A Fuzzy Logic Control Method for MPPT of PV Systems

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***Abstract*- Maximum power point trackers are so important in photovoltaic systems to increase their efficiency. Many methods have been proposed to achieve the maximum power that the PV modules are capable of producing under different weather conditions. This paper proposed an intelligent method for maximum power point tracking based on fuzzy logic controller. The system consists of a photovoltaic solar module connected to a DC-DC Buck-boost converter. The system has been experienced under disturbance in the photovoltaic temperature and irradiation level. The simulation results show that the proposed maximum power tracker could track the maximum power accurately and successfully in all condition tested. Comparison of different performance parameters such as: tracking efficiency and response time of the system shows that the proposed method gives higher efficiency and better performance than the conventional perturbation and observation method.**

I. INTRODUCTION

Energy has the great importance for our life and economy. The energy demand has greatly increased due to the industrial revolution. Fossil fuels have been started to be gradually depleted. The sustainability of our civilization is seriously threatened. On the other hand the greenhouse gas emissions are still increasing due to the conventional generation of energy. It is a really global challenge to reduce carbon dioxide emissions and ensuring secure, clean and affordable energy, and to achieve more sustainable energy systems [1]. Renewable energy sources are considered as a perfect option for generating clean and sustainable energy.

There are many sources of renewable energy such as solar energy, wind energy, etc. Photovoltaic (PV) system has taken a great attention by the researchers where it appears to be one of the most promising renewable energy sources. Solar energy is a clean, maintenance-free, pollution free and no noise produced due to absence of moving parts [1, 2].

However, two important factors limit the implementation of photovoltaic systems. These are high installation cost and low efficiency of energy conversion [2]. In order to reduce photovoltaic power system costs and to increases the utilization efficiency of solar energy, the maximum power point tracking system of photovoltaic modules is one of the effective methods [3]. Maximum power point tracking, frequently referred to as MPPT, is a system used to extract the maximum power of the PV module to deliver it to the load, and the efficiency is increased [4].

Different techniques have been developed to maximize the output power of the photovoltaic modules. Open-circuit voltage Method is one of these methods. This method is based on (1) which states that the open circuit voltage of the PV module is linearly proportional to the voltage of the PV module at the maximum power point [4, 5, and 6].

$$K = \frac{V_{MPP}}{V_{oc}} \cong constant < 1 \qquad (1)$$

The common value of K is about 0.76 (within ±2%) [6]. In order to implement the open circuit voltage method, the PV modules must be interrupted with a certain frequency to measure the output voltage of the PV modules. The measured voltage is multiplied by the factor K to obtain the voltage at maximum power point. Then the operating voltage of the PV module is adjusted to the calculated voltage at maximum power point. Although this method is simple, choosing the value of the constant K is difficult. On the other hand the power losses is high due to the frequently interrupting the system [6]. The flow chart of the open circuit voltage method is shown in Fig. 1.

The other method is the constant voltage tracking (CVT) method. This method compares the measured voltage (current) of the PV module with a reference voltage (current) to continuously alter the duty cycle of the DC-DC converter and hence operate the PV module at the predetermined point close to the MPP [6]. Although the CVT method is very simple, however, the constant voltage cannot track the maximum power point under the temperature changing.

Perturbation and observation (P&O) method is an alternative method to obtain the maximum power point of the PV module. It measures the voltage, current and power of the PV module. Then it perturbs the voltage to encounter the change direction. However, this method suffers of slow of tracking speed and high oscillations around MPP [1, 4, 5, and 6]. Fig. 2 shows the flow chart of the P&O MPPT algorithm.

This paper presents a new method based fuzzy logic controller to achieve maximum power point tracking. The proposed method depends on measuring the change in the PV voltage and current. The performance of the FLC method is evaluated by MATLAB/SIMULINK.

II. CHARACTERISTICS OF SOLAR MODULE

In order to model a PV module, a PV cell model must be initially accomplished. An electrical equivalent circuit makes it possible to model the characteristic of a PV cell. In a practical PV cell, there are two resistances: series resistance and parallel resistance. Series resistance is associated with the losses in the current path due to the metal grid, contacts, and current collecting bus. Parallel resistance due to the loss associated with a small leakage of current through a resistive-path in parallel with the built-in device and due to the p-n junction is not ideal [7]. Since parallel resistance is larger than series resistance, this paper neglects the parallel resistance. The equivalent circuit of the PV cell is shown in Fig. 3.

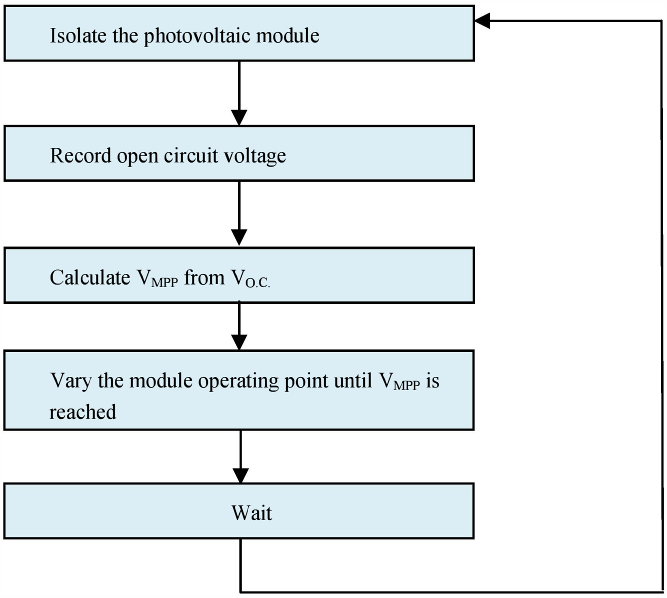

Fig. 1: Open circuit voltage algorithm flow chart.

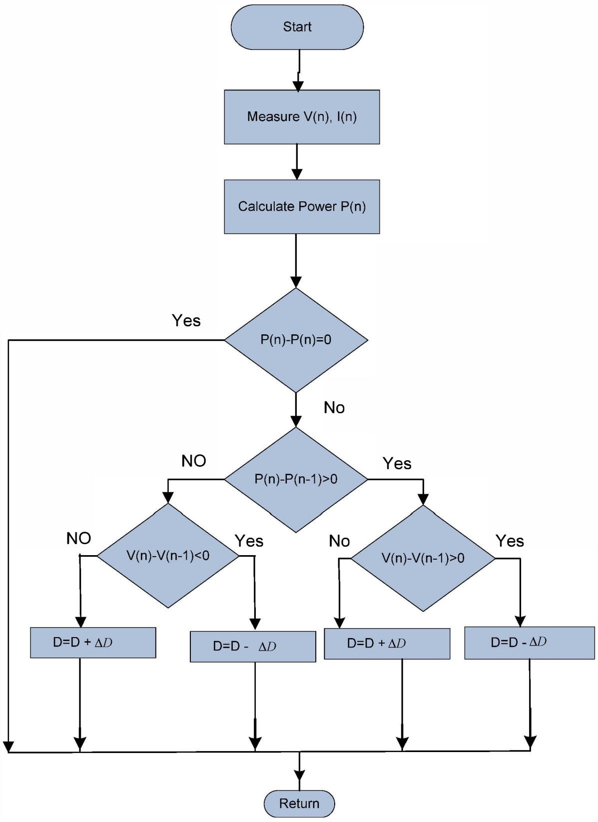

Fig. 2: The flow chart of the P&O algorithm.

The output current delivered to the load can be expressed as [8]:

$$I = I_{PV} - I_o\left(e^{\frac{q(V+IR_S)}{nKT_a}} - 1\right) \qquad (2)$$

Where:

I is the output current of the solar module (A), V is the output voltage of the solar cell (V), which can be obtained by dividing the output voltage of the PV module by the number of cells in series, I_{PV} is the current source of the PV module by solar irradiance (A), T_a is the given temperature (°K), I_o is the reverse saturation current of a diode (A), n is the ideality factor of the diode (n = 1~2), q is the electric charge of electron ($1.6 \times e^{-19}c$), k is the boltzmann's constant ($1.38 \times 10^{-23} j/K$.

In order to model the PV module, the current generated by the incident light should be first calculated. This current is given as [8]:

$$I_{PV} = I_{scn}(1 + a(T_a - T_n))\frac{G}{G_n} \qquad (3)$$

Where I_{scn} is the short circuit current at normal conditions (25°C, 1000W/m^2), I_{PV} is the short circuit current at a given temperature of the cell (T_a), a is the temperature coefficient of I_{sc}, G_n is the nominal value of irradiance, which is normally 1000W/m^2.

The reverse saturation current of diode (I_o) at the reference temperature (T_n) is given as [8]:

$$I_{on} = \frac{I_{scn}}{e^{\frac{qV_{ocn}}{nKT_n}} - 1} \qquad (4)$$

Where V_{ocn} is the open circuit voltage at normal conditions. The reverse saturation current at a given cell temperature (T_a) can be expressed as [8]:

$$I_o = I_{on}\left(\frac{T_a}{T_n}\right)^{\left(\frac{3}{n}\right)} e^{\frac{-qE_g}{nK}\left(\frac{1}{T_a} - \frac{1}{T_n}\right)} \qquad (5)$$

TABLEI

PV MODULE PARAMETERS

Maximum Power (P_{max})	115W
Voltage at P_{max} (V_{mp})	17.1V
Current at P_{max} (I_{mp})	6.7A
Open Circuit Voltage (V_{oc})	21.8V
Short Circuit Current (I_{sc})	7.5A
Temperature coefficient of I_{sc}	0.065 ± 0.015 %/ °C

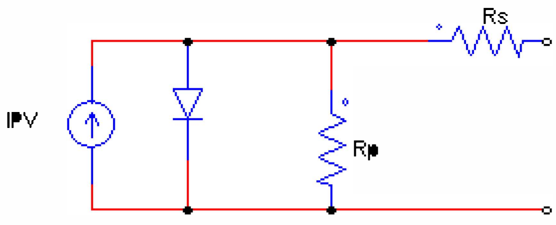

Fig. 3: Equivalent circuit of PV cell.

Equations 2 to 5 are modeled using Matlab/SIMULINK in order to set up the PV model module as well as to simulate the P-V curves under different solar radiation and under different temperature. In this paper, the BP 3115 PV module is chosen for modeling. The specification of BP 3115 under the reference conditions is shown in Table 1. Fig. 4 shows the P-V curves of the PV module under changing solar radiation from $200\mathrm{W/m^2}$ to $1000\mathrm{W/m^2}$ while keeping the temperature constant at 25°C. Fig. 5 shows the P-V curves of the PV module under changing temperature from 10°C to 50°C while keeping the solar radiation constant at $1000\mathrm{W/m^2}$.

III. DC-DC BUCK-BOOST CONVERTER

The DC-DC converter is an electronics circuit which is used to provide a loss less transfer of energy between different circuits at different DC voltage levels. There are many DC-DC converters. One of the popular types of DC-DC converters is buck-boost converter. Buck-boost converter is circuit that operating using switching mode power supply. Buck-boost converter used to step up and step down the DC voltage by changing the duty ratio of the switch. When the duty ration is less than 0.5, the output voltage is less than the input voltage and vice versa. The buck-boost converter circuit is shown in Fig. 6.

The operation of the Buck-boost converter is as follows:

- When the transistor is turned ON, the diode is reverse-biased and being not conducting.
  Turning on the transistor is accomplished during $0 < t < DT_S$ interval. The voltage across the inductor in this stage is given as [9]:

$$V_L = V_{in} \tag{6}$$

- When the transistor is turned off, the diode is conducting. Turning on the transistor is accomplished during $DT_S < t < T_S$ interval. The voltage across the inductor in this stage is given as [9]:

$$V_L = V_{out} \tag{7}$$

It is known that for steady-state operation, the net change in the inductor current must be zero over one switching cycle. By applying volt-second balance we get:

$$V_{in} D + V_{out}(1-D) = 0 \tag{8}$$

Where D is the duty cycle of the converter which is given as:

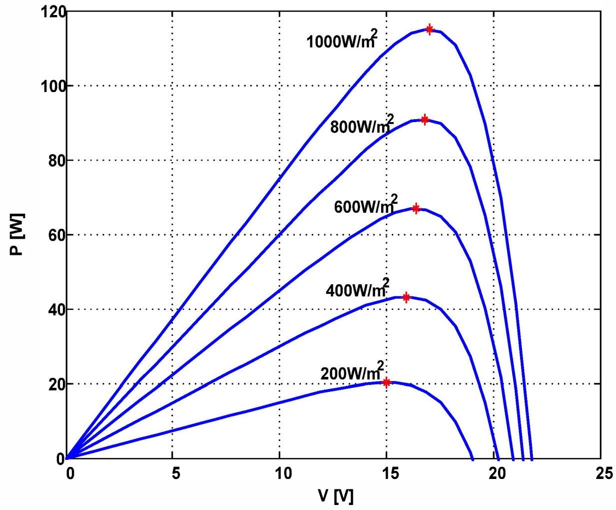

Fig. 4: P-V curves under changing the solar radiation.

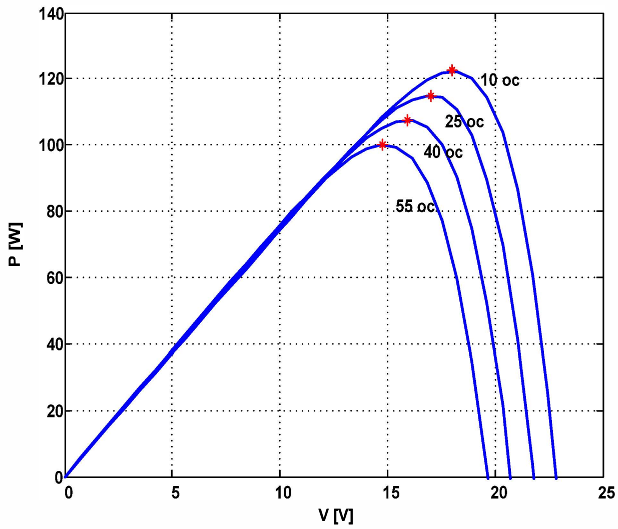

Fig. 5: P-V Curves under changing the temperature.

$$D = \frac{T_{on}}{T_S} \tag{9}$$

Where T_{on} *is* the on-state time of the MOSFET while T_S is the switching time.

From (8) the relation between the input voltage to the output voltage of the buck-boost converter is given as:

$$V_{out} = \frac{-D}{1-D} V_{in} \tag{10}$$

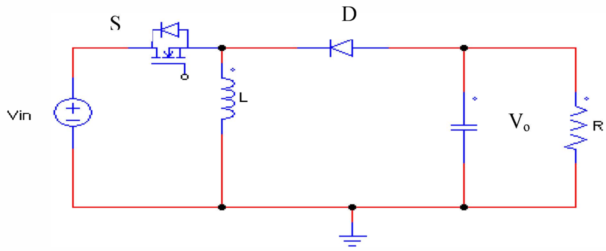

Fig. 6: The buck-boost converter circuit.

IV. THE PROPOSED MPPT FUZZY LOGIC BASE METHOD

Fuzzy logic controller has wide range of applications in renewable energy applications. The use of fuzzy logic controllers has been increased over the last decade because of its simplicity, deal with imprecise inputs, doesn't need an accurate mathematical model and can handle nonlinearity [10]. FLC can be used as a controller to obtain the maximum power that the PV modules capable of producing under changing weather conditions.

The process of FLC can be classified into three stages, fuzzification, rule evaluation and defuzzification. These components and the general architecture of a FLS are shown in Fig. 7.

The fuzzification step involves taking a crisp input, such as the change in the voltage reading, and combining it with stored membership function to produce fuzzy inputs. To transform the crisp inputs into fuzzy inputs, membership function must be first assigned for each input. Once the membership functions are assigned, fuzzification take a real time inputs and compares it with the stored membership function information to produce fuzzy input values.

The second step of fuzzy logic processing is the rule evaluation in which the fuzzy processor uses linguistic rules to determine what control action should occur in response to a give set of input values. The result of rule evaluation is a fuzzy output for each type of consequent action.

The last step in fuzzy logic processing in which the expected value of an output variable is derived by isolating a crisp value in the universe of discource of the output fuzzy sets . In this process, all of the fuzzy output values effectively modify their respective output membership function. One of the most commonly used defuzzification techniques is called Center of Gravity (COG) or centroid method.

Fuzzy logic controller has been used for tracking the maximum power of PV systems since it has the advantages such as it is robust, relatively simple to design and does not require the knowledge of an exact model [10-11]. In this paper, a new method based FLC is proposed to achieve tracking the maximum power of the PV module under changing the weather conditions. The oscillation around MPP is decreased and the response is faster in compared with the conventional P&O method. The proposed inputs of the FLC are the change in the voltage of the PV module (ΔV) and the change in the power of the PV module (ΔP). The proposed output from FLC is ΔU which correspond to the modulation signal which is applied to the PWM modulator in order to produce the switching pulses. The input variables are defined as in (11) and (12). During fuzzification, the numerical input variables are converted into linguistic variables based on the membership functions. Figures 8, 9 and 10 show the membership of $\Delta P, \Delta V\ and\ \Delta U$ respectively. 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).

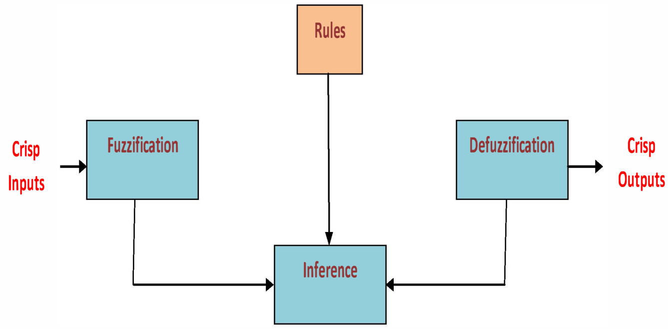

Fig. 7: The stages of the FLC.

$$\Delta V = V(K) - V(K-1) \quad (11)$$
$$\Delta P = P(K) - P(K-1) \quad (12)$$

The theoretical design of the rules based on the fact that if the change in the voltage causes the power to increase, the moving of the next change is kept in the same direction otherwise the next change is reversed. After the theoretical design, all the MFs and the rules were adjusted by the trial and error to obtain the desired performance.

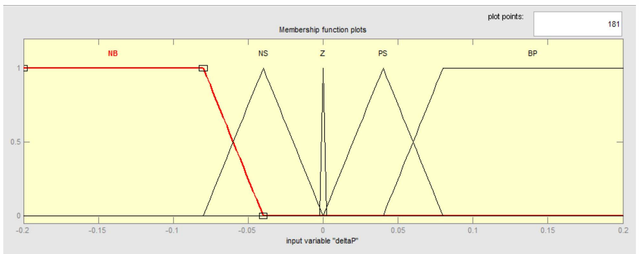

Fig. 8: The Membership function of the input variable (ΔP).

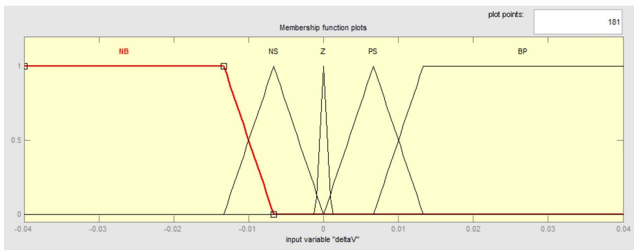

Fig. 9: The Membership function of the input variable (ΔV).

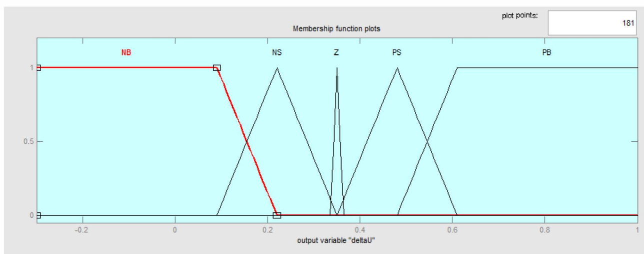

Fig. 10: The Membership function of the output variable (ΔU).

TABLEII

RULE BASE USED IN THE FUZZY LOGIC CONTROLLER

ΔV \ ΔP	**NB**	**NS**	**Z**	**PS**	**PB**
NB	PB	PS	NB	NS	NS
NS	PS	PS	NB	NS	NS
Z	NS	NS	NS	PB	PB
PS	NS	PB	PS	NB	PB
PB	NB	NB	PB	PS	PB

The proposed rules are shown in table 2. The fuzzy rules are designed to track the maximum power point of the photovoltaic system under changing weather conditions. Rapid changing solar radiation is taken in to account while designing these rules.

V. SIMULATION RESULTS

In order to verify the MPP tracker for the photovoltaic simulation system, the proposed MPPT method is compared with P&O MPPT at different ambient conditions to show how the proposed MPPT method can effectively and accurately tracks the maximum power under different. The simulation is done using MATLAB/SIMULINK. The model used for simulation is shown in Fig. 11. The output of the MPPT control block is the gating signal which is used to drive the MOSFET.

The buck-boost converter is designed under the maximum power 115W, under the maximum power point voltage 17.1V and under the output voltage which is set to be between 10V and 24V. The load is set to be 5**Ω**. Table 3 shows the parameters of the DC-DC buck-boost converter.

The MPP tracker must track the maximum power under different atmospheric conditions. The following test conditions are applied to check the effectiveness of the proposed MPPT method in tracking the maximum power point of the photovoltaic systems.

A. CHANGING THE SOLAR RADIATION

Case1: In this case the solar radiation is changed rapidly as a unit step with keeping the temperature constant at 25°C as shown in Fig. 12.

TABLEIII

BUCK-BOOST CONVERTER PARAMETERS

Inductance L	1mH
Capacitance C1	1000 μF
Capacitance C2	300 μF
frequency	40KHZ

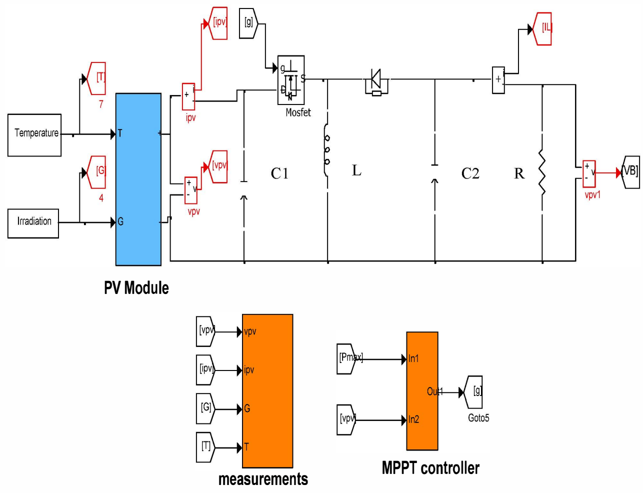

Fig. 11: System used for simulation.

The solar radiation is started with 500W/m^2 and continues until 0.03 sec at which it goes up to 1000W/m^2. At 0.06 sec the solar radiation goes down to 800W/m^2. In this situation the FLC MPPT method could track the maximum power successfully. The MPPT algorithm efficiency is calculated as shown in (13). The efficiency of tracking using FLC MPPT method is 98.77%. The maximum power tracked and the related PV voltage and current at maximum power is shown in Fig. 13. Comparing the tracking using FLC with that obtained using P&O MPPT method, the P&O tracked the maximum power but the oscillation around maximum power is larger in compared with that obtained in the FLC method. On the other hand the efficiency of tracking using P&O MPPT method is 98.02% which is smaller than that obtained using FLC MPPT method.

$$\eta = \frac{E_{PV}}{E_{MP}} \tag{13}$$

Where E_{PV} the energy obtained from the PV module and E_{MP} is the theoretical maximum energy.

Case 2: the proposed method is also tested under different changing in the ambient conditions. In this case the solar radiation is changed as shown in Fig. 15 while the temperature is also kept constant at 25°C. The solar radiation is started with 900W/m^2 and continues until 0.03sec at which it goes down to 200W/m^2 and the goes up again to 500 W/m^2 at 0.06sec. In this situation the FLC MPPT method could track the maximum power successfully. The efficiency of tracking using FLC MPPT method is 97.91%. The maximum power tracked and the PV voltage and current at maximum power is shown in Fig. 16. Comparing the tracking using FLC with that obtained using P&O MPPT method, the P&O tracked the maximum power but the oscillation around maximum power is larger in compared with that obtained in the FLC method as shown in Fig. 17. On the other hand the efficiency of tracking using P&O MPPT method is 97.28% which is smaller than that obtained using FLC MPPT method.

B. Changing The Temperature

The proposed method is also tested under changing the temperature while keeping the solar radiation fixed at 1000W/m^2 as shown in Fig. 18. In this case the temperature is stared at 25^{o}C then goes rapidly up to 50^{o}C at 0.05 sec. The FLC MPPT method tracked the maximum power successfully with efficiency of 98.82% while the efficiency of tracking using P&O MPPT method 97.95%. The maximum power tracked by the proposed method and the related PV voltage and current is shown in Fig. 19 while the maximum power tracked by P&O method is shown in Fig. 20.

VI. Conclusion

Photovoltaic model using Matlab/SIMULINK and design of appropriate DC-DC buck-boost converter with a maximum power point tracking facility are presented in this paper. A new method for MPPT based fuzzy logic controller is presented and compared with the conventional P&O MPPT method. The models are tested under disturbance in both solar radiation and photovoltaic temperature. Simulation results show that the proposed method effectively tracks the maximum power point under different ambient conditions. The oscillation around MPP is decreased and the response is faster in compared with the conventional methods. Comparing the tracking efficiency of both methods indicates that the proposed method has a higher efficiency than the conventional P&O MPPT method.

ACKNOLEDGMENT

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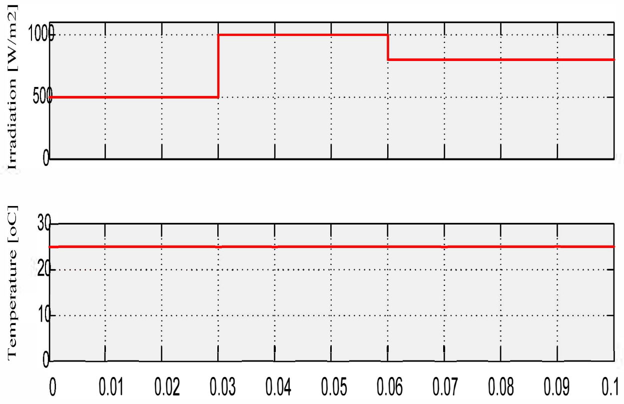

Fig. 12: case 1: changing the solar radiation.

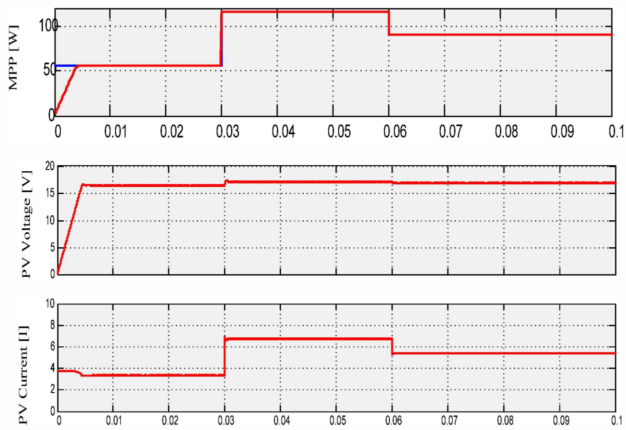

Fig. 13: Case 1: performance of FLC method.

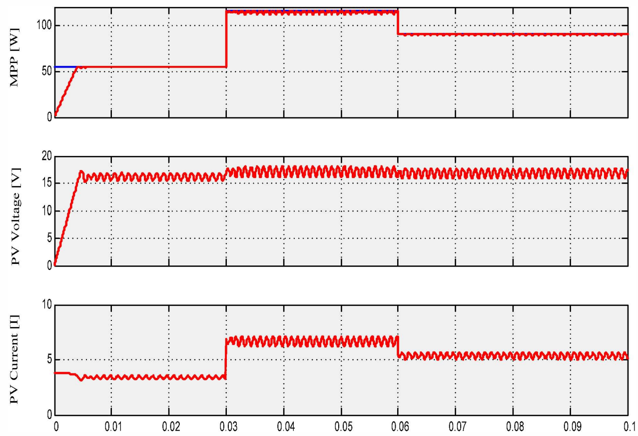

Fig. 14: Case 1: performance of P&O method.

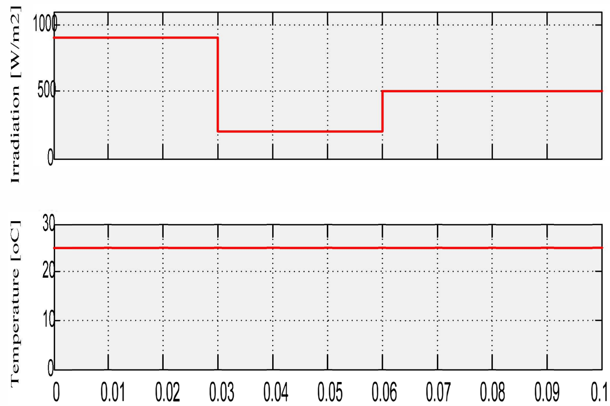

Fig. 15: Case 2: changing the solar radiation.

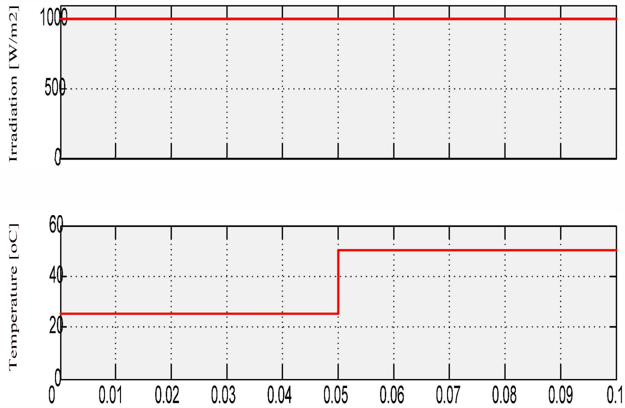

Fig. 18: Changing the temperature.

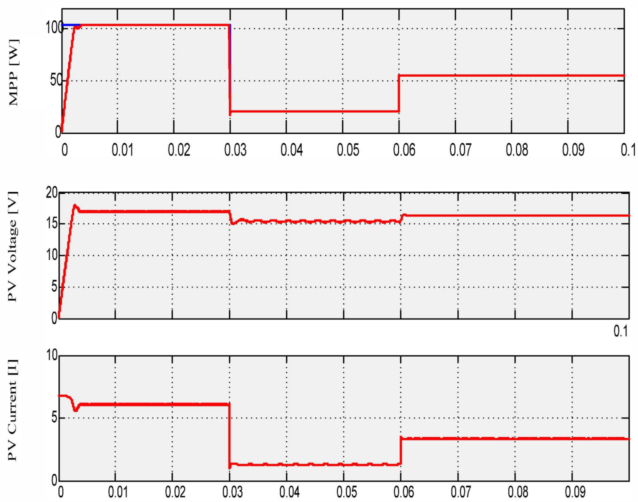

Fig. 16: Case 2: performance of FLC method.

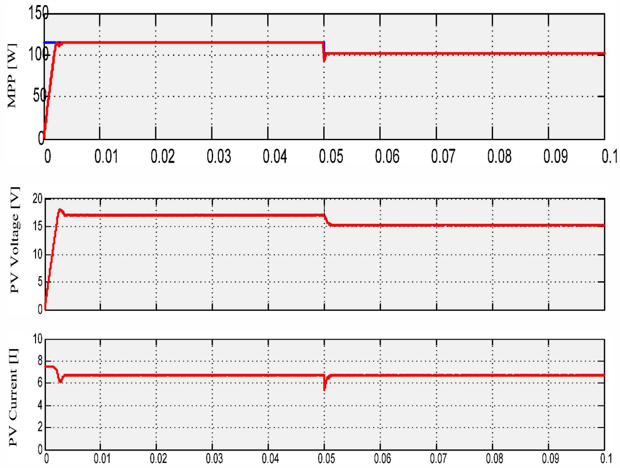

Fig. 19: Performance of FLC method.

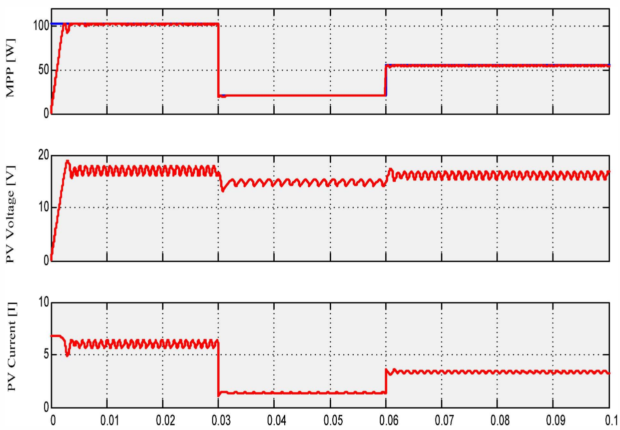

Fig. 17: Case 2: performance of P&O method.

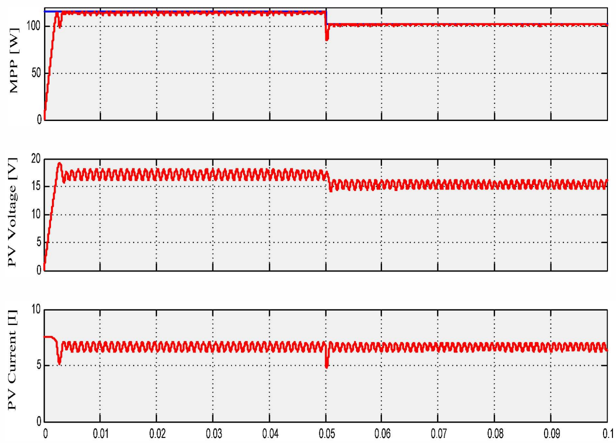

Fig. 20: Performance of P&O method.