International Journal for Modern Trends in Science and Technology
Volume: 03, Issue No: 06, June 2017
ISSN: 2455-3778
http://www.ijmtst.com

Development of Fuzzy Logic- Based Control Strategy for MPPT for Solar Photovoltaic System under Varying Irradiation, Temperature and Load Conditions

S.Karthika[1] | Dr.P.Rathika[2] | Dr.D.Devaraj[3]

[1]Assistant Professor, Department of ECE, V.V.College of Engineering, Tisaiyanvilai, India..
[2]Professor, Department of EEE, V.V.College of Engineering, Tisaiyanvilai, India..
[3]Professor, Department of CSE, Kalasalingam University, Krishnankoil, India..

To Cite this Article
S.Karthika, Dr.P.Rathika and Dr.D.Devaraj, "Development of Fuzzy Logic- Based Control Strategy for MPPT for Solar Photovoltaic System under Varying Irradiation, Temperature and Load Conditions", *International Journal for Modern Trends in Science and Technology*, Vol. 03, Issue 06, June 2017, pp. 166-173.

ABSTRACT

Maximum Power Point Trackers (MPPTs) play an important role in Photovoltaic (PV) power systems because they maximize the power output from a PV system for a given set of conditions, anssd therefore maximize the array efficiency. This paper proposes an intelligent control method for the Maximum Power Point Tracking (MPPT) of a photovoltaic system. A fuzzy logic- based P&O control technique is implemented to generate the optimal voltage from the photovoltaic system by modulating the duty cycle applied to the buck boost Dc-Dc converter. The proposed algorithm gives a good maximum power operation of the PV array under different conditions such as varying irradiation, temperature and load. Simulation results obtained are presented and compared with the conventional MPPT controller. Simulation results show the effectiveness of the proposed technique.

Index Terms *— MPPT -DC-DC Converter- Fuzzy logic controller –Photovoltaic (PV) system-P&O*

I. INTRODUCTION

Providing more secure power sources and pollution-free electric supplies, the photovoltaic (PV) system technologies have increasing roles in electric power technologies [1]-[4]. Solar photovoltaic is a phenomenon where the solar irradiation is converted directly into electricity through solar cell [5]. The PV array can supply the maximum power to the load at a particular operating point which is generally called as Maximum Power Point (MPP), at which the entire PV system operates with maximum efficiency and produces its maximum power.

A major challenge in the use of PV is posed by its nonlinear current-voltage (I-V) characteristics, which result in a unique Maximum Power Point (MPP) on its power-voltage (P-V) curve. The high initial capital cost of a PV source and low energy conversion efficiency make it imperative to operate the PV source at MPP so that maximum power can be extracted. The PV maximum output power is dependent on the operating conditions and it varies from moment to moment due to temperature, shading, soilage, cloud cover, and time of day. So tracking and adjusting for this Maximum Power Point is a continuous process. In general, a power source is operated in conjunction with a dc-dc power converter, whose duty cycle is modulated in order to track the instantaneous MPP of the PV source.

There are several methods and controllers that have been widely developed and implemented to track the MPP. In the last years researchers and practitioners in PV systems have presented survey or comparative analysis of MPPT techniques. The various MPPT techniques are Perturb and Observe

(P&O) method [6]-[9], Incremental Conductance (IC) method [6]-[10], Artificial Neural Network method [11], Fuzzy Logic method [12], Constant Voltage [13], Three Point Weight Comparison [14],[15], Short Current Pulse [16], Open Circuit Voltage [17] and the temperature method [18]. The most commonly used methods are Perturb and Observe (P&O), Incremental Conductance and Three-Point Weight Comparison.

Among these, Perturb and Observe (P&O) method is predominantly used in practical PV systems for the MPPT control due to the method's simple implementation, high reliability, and tracking efficiency [5],[19],[20]. P&O technique applies perturbation to the buck-boost DC-DC controller by increasing or decreasing the voltage reference of the PWM (Pulse Width Modulation) signal and subsequently observes the effect on the PV output power . Problem that arises in P&O MPPT method is that the operating voltage in PV panel always fluctuates due to the needs of continuous tracking for the next perturbation cycle.

In this paper a fuzzy logic-based MPPT technique is proposed. The fuzzy logic-based MPPT can track the Maximum Power Point faster than the conventional controllers and also it can minimize the voltage fluctuation after maximum power point has been recognized.

The proposed technique has been tested for changes in climate under different temperature and irradiation and load conditions.

II. MATHEMATICAL MODEL OF PHOTOVOLTAIC MODULE

The general model of solar cell can be derived from physical characteristic of the diode, which is usually called one diode model. The equivalent circuit of solar cell is shown in fig.1 [21], [22]. Equation 1 shows the Shockley diode equation which describes the I-V characteristic of diode D,

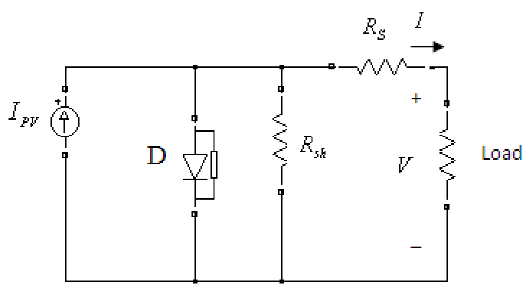


Fig.1. Equivalent circuit of a solar cell

$$I_D = I_{sat}[\exp(\frac{V_D}{nV_T}) - 1] \quad (1)$$

where I_D is the diode current, I_{sat} is the reverse bias saturation current, V_D is the voltage across the diode, n is the solar ideal factor of the diode and V_T is the thermal voltage.

Thermal voltage V_T however can be defined as

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

where K is Boltzmann constant ($1.3806503*10^{-23}$ J/K), T is temperature in degrees Kelvin and q is electron charge ($1.6021764*10^{-19}$ C).
To model the I-V characteristic of PV array, equation (3) can be derived from the circuit shown in Fig. 1,

$$I = I_{PV} - I_0[\exp(\frac{V + R_S I}{V_t a}) - 1] - \frac{V + R_S I}{R_{sh}} \quad (3)$$

where I_{PV} is the light-generated current, I_0 is the reverse saturation current, V is the PV array terminal voltage, R_S is the equivalent series resistance of the array and R_{sh} is the equivalent parallel resistance. In addition, the I-V characteristic of the PV panel also depends on the internal characteristics such as the series resistance R_S and parallel resistance R_{sh} . The series resistance is the sum of structural resistance of PV panel and it has strong influence when PV panel act as voltage source. The parallel resistance R_{sh} has great influence when PV panel acts as a current source.

The light-generated current of the photovoltaic cell depends linearly on the solar irradiation and is influenced by the temperature according to the following equation

$$I_{pv} = (I_{pv,n} + k_I \Delta_T)\frac{G}{G_n} \quad (4)$$

where $I_{PV,n}$ is the light-generated current at the nominal condition (usually 25^0 C and 1000W/m^2), Δ_T =T-T_n (being T and T_n the actual and nominal temperatures [K]), G[W/m^2] is the irradiation on the device surface, and G_n is the nominal irradiation.

The diode saturation current I_0 and its dependence on the temperature is given by,

$$I_0 = \frac{I_{sc,n} + K_I \Delta_T}{\exp\left(\frac{V_{oc,n} + K_V \Delta_T}{aV_t}\right) - 1} \qquad (5)$$

where a is the diode ideality constant. K_V and K_I is the current and voltage coefficients. $I_{sc,n}$ and $V_{oc.n}$ are the nominal short circuit current and nominal open circuit voltage.

III. PROPOSED METHOD

The block diagram of the proposed solar PV system is shown in Fig. 2. It mainly consists of a PV Module, a buck-boost Dc-Dc converter, MPPT control unit and a load. The PV panel contains 200 solar cells in series and 200 solar cells in parallel. When the modules are wired in parallel, their current is increased while the voltage remains constant. When the modules are wired together in series, their voltage is increased while the current remains constant. A pure resistive load is connected to the PV module through the buck boost Dc-Dc converter.

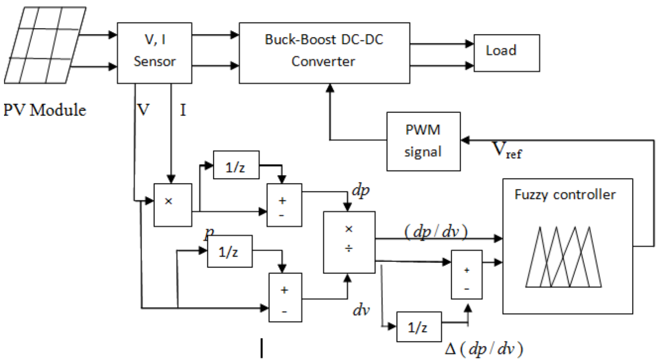


Fig. 2 Fuzzy logic based MPPT solar PV panel

The Photovoltaic module generates the DC voltage from solar temperature and irradiation. The energy supplied by the module does not have constant values, but fluctuates according to the surrounding conditions such as intensity of solar rays and temperature. These supplies are therefore supplemented by additional converters. The DC to DC boost converter is used to regulate a chosen level of the solar photovoltaic module output voltage and to keep the system at the Maximum Power Point. It is mainly useful for PV maximum power tracking purposes, where the objective is to draw maximum possible power from solar panels at all times, regardless of the load. It can able to regulate the perturbed voltage by increasing or decreasing the voltage reference of the PWM (Pulse width modulation) signal [23]. The output voltage and current of the PV panel are measured and fed to the fuzzy based MPPT control unit for MPP tracking. Based on the change of power with respect to change of voltage $\frac{dp}{dv}$ and $\Delta\frac{dp}{dv}$, fuzzy determines the voltage reference of the PWM (Pulse Width Modulation) signal. The proposed fuzzy logic based MPPT technique is discussed in section V.

IV. REVIEW OF FUZZY LOGIC

Fuzzy logic uses fuzzy set theory, in which a variable is a member of one or more sets, with a specified degree of membership. Fuzzy logic allows us to emulate the human reasoning process in computers, quantify imprecise information, make decision based on vague and in complete data, yet by applying a “defuzzification” process and arrive at definite conclusions.

The FLC (Fuzzy Logic Controller) mainly consists of three blocks

- Fuzzification
- Inference
- Defuzzification

(i) Fuzzification

The fuzzy logic controller requires that each input/output variable which defines the control surface be expressed in fuzzy set notations using linguistic levels. The linguistic values of each input and output variables divide its universe of discourse into adjacent intervals to form the membership functions. The member value denotes the extent to which a variable belongs to a particular level. The process of converting input/output variable to linguistic levels is termed as Fuzzification.

(ii) Inference

The behavior of the control surface which relates the input and output variables of the system is governed by a set of rules. A typical rule would be If x is A THEN y is B. When a set of input variables are read, each of the rule that has any degree of truth in its premise is fired and contributes to the forming of the control surface by approximately modifying it. When all the rules are fired, the resulting control surface is expressed as a fuzzy set to represent the constraints output. This process is termed as Inference.

(iii) Defuzzification

Defuzzification is the process of conversion of fuzzy quantity into crisp quantity. There are several methods available for defuzzification. The most prevalent one is centroid method, which utilizes the following formula:

$$\frac{\int(\mu(x)x)dx}{\int \mu(x)dx}$$

(6) where μ is the membership degree of output x.

V. PROPOSED FUZZY LOGIC CONTROLLER

Fuzzy logic is implemented to assist the conventional MPPT technique to obtain the MPP operating voltage point faster and also it can minimize the voltage fluctuation after MPP has been recognized [24],[25].

The proposed fuzzy logic based MPPT controller, shown in Fig. 3, has two inputs and one output.

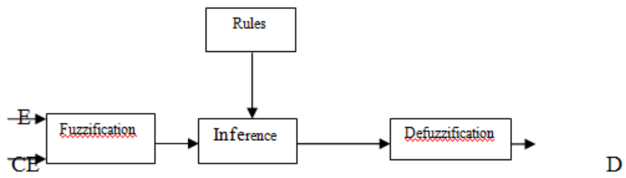


Fig. 3 General diagram of a fuzzy controller

In the proposed fuzzy logic based technique the error (E) and change of error (CE) are taken as input variables which are as below for k th sample time.

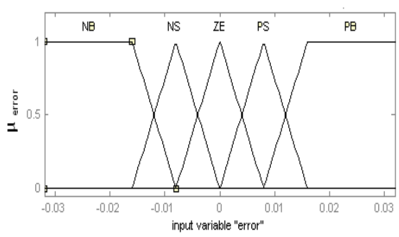
$$E(k)=\frac{dP}{dV}=\frac{P_{ph}(k)-P_{ph}(k-1)}{V_{ph}(k)-V_{ph}(k-1)} \quad (7)$$

$$CE(k)=E(k)-E(k-1) \quad (8)$$

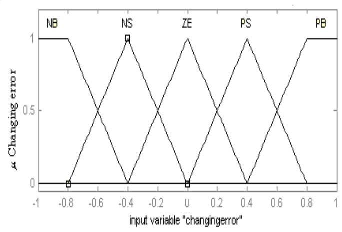
where $P_{ph}(k)$ is the power of the photovoltaic generator. The input E (k) shows the change of power with respect to the change of voltage. Another input CE (k) expresses the change of error.

Table 1: Fuzzy Rule Table.

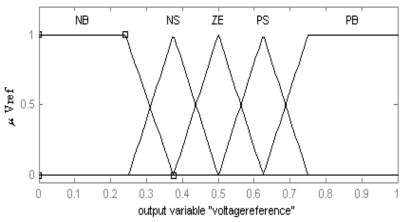
CE \ E	NB	NS	ZE	PS	PB
NB	ZE	ZE	PB	PB	PB
NS	ZE	ZE	PS	PS	PS
ZE	PS	ZE	ZE	ZE	NS
PS	NS	NS	NS	ZE	ZE
PB	NS	NB	NB	ZE	ZE



(a)



(b)



(c)

Fig. 4 Membership functions of (a) error E (b) Change of error CE (c) Voltage reference V_{ref}

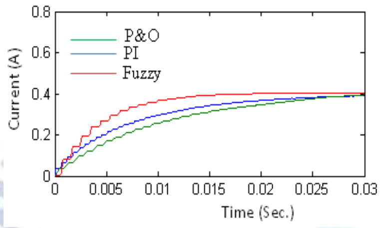
To design the FLC, variables which can represent the dynamic performance of the system to be controlled should be chosen as the inputs to the controller. In the proposed method, the derivative of the change of power with respect to change of voltage (dP/dV) and change of (dP/dV) are considered as the inputs of the FLC and the voltage reference for modulated signal generation is taken as the output of the FLC. The input and output variables are converted into linguistic variables. In this case, five fuzzy subsets, NB (Negative Big), NS (Negative Small), ZE (Zero), PS (Positive Small) and PB (Positive Big) have been chosen. Membership functions used for the input and output variables are shown in Fig.4. As both inputs have five subsets, a fuzzy rule base formulated for the present application is given in table I. The performances of fuzzy logic based MPP tracking are able to reduce the perturbed voltage after the MPP operating voltage has been recognized.

VI. SIMULATION RESULTS

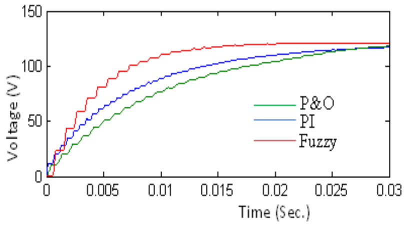
The PV module is modeled using MATLAB-SIMULINK for the standard conditions such as constant temperature of 25°C and irradiation at 1000W/m². The PV module contains 200 solar cells in series, and generates the output voltage as 120V. A pure resistive load is connected to the PV module through the buck boost dc-dc converter. The performance of the proposed technique has been examined under the following conditions.

Case A: Under standard conditions (Temperature 25⁰C and Irradiation 1000W/m²)

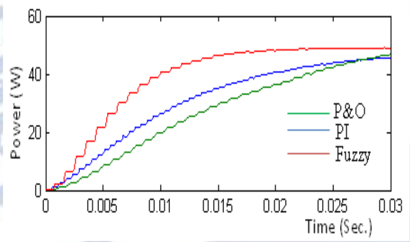
The performance of the proposed technique has been examined for fixed solar radiance at 1000W/m² and at cell temperature 25⁰C. First, the PV system is simulated for the standard conditions i.e. temperature=25 $^{\circ}C$, irradiation=1000W/m². Fuzzy logic based MPPT technique is applied to the controller of buck boost dc-dc converter. For comparison, the PV system is simulated using conventional P&O and PI based MPPT techniques and the result is shown in Fig.5 (a), (b) and (c).



(a) Current



(b) Voltage



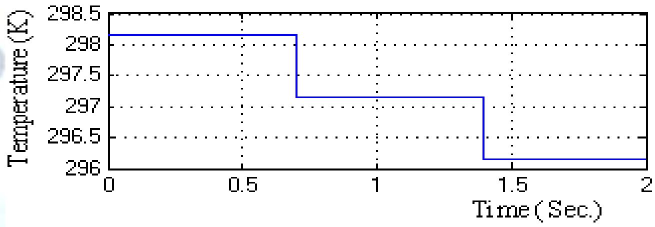
(c) Power

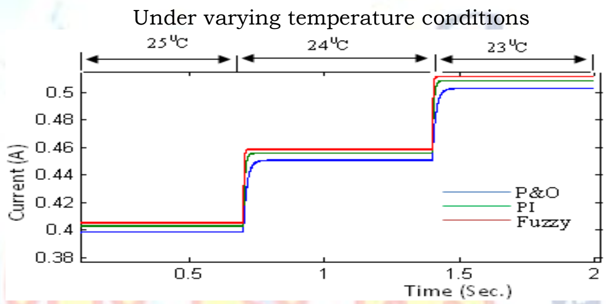
Fig. 5 Fuzzy, PI and P&O responses: For standard conditions of temperature 25⁰C and Irradiation 1000 W/m².

It shows that the fuzzy logic controller can track the maximum power point faster than the conventional tracking controller. From the figure, it is observed that the fuzzy controller can track the maximum power point at 0.015s and also it generates constant voltage without any deviations. Therefore, the MPPT fuzzy logic control has better performance compared to the conventional P&O and PI based MPPT techniques.

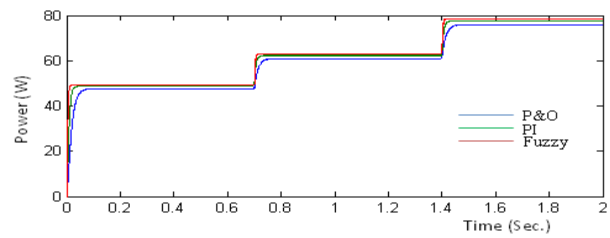
Case B: Under varying temperature conditions (Temperature 25⁰C to 23⁰C and Irradiation 1000W/m²)

In this case, the temperature is reduced to 23 $^{\circ}C$ and the results are analyzed. The proposed fuzzy logic based MPPT has been tested under different temperature conditions to increase the output voltage. The solar temperature level is started from 25⁰C (298K) and reduced to 23⁰C (296K) with 1⁰C (293K) steps at the time instants 0.7 to 1.4s as shown in fig. 6 (a).

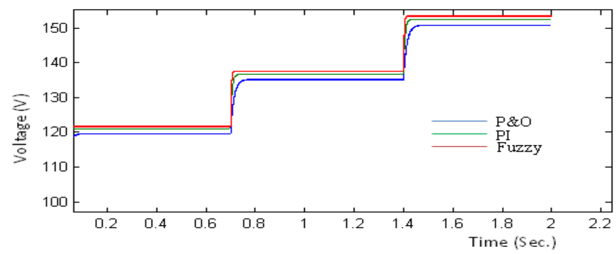




(a) Current



(b) Power

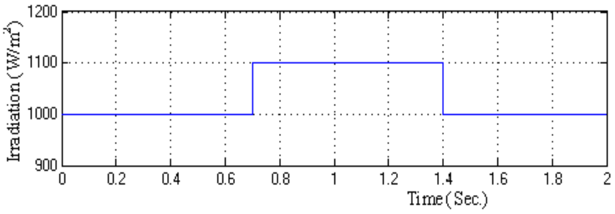


(c) Voltage

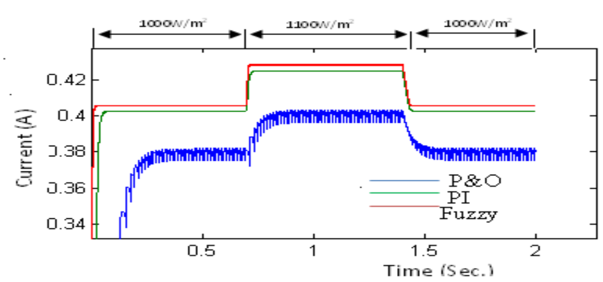
Figure 6 Fuzzy, PI and P&O responses: For varying temperature conditions of temperature 250C to 230C and Irradiation 1000 W/m2.

Fig. 6 (b), (c) and (d) show the results of PV operating voltage, power and current. From the fig. 6 (c), it is observed that the decreasing level of temperature always involves in increasing the power of PV system. . Due to Fluctuation in temperature causes reduction in band gap. This in turn causes some increase in photo-generation rate and thus, a marginal increase in current. However, the reverse saturation current of increase rapidly with temperature. Due to this, the cell voltage decreases approximately 2.2mV per 1 °C rise in its operating temperature. The performance of the proposed technique is compared with the conventional techniques and the result is shown in Fig.6. The conventional techniques produce outputs with ripples while the proposed fuzzy logic based controller gives better results without undulations reflecting the non-sensitivity to temperature variations.

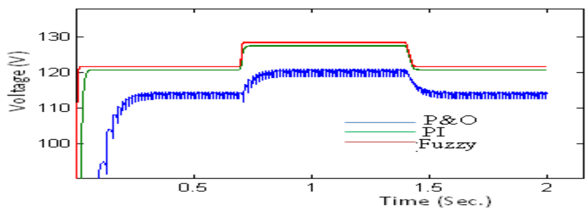
Case C: Under varying irradiation conditions (Temperature 250C and Irradiation 1000W/m2 to 1100 W/m2)



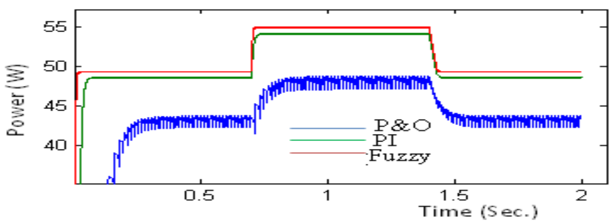
(a) Under varying irradiation condition



(a) Current



(b) Voltage



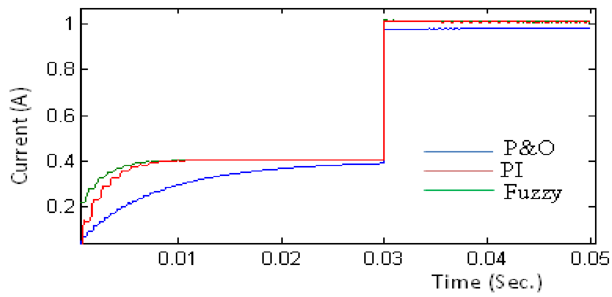
(c) Power

Figure 7 Fuzzy, PI and P&O responses: For varying irradiation conditions of temperature 250C and Irradiation 1000 W/m2 to 1100 W/m2

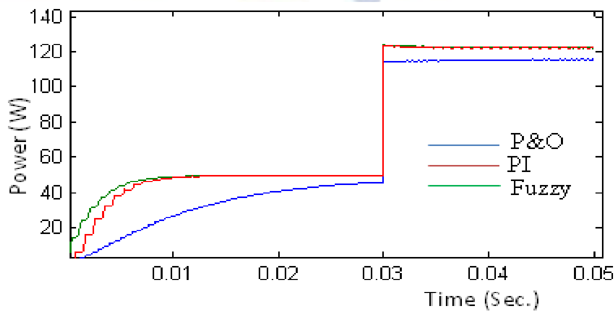
In this case, the irradiation is increased to 1100W/m2 and the results are analyzed. The proposed MPPT technique is used to obtain the MPP operating voltage point faster than conventional controller and also it can minimize the voltage fluctuation. The behavior of the system under variation of irradiation at 1000 W/m2 to 1100 W/m2 over an interval of 2s with a constant temperature T=250C as shown in Fig.7 (a). Fig.7 (b), (c) and (d) shows the results of PV operating voltage, power and current. From the figure, it is observed the proposed fuzzy controller can track the Maximum Power Point without any deviations. But the conventional P&O and PI based MPPT tracks the Maximum Power Point with fluctuations and also it does not have the ability to reduce the perturbed voltage.

Case D: Under varying load conditions (from 300Ω to 200Ω)

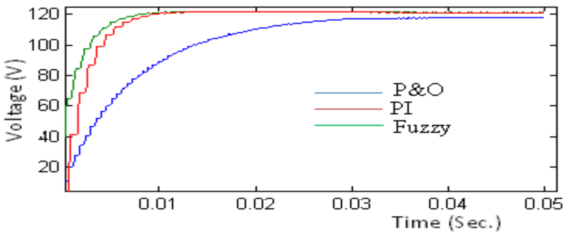
In this case the electrical load connected to the solar panel is varied and the response is analyzed. This load variation in turn causes a change in the operating point (current and voltage characteristics) of the panel. Thus by intelligently controlling the operation of the DC-DC converter, the power output of the panel can be intelligently controlled and made to output the maximum possible power. Fig. 8(a), (b) and (c) shows that the output voltages, current and power waveforms under varying load conditions. The load connected to the buck boost dc-dc converter is varying from 300Ω to 200Ω. From the investigation, it is clear that the PV power which is controlled by fuzzy logic is more stable than the conventional P&O and PI based MPPT.



(a) Current



(b) Power



(c) Voltage

Figure 8 under varying load conditions (from 300Ω to 200Ω)

The energy supplied by the PV system was calculated over a given time interval and the results are shown in Table 2.

From the data given in Table 2, it is observed that the fuzzy can track the maximum efficiency compared to the conventional P&O and PI based MPPT techniques under varying temperature irradiation and load conditions.

Table.2 Energy generated as a function of MPPT technique

Conditions	MPPT Methods	Theoretical Energy (J)	Actual Energy (J)	Efficiency (%)
Under standard conditions (Temperature 25ºC and Irradiation 1000W/m²)	P&O	1.4943	1.3692	91.6
	PI	1.4943	1.4007	93.7
	Fuzzy	1.4943	1.469	**98.3**
Under varying temperature conditions (Temperature 25ºC to 23ºC and Irradiation 1000W/m²)	P&O	99.62	86.42	86.74
	PI	99.62	97.12	97.4
	Fuzzy	99.62	98.24	**98.6**
Under varying irradiation conditions (Temperature 25ºC and Irradiation 1000W/m² to 1100 W/m²)	P&O	158.52	153.8	97
	PI	158.52	155.4	97.8
	Fuzzy	185.52	156.3	**98.6**
Under varying load conditions (from 300Ω to 200Ω)	P&O	9.905	8.845	89.2
	PI	9.905	9.59	96.8
	Fuzzy	9.905	9.645	**97.4**

VI. Conclusion

This paper has presented an intelligent MPPT control strategy for the PV system using fuzzy logic controller. The Maximum Power Point tracking technique was simulated using MATLAB/Simulink. The fuzzy logic based controller can track the maximum power point, faster compared to conventional P&O and PI based MPPT technique .It has the capability of reducing the voltage fluctuation after MPP has been recognized. The simulation results show the efficiency of the fuzzy logic controller in maintaining the stable maximum power point under change in irradiation and temperature conditions.

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