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An Efficient Fuzzy Logic Based Maximum Power point Tracking Controller for Photovoltaic Systems

Muhammad Sheraz and M.A.Abido

Department of Electrical Engineering
King Fahd University of Petrolium and Minerals
Dhahran, 31261 (Saudi Arabia)
Phone/Fax number: +966 3 860 1681/+966 3 860 3535, e-mail: isheraz@kfupm.edu.sa, mabido@kfupm.edu.sa

Abstract. This paper represents a Fuzzy Logic (FL) based Maximum Power Point Tracking (MPPT) controller for a PV array. The proposed controller is aimed at adjusting the duty cycle of the DC-DC converter switch to track the maximum power of a PV array. MATLAB/Simulink is used to develop and design the PV array system equiped with the proposed MPPT controller. The developed model has been examined under different operating conditions. The performance of the proposed controller has been compared with conventional ones. The results show that the proposed controller is able to track the MPP in a shorter time with less fluctuations. In addition, the robustness of the proposed controller has been confirmed in the rapidly changing irradiation conditions.

Key words

PV system, maximum power point tracking, MPPT, DC-DC boost converter, Fuzzy Logic

1. Introduction

Solar energy is the most abundant and environmental friendly RES and can be converted to electrical energy directly using the photovoltaic arrays. PV arrays have a non-linear I-V and P-V characteristics and have one optimum point called Maximum Power Point (MPP). This MPP is highly vulnerable to the ambient conditions, that are irradiation and cell temperature, and these conditions are always changing with time which keep varing the MPP. Therefore the maximum power point tracking (MPPT) controller is of the great importance and are coupled with the PV arrays to track the MPP and extract maximum possible power from the array. Maximum power point tracker works with the DC-DC converter which is operated as an interface between the PV panel/array and load/inverter. DC-DC converter performs two major tasks, one is to track the maximum power point and to regulate and step up or step down the output voltage. Voltage from the PV panel, which is varying depending on ambient conditions, is given as input to the DC-DC converter and its output is constant voltage across the capacitor where load/inverter can be connected. MPPT works as a controller for the DC-DC converter and controls the duty ratio of the switch such that it tracks the MPP under the changing ambient conditions.

The idea of MPPT is not new, many MPPT methods have been proposed by researchers to improve the tracking efficiency. These techniques differ in sensor required, complexity, cost, and convergence speed [1]-[3]. In [4] and [5] fractional open circuit voltage method is implemented that based on the fact that the ratio of the maximum power voltage (V_{MP}) and the open circuit voltage (V_{OC}) are approximately linearly proportional under varying weather conditions. The yielded power from PV panel definitely is less than the real power at MPP because of the obvious reason that this method is based on the approximation. Following the same pattern fractional short circuit current method is shown in [6] which uses the fact that the ratio of maximum power current (I_{MP}) and short circuit current (I_{SC}) are linearly proportional. This method has the same drawbacks and weakness as that of fractional open circuit voltage method. Perturb and Observe (P&O) method [7], [8] and Hill climbing method [9] are most popular because of their simplicity and low cost. Both the methods work on the same principle of perturbing the PV system and observing its effect on the PV panel power output. Difference lies in the method of perturbation, in P&O panel output voltage/current is perturbed while in Hill climbing duty cycle of DC-DC- converter is perturbed. Incremental Conductance (InCond) method is used in [10] to MPP tracking. All these methods may fail to track MPP in rapidly varying atmospheric conditions and have oscillations in the steady state which can be reduced by decreasing the perturbation size but at the expense of tracking speed [3], [11]. Many modifications have been employed in P&O and InCond by researchers but cannot overcome the shortcoming thoroughly [11]-[16].

In recent years some Artificial Intelligence (AI) techniques like Artificial Neural Network (ANN) [17] and Fuzzy Logic [18] have been implemented to prevail over these problems. The fuzzy-logic controller (FLC) based MPPT has been proposed in [19]-[22] to overcome the shortcoming of the conventional algorithms. All proposed FLC in the literature have the same output that is change in duty cycle (ΔD), but they are differ in their input variables, linguistic rules and membership functions. Most of the Fuzzy logic based MPP controllers have error and change in error as input variables. Basically this error and change in error represent the slope and change in slope of the P-V curve. The problem with such inputs is that, as the duty cycle is not considered as input, operating point moves away from the original MPP in the varying atmospheric condition [19]. In [20] a fuzzy controller is presented with the inputs of array power variation and duty cycle. The dynamic behaviour is improved in changing ambient conditions but this method added the steady state oscillation in the PV output which causes the power loss. Fuzzy cognitive networks are used in [21] to improve the efficiency of the fuzzy-based MPP tracker but it added complexity in the hardware design. In [22] drawbacks of Hill Climbing method have been discussed and improvement in the conventional Hill climbing method is shown by fuzzifying its rules and demonstrated it to be better than the existed MPPT methods.

In this paper scaling factor and membership functions of FLC MPPT are investigated to improve the tracking speed and steady state fluctuations. Increasing the scaling factor (range) of output variable will improve the tracking speed but add large oscillations in the steady state which cause considerable power loss. To tackle this problem new memberships functions are introduced which control the operating point closer to the MPP and reduce the fluctuation.

Futher the paper is organized as follow. In section 2 PV system model is described that include PV array, DC-DC converter, maximum power point tracker (MPPT) and load. After that the proposed Fuzzy based MPPT controller is discussed in section 3. It is followed by results and discussion in section 4 and conclusion is made in the end.

2. PV System Modelling

Fig. 1 shows the PV system which consists of PV array, DC-DC converter, MPPT controller and load/inverter. PV array generates the voltage and current depending upon the ambient conditions (irradiation and temperature). The current and voltage are varying due to changing atmospheric condition and so the DC-DC converter is used to make the output constant and available for the load/inverter. MPP tracker works as a controller for the DC-DC converter and accepts PV panel current (I_{PV}) and voltage (V_{PV}) as an input and provides with the desired change in duty cycle for the switching of the converter such that PV system works at the optimum point. Fig. 2 shows the logic inside the MPPT control block where power of the PV panel (P_{PV}) is calculated. Change in power and change in current is given as an input to the controller whose output is a change in duty cycle.

A. PV Array

Five parametric model of the PV array shown in Fig. 3 is used in this study. These five parameters are I_L, I_0, R_S, R_p and the factor (a). They are defined as: -

I_L is the light current,
I_0 is the diode saturation current,
R_S is the series resistance, and
R_{SH} is the shunt resistance,
"a" is the ideality factor of the diode

By Kirchhoff's law simple current relationship can be found equation (1).

$$I_{PV} = I_L - I_D - I_{SH} \qquad (1)$$

$$I_{PV} = I_L - I_0\left\{\exp\left[\frac{(V_{PV}+I_{PV}R_S)}{a}\right]-1\right\} - \frac{V_{PV}+I_{PV}R_S}{R_{SH}} \qquad (2)$$

$$a = \frac{nkT}{q} \qquad (3)$$

$$P_{PV} = V_{PV} * I_{PV} \qquad (4)$$

Where; I_{PV} is the PV array output current and V_{PV} is the output voltage. Eq. (2) represents the I-V characteristics of the PV array. Having the five parameters known, Eq. (2) can be solved. With different atmospheric conditions, these parameters have different values that can be calculated at any ambient condition using equations (5)-(9) assuming their values at standard test conditions (25^0C, 1000W/m^2) are known.

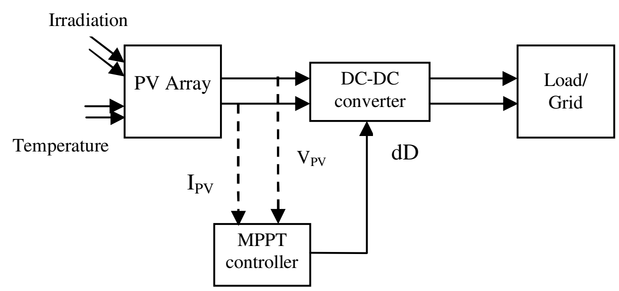

Figure 1: PV system used.

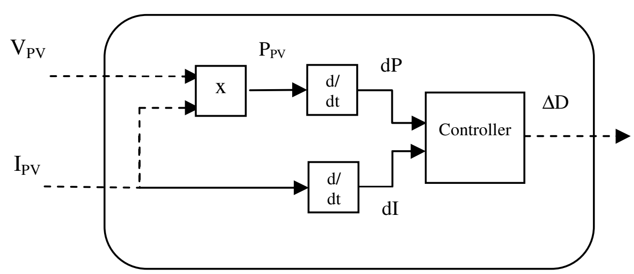

Figure 2: MPPT controller block.

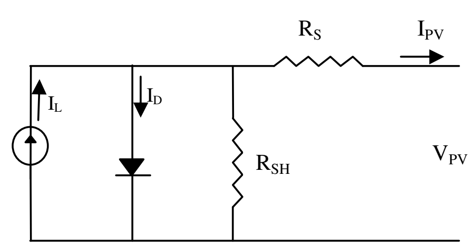

Figure 3: Equivalent circuit of PV array.

$$a = a_{ref}\left(\frac{T_c}{T_{c,ref}}\right) \qquad (5)$$

$$I_L = \frac{S}{S_{ref}}\left[I_{L,ref} + \mu_{I,sc}\left(T_c - T_{c,ref}\right)\right] \quad (6)$$

$$R_{SH} = R_{SH,ref}\frac{S_{ref}}{S} \quad (7)$$

$$R_S = R_{S,ref} \quad (8)$$

$$\frac{I_0}{I_{0,ref}} = \left(\frac{T_c}{T_{c,ref}}\right)^3 exp\left(\frac{E_g}{kT}\Big| - \frac{E_g}{kT}\Big|\right) \quad (9a)$$

$$\frac{E_g`}{E_{g,ref}} = 1 - C\left(T - T_{ref}\right) \quad (9b)$$

Where,
$E_{g,ref}$= 1.12eV; C = .0002677; $\mu_{I,sc}$=3.5 mA/k
The values of parameters at reference condition are calculated using five parameter model [23] and data provided by the manufacturer which is shown in Table. 1. The Sun Power solar panel data is used in this paper and its electrical data is shown in Table.2 [24]. PV array is simulated in the MATLAB/simulink using the equation (1)-(9).

Table 1: Values of five parameters at reference conditions.

Parameter	Value
I_L	5.99 A
I_O	1.4032e-7 A
R_S	.008686 ohms
R_{SH}	95658.6045 ohms
a	2.7715

Table 2: Sun power solar panel electrical data from the data sheet

Parameters	Values from Data sheet
Peak Power (P_{MPP})	230 W
Rated Voltage (V_{MPP})	41.0 V
Rated Current (I_{MPP})	5.61 A
Open Circuit Voltage (V_{OC})	48.7 V
Short Circuit Current (I_{SC})	5.99 A

B. DC-DC Converter:

Fig. 4 shows the DC-DC boost converter. It performs two major tasks; it regulates the fluctuating input voltage coming from the PV panel and tracks the maximum power point by adjusting the duty cycle.Transfer function of boost converter is given as.

$$M_V = \frac{V_O}{V_S} = \frac{1}{1-D} \quad (10)$$

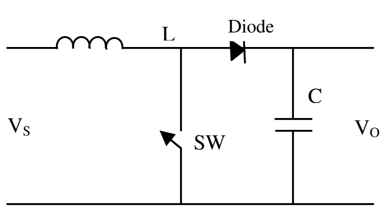

Figure 4: Circuit for DC-DC Boost converter.

Where,
$V_O$is the constant output voltage.
V_S is the fluctuating input voltage.
D is the duty ratio and given by:

$$D = \frac{t_{on}}{t_{on}+t_{off}} = \frac{t_{on}}{T} \quad (11)$$

Control of boost converter switch is done by MPPT controller that will vary the duty cycle of the converter and extract the maximum possible power from the PV array.

3. The Proposed Fuzzy based MPPT controller

The FL controller contains a Fuzzy Inference System (FIS) whose structure is shown in Fig. 5. Fuzzy logic control generally consists of three stages: fuzzification, rule base table/inference engine, and defuzzification.

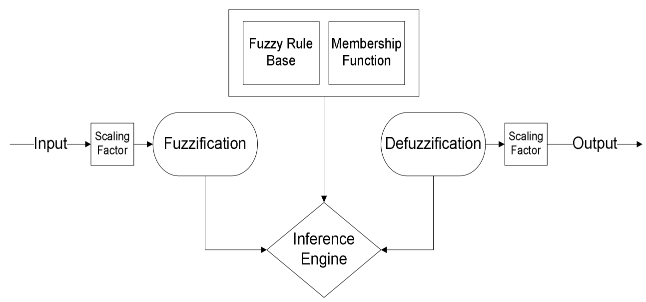

Figure 5: Structure of the Fuzzy Inference System (FIS).

In this work,the inputs used for the FL based MPPT are

$$\Delta P = P(n) - P(n-1) \quad (12)$$
$$\Delta I = I(n) - I(n-1) \quad (13)$$

Where, ΔI is the change in output current of the PV array and ΔP is the change in output power of the PV array.
Output of the FLC is given by

$$\Delta D = D(n) - D(n-1) \quad (14)$$

Where, ΔD is the change in duty ratio of the boost converter. These inputs and output are same as taken in [22] with little modification in scaling factor and membership functions. Six memberships are used for inputs and outputs: PB (Positive Big), PM (Positive Medium), PS (Positive Small), NB (Positive Big), NM (Negative Medium), NS (Negative Small) as shown in Fig. 6.
Voltage and current from the PV array are measured first and then multiplied to get power. Using eq (12) and (13) change in power and change is current is computed and given as input to the FLC MPPT. These inputs are multiplied by scaling factor and then processed by Fuzzy Inference System (FIS).
In the fuzzification stage, the crisp input variables are converted into linguistic variables based on a membership function. Membership functions for inputs and output are shown in Fig. 6. Several fuzzy inference methods were

introduce in the literature, but commonly used method is Mamdani Max-Min [25]. Table.4 shows the rule base of the fuzzy logic controller. In defuzzification, the FLC output is converted back to numerical variable from a linguistic variable using a similar membership function. In literature a number of methods were described for defuzzification such as the centroid, first of maxima (FOM), last of maxima (LOM) and the mean of maximum (MOM) [24]. In this paper centroid method is used which is generally used in the design of FLCs [26]. This method is expressed as:

$$\Delta D = \frac{\sum_i^n \mu(D_i) D_i}{\sum_i^n \mu(D_i)} \tag{15}$$

ΔD is the change in duty cycle which will adapt the duty ratio of the PWM signal that is used by the DC-DC converter switch to track the MPP of the PV array.

It is worth mentioning that the scaling factor has a valueable effect on the controller performance. Increasing the scaling factor of the output will improve the tracking speed but increases the steady-state oscillations. Similarly lessening its value will improve these oscillation but in the expense of large convergence time.

Table 3: Fuzzy rule base table.

dI / dP	NB	NM	NS	PS	PM	PB
NB	PB	PB	PS	NS	NB	NB
NM	PM	PM	PS	NS	NM	NM
NS	PM	PS	PS	NS	NS	NM
PS	NM	NS	NS	PS	PS	PM
PM	NM	NM	NS	PS	PM	PM
PB	NB	NB	NS	PS	PB	PB

In this paper tracking speed is improved using the large scaling factor for output variable and two membership function (NS and PS) are used to reduce the oscillations in the steady state. These membership functions will restrict the output variable, change in duty ratio (dD), from being large which result in low oscillations. The values of the scaling factor used in this paper are 10 and .15 for change in power (dP) and change in current (dI), respectively and .015 for change in duty cycle (dD). Circuit parameters and design specification for the boost converter used in this paper are given in Table.3.

Table 4: Design specification and circuit parameters.

Item	Value
Capacitor C1 (F)	1.00E-04
Boost Inductor (H)	5.00E-03
Smoothing Capacitor (F)	2.00E-04
Switching frequency (kH)	5
Load Voltage (V)	100
Load Resistance (ohms)	47.43

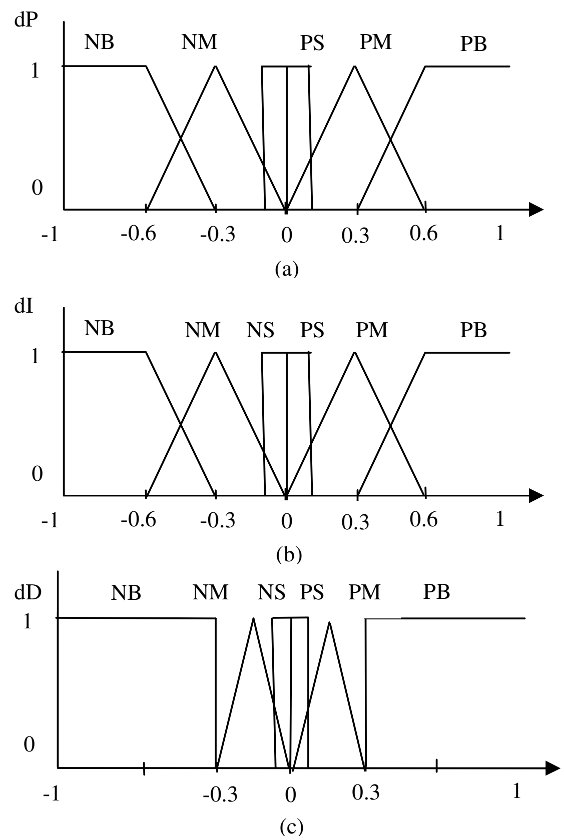

Figure 6: Membership functions of the fuzzy subsets inputs (a) dP (b) dI and output (c) dD.

4. Results and Discussion:

Effectiveness of the proposed FLC controller, P&O and the controller designed in [22] is determined under the irradiation pattern shown in Fig.7. Irradiation level is constant with a value of 1000 (W/m^2) up to .2 seconds and then reduces drastically to 250 (W/m^2). It remain at this value up to .4 seconds after that returns to its initial value of 1000 (W/m^2) . Tracking speed and steady oscillation of the MPPT's controllers can be judge under this irradiation pattern.

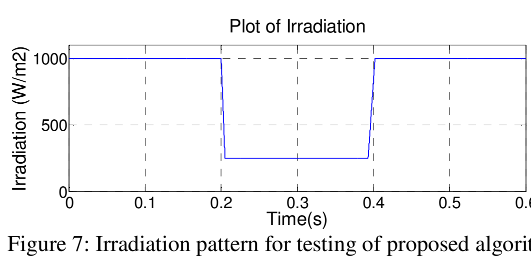

Figure 7: Irradiation pattern for testing of proposed algorithm.

The PV curves in normal condition (1000 W/m^2) and shaded condition (250 W/m^2) is shown in Fig. 8. In normal condition the maximum power that can be generated by PV panel is 229.7W at the voltage of 41.1V and in shaded condition it can produce only 22.33% of this value that is 51.3W at voltage of 39.6V. Table. 5 shows the P_{MPP} and V_{MPP} under normal and shaded condition.

Table 5: Maximum power at normal and shaded condition.

Condition	P_{MPP}(W)	V_{MPP}(V)
Normal	229.7	41.1
Shaded	51.3	39.6

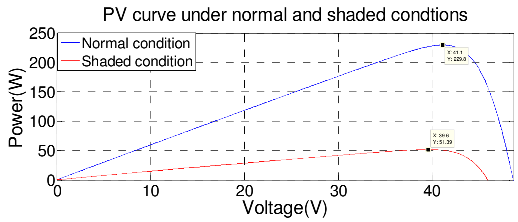

Figure 8: PV array I-V curve under normal and shaded condition.

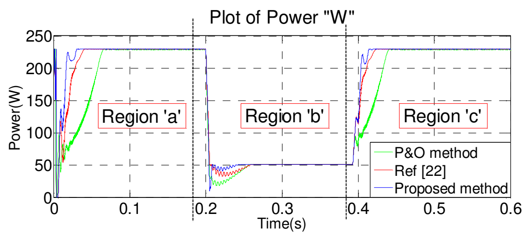

Figure 9: Plot of PV array Power (P_{PV}) vs time.

Fig. 9 shows the plot of power (W) verses time (s) and represents a comparison of the PV output power for the proposed FLC compared to the FLC in ref [22] and conventional Perturb and Observe method. Fig.9 is divided into 3 regions, region 'a' representing the start of the algorithm, region 'b' showing the rapidly decrease in irradiation, region 'c' shows the rapidly increase in irradiation. It is apparent from the plot that proposed FLC have faster convergence time than the other two methods.

Fig. 10 shows the behaviour of the proposed FLC, FLC in [22] and P&O in the region 'a' and it is clear from the plot that proposed FLC can track the maximum power point much faster than the other two methods. Proposed FLC attain its steady state in .03s as compare to FLC in [22] and P&O which took .04s and .065s with the improvement of 25% and 53.84% respectively. In fig. 11 proposed FLC tracker is compared with the other two under the rapidly decreasing irradiation condition (region 'b' in the Fig. 9). Plot shows that proposed FLC can track the optimum point faster and reaches its steady state before than the other methods. Improvement in region 'b' is 27.27% and 33.33% from FLC in [22] and P&O respectively. Similarly Fig. 12 shows its performance in rapidly increasing irradiation condition (region 'c' in Fig. 9). Improvement in region 'c' is 20% and 50% form ref [22] and P&O method respectively.

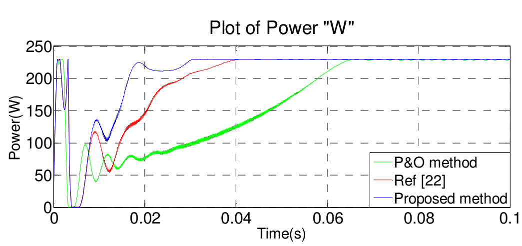

Figure 10: Plot of Power (P_{PV}) vs time in region "a".

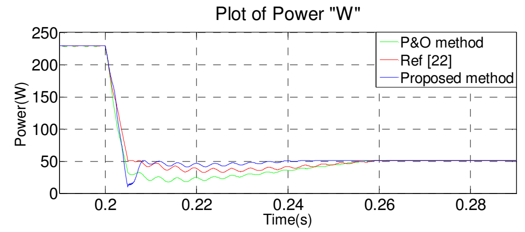

Figure 11: Plot of Power (PPV) vs time in region "b".

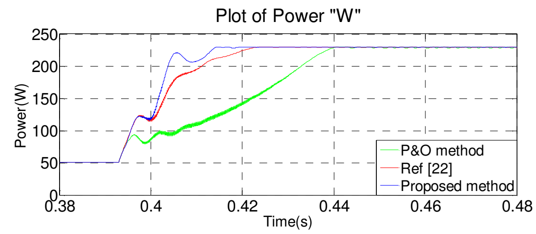

Figure 12: Plot of Power (PPV) vs time in region "c".

Table 6: Comparison between proposed method and previous literature.

	Power W (mean) at STC	Region "a"	Region "b"	Region "c"	Steady state Oscillation
Proposed	**229.68**	**0.03s**	**0.24s**	**0.42s**	**Less**
Ref[22]	229.5	0.04s	0.255s	0.425s	Medium
PnO	229.3	0.065s	0.26s	0.44s	High
	improvement from Ref[22]	**25%**	**27.27%**	**20%**	
	Improvement from PnO	**53.84%**	**33.33%**	**50%**	

Table. 6 shows the comparison and improvements of the proposed FLC with P&O and ref [22] for all the three regions. The proposed FLC have also reduced the steady state fluctuation as can be seen in the Fig. 13. Reduction in steady state oscillation causes less power losses and results in more power output. It is shown in table 3 that proposed FLC is extracting more power than the other two methods. Though the increase in power is less but it can be high if large number of PV panels are connected in series or parallel..

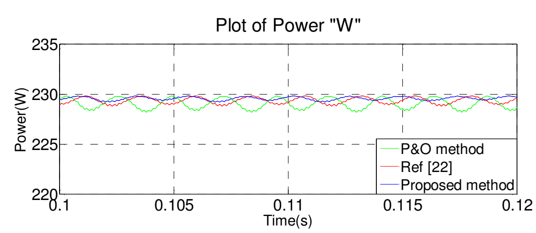

Figure 13: Graph showing steady state oscillations.

5. Conclusion

A new Fuzzy Logic based Maximum power point tracker (MPPT) controller has been proposed in this paper. MPPT is used to extract maximum power from the PV array under varying environment conditions. Performance of the proposed controller is assessed using the PV array model developed in MATALB/Simulink software. Results show that the proposed FLC MPPT has faster converging speed, less fluctuation in the steady state and may not fail under rapidly changing irradiation conditions. The robustness of the proposed FLC MPPT has been tested under rapidly changing irradiation condition and compared with the existed MPPT methods.

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