (PV) systems, the maximum power point trackers are very important for increasing their efficiency. Maximum power can be achieved by using different methods such as P&O, INC so that the PV module can operate under different weather conditions and still produces maximum output power. In this paper, a smart method is presented for a maximum power point tracking (MPPT) based on a fuzzy logic control (FLC). The photovoltaic system consists of a solar panel type MXS 60W, DC-DC boost converter, FLC (MPP) tracker and resistive load are analyzed and simulated in MATLAB program. The output voltage of the solar panel is increased by the boost converter and it depends upon the duty cycle (D) of the MOSFET of the boost converter. Any change in the duty cycle is performed through sensing the output power of the solar panel. The controller tracks the maximum power of a solar panel by adjusting the duty cycle of the DC-DC converter switch. The simulation results show that the FLC controller can track the Maximum Power Point in a shorter time with less power oscillation around the MPP as compared to the most widely conventional method known as perturb and observe (P&O). Both techniques have been modeled and simulated in (MATLAB/ Simulink).

1. Introduction
The renewable energy sources like tidal energy, sea wave energy, wind energy, and solar energy have gained significant improvements in the research field over the last few years. Nowadays, the solar energy systems considered as an environment-friendly, daily available, and most reliable renewable energy sources [1,2]. However, the photovoltaic system implementation is limited by two important factors. These factors are the high costs of installation and low energy conversion efficiency due to clouds, shading effect, and solar insolation [3]. The maximum power point tracking (MPPT) system is one of the effective methods in photovoltaic modules to increase the efficiency of solar energy and reduce the cost of the photovoltaic power system. In general, the (MPP) is the point on the power–voltage curve (P–V) or current–voltage curve (I–V) at which the PV cell will operate at a maximum output power [4]. The DC-DC boost converter design helps in increasing the output and the efficiency of the PV panel using proper control techniques [5]. P&O and Hill Climbing (HC) methods are very commercially used techniques [6]. The other modified techniques like incremental conductance technique (INC), neural network technique (NN), and fuzzy logic control technique (FLC). They are used for improving the efficiency of MPPT system performance. In the HC method, the increase or decrease in the duty cycle is directed with constant steps that depend on the value of power and voltage of the PV panel until the maximum power point is attained [6,7]. The P&O is an alternative technique method that measures the current, voltage and power of the PV panel to get the maximum power out of the PV module. Then the voltage is perturbed by P&O according to the
direction change. So it has better efficiency, better PV output voltage and faster dynamic performance as compared to HC [8,9]. The disadvantages of the P&O technique is that it's nearly fails to track the MPP when the irradiation of the solar changes in a quick manner and the MPPT system might not be able to track the MPP when intensity of sunlight decreases because the graph of PV flattens out [10]. Therefore a more advanced intelligent control technique based on a fuzzy logic controller algorithm associated with an MPPT controller can be applied to improved efficiency and management the energy conversion.

Figure 1 presents a block diagram of the FLC system in solar power energy conversion system, which is consists of PV panel, DC–DC boost converter, an FLC controller unit to control the entire system, and resistive load. The simulation study and analysis of FLC performance and P&O are presented in MATLAB/SIMULINK.

2. Modeling of photovoltaic array
The PV cell is the most important part of the photovoltaic generation system. It is basically a P-N semiconductor junction which converts the solar irradiation light to electrical energy. Figure 2 presents a simple equivalent circuit model of a PV cell. This circuit contains an ideal current source, diode, parallel resistance $R_{sh}$ and series resistance $R_s$.

The solar cell can be mathematically constructed by the following equations [11,12]. $I_{pv}$ is expressed by (1):

$$I_{pv} = I_{ph} - I_o \left[ \exp \left( \frac{q(V_{pv}+R_{p}I_{pv})}{nKT} \right) - 1 \right] - \frac{V_{pv}+R_{p}I_{pv}}{R_{sh}}$$

(1)

Where ($I_{pv}$) and ($V_{pv}$) are the current and voltage output from PV cell, ($n$) is the ideality factor which = (1.6), ($K$) is the Boltzmann's constant which = $(1.3805 \times 10^{-23})$ J/K, ($T$) is the operating temperature of the cell’s in Kelvin, ($q$) is the electron charge which = $(1.6 \times 10^{-19})$ C, ($I_o$) is the reverse-saturation current and ($I_{ph}$) is photo-generated current that varies with solar insolation and temperature. $I_{ph}$ is expressed by (2):

$$I_{ph} = [I_{sc} + K(T - T_{n})] \frac{G}{1000}$$

(2)
Where $I_{SC}$ is the short-circuit current at irradiation in W/m$^2$ and temperature in $^0$C, $K_t$ is the short-circuit current temperature-coefficient of the cell’s which $= 0.0032$ A / $^0$C, $T_n$ is the reference temperature which $= 298$ K. $I_o$ is expressed by (3):

$$I_o = I_{rs} \left( \frac{T}{T_n} \right)^3 \exp\left[ \frac{qE_g}{nK} \left( \frac{1}{T_n} - \frac{1}{T} \right) \right]$$  

(3)

Where ($E_g$) is the energy bandgap of the semiconductors used in the photovoltaic cell which is $= 1.1$ eV, $I_{rs}$ is the reverse-saturation current at reference temperature. These equations are designed and simulated in MATLAB/ Simulink as shown in Figure 3.

![Simulation of a solar cell](image)

Table 1 shows the specifications of MXS 60W PV module [13].

| Parameters                              | 60W PV module |
|-----------------------------------------|---------------|
| Rated Power                             | 60 W          |
| Voltage at Maximum power ($V_{mp}$)     | 17.1 V        |
| Current at Maximum power ($I_{mp}$)     | 3.5 A         |
| Open circuit voltage ($V_{OC}$)         | 21.1 V        |
| Short circuit current ($I_{SC}$)        | 3.8 A         |
| Total number of cells in series ($N_s$) | 36            |
| Total number of cells in parallel ($N_p$) | 1             |

The output characteristics of 60W PV module are simulated with constant temperature of 25$^0$C while varying irradiation as in Figure 4 and with constant irradiation of 1000 W/m$^2$ while varying the temperature as in Figure 5. The voltage-current (V-I) characteristics of photovoltaic panel are nonlinear, and the PV power generation system with maximum output power only has a single operating point under a nominated environmental condition.

![Output characteristic curve with constant temperature](image)
3. The conception of the maximum power point

The maximum power point of a PV array relies on the solar panel insolation level, temperature and the load characteristics at which it is connected to. So it is necessary to track the MPP of solar panels frequently. From the I-V and P-V characteristics curve in Figure 5, we can see that maximum power will happen only in the $P_{mpp}$ point.

![Figure 5](image)

**Figure 5.** Output characteristic curve with constant irradiation.

4. DC-DC boost converter

DC-DC boost converter is a step-up power converter that most widely used in photovoltaic systems as a mediator between the connected load and PV panel to track the maximum power point. Figure 7 shows the boost converter circuit using a MOSFET switch. The switch adjusts the duty cycle (D) to modify the transfer of energy from the source to the load.

![Figure 7](image)

**Figure 7.** Circuit diagram of the boost converter.

When the switch is turned ON, the current pass through it and the inductor will charge linearly, while the diode is in OFF state. When switch is turned off, the diode is biased forward and the inductor will discharge the stored power through the diode to the load. Equation (4) shows the relationship between the input and output voltages [15].
Where $V_o$ is the output voltage of the boost converter, $V_i$ is the PV output voltage, (D) is the duty-cycle and can be expressed by the equation (5).

$$D = \frac{T_{on}}{T}$$

Where $T_{on}$ is a time when the MOSFET is turned on, (T) is the period time cycle. The ON and OFF operational time of the MOSFET depends on the control signal from pulse-width modulation (PWM). The PWM operates with a constant frequency i.e, $T_{on}$ is varying and T is constant, So D can change from (0 to 1). Details of the DC–DC boost converter is given in Table 2.

**Table 2.** The component values of DC–DC boost converter

| Component | Rating |
|-----------|--------|
| L         | 623[μH]|
| C1        | 470[μF]|
| C2        | 323[μF]|
| R         | 10[Ω]  |

**5. Maximum power point controller**

Essentially, MPPT is a real–time process to find the maximum power available that can be taken from the PV array system at any insolation levels. Two effective MPPT control methods will be presented and simulated.

**5.1. P&O control method**

In general, the algorithm of the Perturb and Observe method is used in the photovoltaic system's application because it’s easy to implement. P&O is an iterative process to achieve the maximum power point by measuring current and voltage of PV panel, and then perturb the PV operating point by an increase or decrease in the PWM duty-cycle of boost converter to observe the change direction of PV output power [16]. Figure 8 shows the flow–chart of the P&O algorithm.

![Figure 8. Flow–chart of P&O MPPT algorithm.](image-url)
If the output PV voltage $V(t)$ & power $P(t)$ at any instant time $(t)$ is greater than the previous calculate voltage $V(t-1)$ & power $P(t-1)$, then the perturbation direction is preserved else it is reversed. In the simulation, the $\Delta D$ $(dd)$ value in Figure 9 is chosen by trial and error. The P&O algorithm has some disadvantages: Because of the slow process of trial and error, it cannot always operate at the MPP, thus the maximum solar power available cannot be extracted from the PV array at all the time. The Photovoltaic systems always operate in the oscillation mode, resulting in the need for complex input and output filter to absorb the generated harmonics. Figure 9 shows the simulation of the P&O MPPT algorithm.

5.2. Fuzzy Logic Control Method
The fuzzy logic control system is one of the most robust control methods used in the applications of renewable energy. The uses of FLC has been increasing over the past decade because it working with inaccurate input, does not require precise mathematical models, and it can deal with nonlinearity [17]. The FLC controller can be used to get the maximum power that the PV modules can produce under variable weather condition. The FLC process can be categorized into three basic components: fuzzification, rule evaluation, and defuzzification. These components are shown in Figure 10.

The fuzzification process includes taking crisp input, like a change in reading voltage, and merge it with the stocked membership functions for producing the fuzzy inputs. For each inputs, the membership functions must be first set to convert the crisp inputs into fuzzy inputs. When membership functions are set, the fuzzification process takes a real-time input and compare it with the stocked membership functions information to produce the fuzzy input values. The rule-based process is a collection of a linguistic rule that uses for determining which control action must happen in response to a specific set of the input values. The results of this process are the fuzzy output of each type of resultant procedure. The defuzzification of the inference engine carried out by using Mamdani’s method is the last step in the fuzzy logic process that evaluates rules-based on the set of control procedures for the given fuzzy input set. In this process, the conclusion fuzzy control action will convert to numerical values at the output via forming the confederation outputs generated from each rules. The Center of Gravity (COG) or centroid method is one of the most commonly used defuzzification techniques.

The advantages of fuzzy logic control are that it is fast, robust, and immediately respond to weather changes, so it was used to track the maximum power of PV systems [18,19]. In the FLC method, the oscillation around the MPP is reduced and the response to the maximum output value is faster as compare it with the most conventional P&O method. The proposed inputs of the fuzzy logic system are
the error (E) and the change of error (CE). The proposed output from FLC is the change in duty-cycle (ΔD) at sampling instant(t) which corresponds with the modulation signal that is applied to the PWM modulator to produce switch pulses. The input and the output variables are expressed by equation (6), (7), (8).

\[
E(t) = \frac{P(t) - P(t - 1)}{V(t) - V(t - 1)} = \frac{\Delta P}{\Delta V}
\]

\[
CE(t) = E(t) - E(t - 1) = \Delta E
\]

\[
D(t) = D(t - 1) + \Delta D(t)
\]

Where E(t) is the slope of P-V curve which defines the MPP location in the PV modules. While CE(t) defines whether operating point movement in MPP direction or not. While the output is a (ΔD), in which their values can be (positive) or (negative) according to the operating point location. During the fuzzification process, the input numerical variables are converted to linguistic variables based on the membership functions. Figure 11 shows the membership of E, ΔE and ΔD respectively. All input and output variables have five fuzzy organization levels; (NB) is the negative big, (NS) is the negative small, (ZE) is the zero, (PS) is the positive small, and (PB) is the positive big.

![Membership functions](image.png)

(a) Input variable (E)  
(b) Input variable (ΔE)  
(c) Output variable (ΔD)

**Figure 11.** Membership function of FLC

The rules design is based on if any change in the voltage causes increased in power, the next change movement is preserved in the same direction otherwise, the next change is reversed. All the rules and the membership functions (MFs) are adjusted by trial and error to get the performance required. Table 3 shows 25 rules applied in the FLC controller. The two input variables (E) and (ΔE) represented by the rows and columns, while the intersection of a row with a column represents the output variable (ΔD).

| \meter | \text{NB} | \text{NS} | \text{ZE} | \text{PS} | \text{PB} |
|-------|--------|--------|--------|--------|--------|
| \text{NB} | ZE | ZE | NB | NB | NB |
| \text{NS} | ZE | ZE | NS | NS | NS |
| \text{ZE} | NS | ZE | ZE | ZE | PS |
| \text{PS} | PS | PS | PS | ZE | ZE |
| \text{PB} | PB | PB | PB | ZE | ZE |

**Table 3.** Rules base for fuzzy logic control

The fuzzy logic MPPT algorithm has been modelled & simulated as shown in Figure 12.
6. Simulation Results

6.1. Operating the PV system in standard environmental conditions
Figure (13&14) allows us to envisage the outputs of PV panel that is used in this paper without MPPT, with (P&O) based MPPT technique, and with Fuzzy Logic Control MPPT technique at standard weather conditions (25°C, 1000W/m²).

From the figure (13) when the PV panel is directly connected to load it will give (1.998A) current, (19.98V) voltage and (39.91W) power to load. From the figure (14) when boost converter with MPPT P&O controller is connected to the PV panel, the output will be (2.4A) current, (24V) voltage and (57.79W) power to load. When FLC controller is connected to the PV panel, the output will be (2.44A) current, (24.44V) voltage and (59.7W) power to load.
It is clear that the (MPPT) technique increases the output power of the PV panel. Fuzzy logic based-MPPT gives more power with less time of about (0.1s) than the P&O (MPPT) and as well the output of FLC contains less oscillations.

6.2. Operating the PV system in variable solar irradiation conditions

Figures (15&16) allow us to visualize the outputs of PV panel that is used in this paper without MPPT, with P&O based MPPT Technique, and with FLC based MPPT technique in variable solar irradiation conditions.

To analyze this system in actual conditions, we change the irradiation in gradual steps. These differences allow us to use a fuzzy logic controller to study the durability of the system. We tested the responses of the two controller methods under varying solar irradiation from 600W/m² to 800W/m² to 1000W/m² with T=25°C to evaluate and compare the performance of the FLC (MPPT) controller over the other types of the classical controllers.
Obviously, the maximum power point of the PV panel changes with the change of radiation, and therefore the energy from the PV panels increases with increasing radiation. Fuzzy Logic–based MPPT outputs are smoother than the P&O-based (MPPT), it also clear that Fuzzy–based (MPPT) gives more output power than the P&O-based (MPPT) in each period. The efficiency of the MPPT algorithms is calculated as shown in equation (9). The efficiency of the FLC MPPT method is 98.4% while the efficiency of the P&O MPPT method is 96.3%. So it clear that the FLC based (MPPT) is more efficient than the P&O based (MPPT).

\[ \eta = \frac{P_{PV}}{P_{MP}} \]  

(9)

Where \( P_{PV} \) is the power obtained from the PV module and \( P_{MP} \) is the theoretical maximum power.

7. Conclusions

This paper discusses two control techniques methods: perturb and observe, and fuzzy logic control. When both methods are applied to the PV system with a DC-DC boost converter, the results obtained are compared under different weather conditions which give that the FLC method effectively tracks the maximum power point better than the P&O method. In FLC the response is faster and the oscillation around MPP is decreased as compared with the conventional methods. Simulation results show that the overall efficiency of the system can be improved with the help of the FLC by reducing energy loss when irradiation variation is recurrent. Comparing the efficiency tracking of both methods indicate that the FLC method has higher efficiency than the P&O-based (MPPT) method. The above advantages illustrate that the proposed FLC of the PV conversion system is highly effective and works effectively and efficiently under standard and changing environmental conditions.
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