

Maximum Power Point Tracker for a PV Cell using a Fuzzy Agent adapted by the Fractional Open Circuit Voltage Technique

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Abstract— The Photovoltaic cells have P-V characteristics which indicate that there is only one point that produces a maximum output power. The point of the maximum power lies at the knee of the I-V curve. Tracking this point is a very important issue concerning the energy yield of the PV systems. One of the efficient tracking techniques is based on the Fuzzy agents which are able of fine tuning the cell operating voltage and current to keep the maximum possible output power. In this paper, a fuzzy agent with two input parameters enhanced by the fractional open circuit voltage technique will be used to track the MPP in a fast and accurate manner that is better than the traditional techniques. Assigning different weights for the two inputs of the fuzzy agent adapts the power response to achieve fast settling and accurate tracking of the cell maximum output power even under extreme variable atmospheric conditions in an efficient manner with better performance than conventional fuzzy MPPT technique.

Keywords- Adaptive Fuzzy agent, Fractional Open circuit Voltage, Fuzzy Control, MPPT, Photovoltaic modules.

I. INTRODUCTION

Achieving the maximum possible output power from a PV module is an important aim in any PV system to compensate its initial cost. The task can be handled using a DC-DC converter with variable duty cycle D that is determined through a maximum power point tracker MPPT. The aim of the tracker is to vary the module operating current and voltage such that the maximum output power is achieved in a fast and accurate manner even under variable irradiance or temperature conditions. At the maximum power point, the power variation with respect to voltage variation or current variation is zero as will be seen. So, using this variation as an input signal to a fuzzy agent beside another input which is the variation of the first input helps the fuzzy agent to vary and fine tune the duty cycle of the DC-DC converter in a manner that keeps the maximum power transfer to the desired load even under large atmospheric variations. The usage of the fractional open circuit voltage is useful in reducing the searching and hence the settling times. The proposed technique has the advantage of fast settling and accurate tracking without steady state error.

II. MPPT TECHNIQUES

The I-V and P-V characteristics of the photovoltaic module under study are shown in fig. 1. The maximum power occurs at the knee of the I-V curve as shown in the same figure. The characteristics are for the module GUC09 of the commercial type BP7185S-Saturn 7 series.

Many MPPT techniques were developed in the literature aiming at fast and accurate tracking. As in [1] and [2], some of them will be discussed.

A. Fractional Open-Circuit Voltage

This method uses the approximate ratio of the PV module maximum power point voltage V_{MPP} to the to its open circuit voltage V_{OC} which is nearly constant as a simple feed forward technique for tracking the maximum output power, as can be seen from (1).

$$V_{MPP} \approx K_1 \times V_{OC} \quad (1)$$

The factor K_1 has been reported to be between 0.71 and 0.78. Once the constant K_1 is calculated, V_{MPP} is computed by measuring V_{OC} periodically using pilot PV cells.

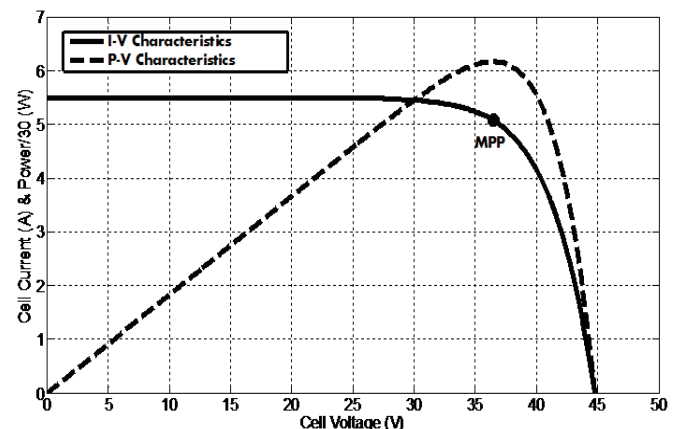


Fig. 1. I-V & P-V characteristics of a PV module

The problem is that the factor K_1 is temperature and irradiance dependent as was stated in [3] and hence the obtained results of such a technique are not accurate. Although the implementation of this method is simple and cheap, its tracking efficiency is relatively low due to the utilization of inaccurate values of the constant K_1 in the computation of V_{MPP} .

B. Fractional Short-Circuit Current

As in the fractional open circuit voltage, it was found also that the ratio between the maximum power point current and the short circuit current is also constant as in (2).

$$I_{MPP} = K_2 \times I_{SC} \quad (2)$$

Where I_{MPP} is the maximum power point current, I_{SC} is the short circuit current, and K_2 is the proportionality constant. According to [1], the constant K_2 ranges between 0.78 and 0.92 and depends on the PV module characteristics and the atmospheric conditions. The method depends on periodic measurements of the short circuit current as it is not fixed. The measurement of the short circuit current requires the usage of a pilot cell for periodic measurement. The method is then simple but needs a current sensor which is expensive and unreliable. The method can be either analog or digital. An atmospheric compensation for K_2 is proposed also in [4].

C. Perturb and Observe P&O

According to [5], the Perturb & Observe method operates by setting an initial operating voltage for the PV module and then a perturbation or voltage change is made and afterwards an observation for the power is made. If the perturbation (voltage change) is positive (increase) and a positive observation (power increase) is detected, the next perturbation will be positive and if a negative observation is detected, the next perturbation will be negative. While if the perturbation is negative (decrease) and a positive observation is detected, the next perturbation will be negative and if a negative observation is detected, the next perturbation will be positive. Of course this is done by sampling both the PV current and voltage. The tracker operates by periodically incrementing or decrementing the solar module voltage. Actually, the system oscillates about the MPP. Reducing the perturbation step size can minimize the oscillation. However, small step size slows down the MPPT. To solve this problem, a variable perturbation size that gets smaller towards the MPP should be used. However, the P&O method can fail under rapidly changing atmospheric conditions. Several research activities have been carried out to improve the traditional Hill-climbing and P&O methods.

D. Incremental Conductance

The method is based on the principle that the slope of the PV module power curve is zero at the maximum power point. In this method, the operating voltage is changed until dP/dV equals zero which occurs at the maximum power point as stated in [6]. Using fig.1, the ratio $\Delta P/\Delta V$ follows one of the cases described in (3). The incremental conductance method requires both voltage and current sensors in addition to a DSP or microcontroller. This method is a digital tracking method not an analog one and hence cost factor may be taken into

consideration. The accuracy of this technique is good but it is usually better when combined with the P&O MPPT technique.

$$\begin{cases} \frac{\Delta P}{\Delta V} = 0, \text{ at } MPP \\ \frac{\Delta P}{\Delta V} > 0, \text{ left of } MPP \\ \frac{\Delta P}{\Delta V} < 0, \text{ right of } MPP \end{cases} \quad (3)$$

III. PROPOSED MPPT TECHNIQUE

Using (3) and fig. 1, the parameter $\Delta P/\Delta V$ will be defined as the error signal E which should be equal to zero for best performance and it will be fed to a Fuzzy agent for the purpose of maximum power point tracking. At the maximum power point, the error signal equals zero and hence it is desired to keep the error signal at zero value in order to track the MPP. For fine tuning, the variation of the error signal ΔE is defined as a second input for the fuzzy agent. For simulation purposes, the PV model driven in [7] and [8] will be adapted to the available practical module and will be used. According to [1], the error E and its change ΔE can be defined by (4) and (5) respectively.

$$E(k) = \frac{P(k) - P(k-1)}{V(k) - V(k-1)} \quad (4)$$

$$\Delta E(k) = E(k) - E(k-1) \quad (5)$$

The fuzzy knowledge-base controller is one part of Fuzzy Logic Control which is composed of three main parts: fuzzification, inference engine, and defuzzification as in [9].

A. Fuzzification

Membership function values are assigned to the linguistic variables, using five fuzzy subsets: NB (negative big), NS (negative small), ZE (zero), PS (positive small), and PB (positive big). The partition of fuzzy subsets and the shape of membership functions, which can adapt shape up to appropriate system, are shown in fig. 2.

The choice of the member ship functions is based on the error signal variations with voltage as can be seen from fig. 3.

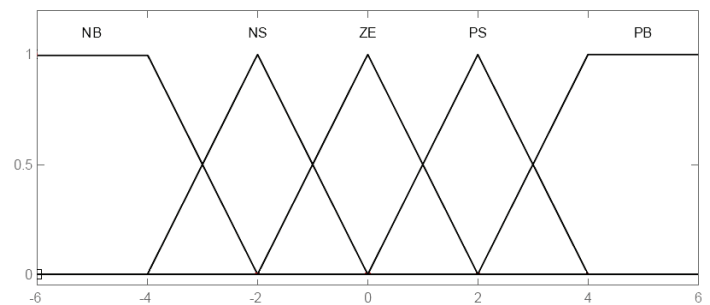


Fig. 2. Membership functions of E and ΔE

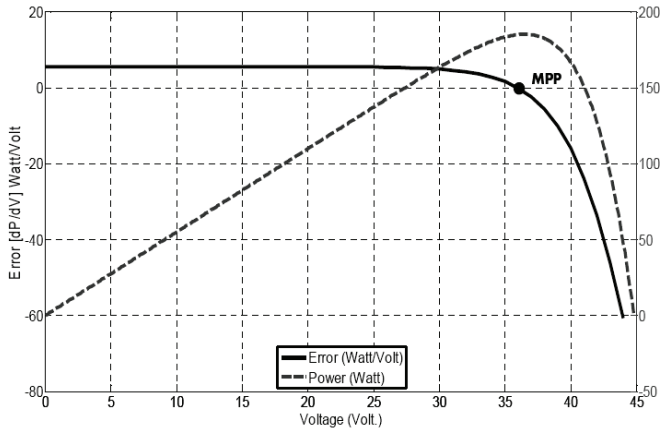


Fig. 3. Error Variations with the module voltage

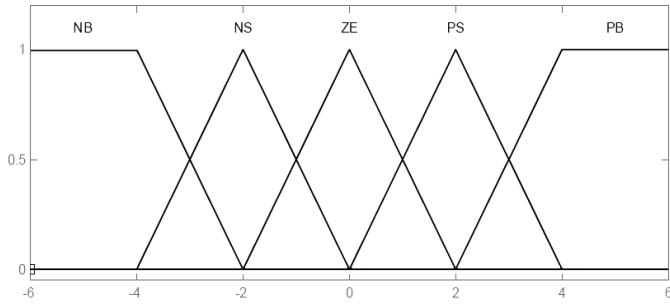


Fig. 4. Output Membership functions

The output (ΔV) membership functions are shown in fig. 4.

B. Inference method

As in [9], the composition operation is the method by which a control output is generated. Several composition methods such as Max–Min and Max–Dot have been proposed in the literature. The commonly used method, Max–Min, is used in this paper. The output membership function of each rule is given by the Min (minimum) operator and Max (maximum) operator. Table 1 shows the rule base of the FLC like some rules of [10]. The fuzzy rule base table depends basically on the error E variations with voltage change shown in fig. 3. From fig. 3, it is clear that the error is positive constant till $V=25$ V and then it will be positive decaying till $V=36$ V (at MPP). After the MPP, the error is negative decaying. As long

TABLE I. FUZZY RULE TABLE

Error E	Change of Error ΔE				
	NB	NS	ZE	PS	PB
NB	NS	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	PS

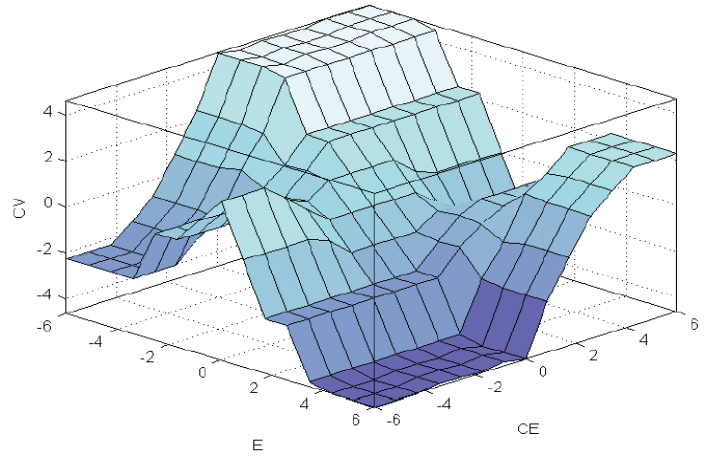


Fig. 5. Fuzzy Rule Surface

as the error is positive, the voltage should be increased and the rate of increase depends on the rate of change of the error signal ΔE which is used for fine tuning. When the error is negative, the voltage should be decreased and the rate of decrease depends on the fine tuning factor (ΔE). The control rule surface is shown in fig. 5.

C. Defuzzification

The output of this fuzzy controller is a fuzzy subset of control. To get a non-fuzzy value of control, a defuzzification stage is necessary. Defuzzification for this system can be performed by height method. The non fuzzy value of control output can be gained using a discrete time integrator simply and quickly because the output is the voltage change ΔV .

A simple block diagram representation of the whole PV and MPPT system is shown in fig. 6. The controller is a fuzzy agent adapted by the fractional open circuit voltage technique to reduce the settling or tracking time by giving an initial estimation for the operating voltage. The technique is applied to the BP7185S-Saturn 7 series with the electrical characteristics shown in Table 2 with 72 series PV cells. If no fractional open circuit voltage is used as the traditional fuzzy techniques, the power response of the module will have a large settling time (62 m sec) as shown in fig. 7 and hence the use of the fractional open circuit voltage leads to a faster power response as shown in fig. 8. The time step in the graph is (m sec) and it may depend on the used data acquisition system.

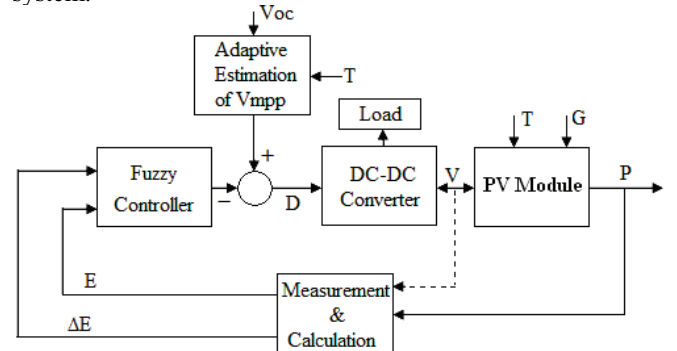
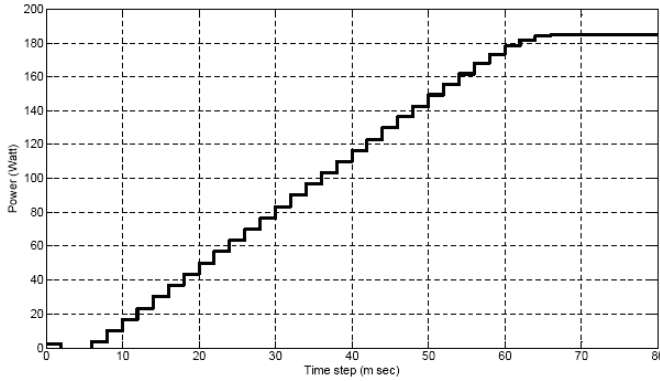
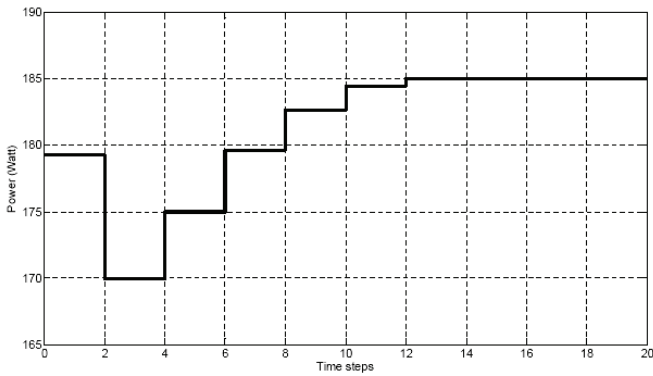


Fig. 6. PV MPPT System

TABLE II. ELECTRICAL CHARACTERISTICS OF BP7185S

Parameter	Value
Warranted minimum power	185 W
Voltage at MPP (V_{MPP})	36.5 V
Current at MPP (I_{MPP})	5.1 A
Open Circuit Voltage (V_{OC})	44.8 V
Short Circuit Current (I_{SC})	5.5 A
Temperature coefficient of V_{OC}	$-(160 \pm 20) \text{ mV/K}$
Temperature coefficient of I_{SC}	$(0.065 \pm 0.015) \%/\text{K}$
Temperature coefficient of P	$-(0.5 \pm 0.05) \%/\text{K}$
NOCT (Air 20°C; Sun 800W/m ² ; wind 1m/s)	47±2 C°
Maximum series fuse rating	15 A
Maximum System Voltage	1000 V (IEC 61215 rating)

Fig. 7. Power response for no Fractional V_{OC} Fig. 8. Power response using Fractional V_{OC}

In fig. 8, there is no steady state error in the output power (which settles at 185 W) and the searching time is smaller than the traditional fuzzy method of fig. 7 by more than 50 m sec, which is a good improvement.

The fuzzy agent in turn controls the duty cycle of the DC-DC converter used for load matching in order to keep the operating point of the PV module at (V_{MPP} , I_{MPP}). For a load of 12 V DC as an example, the duty cycle will vary with time as shown in fig. 9 through a fuzzy agent adapted by fractional open circuit voltage.

Based on the adaptation idea developed in [11], another adaptation idea is to add different weights for the inputs of the fuzzy agent. The error signal should have the full weight while the fine tuning signal which is the change in the error signal

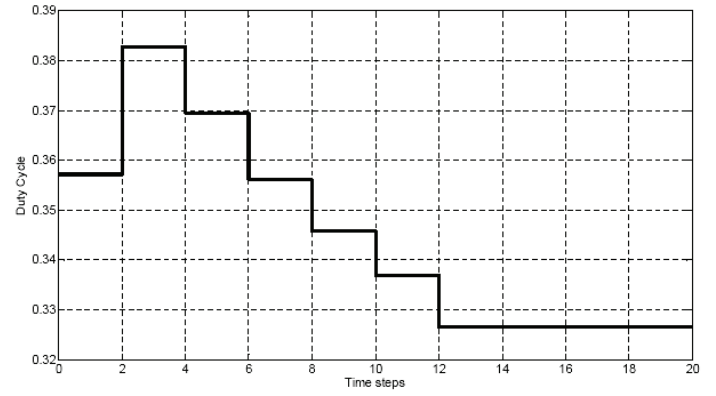
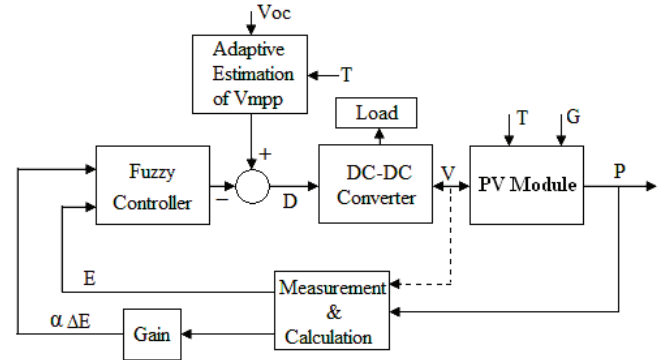
Fig. 9. Duty cycle variations using fractional V_{OC} 

Fig. 10. Adaptive Fuzzy MPPT

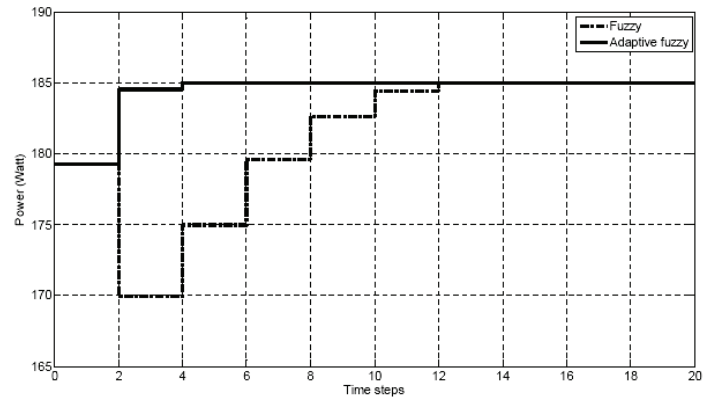


Fig. 11. Fuzzy vs. Adaptive fuzzy power response

may have a smaller weight compared to the error signal. The block diagram of the adaptive technique is shown in fig. 10.

The response of this case in comparison with the previous case is shown in fig. 11 knowing that both techniques use fractional open circuit voltage for initial estimation of V_{MPP} .

The proposed adaptive tracking technique shows a good response even under variable atmospheric conditions as can be seen in fig. 12.

Fig. 12 shows that the proposed technique is suitable for any atmospheric conditions such as variable module temperature or variable irradiance. The proposed technique has a better response under variable atmospheric conditions than the traditional MPPT technique driven in [12].

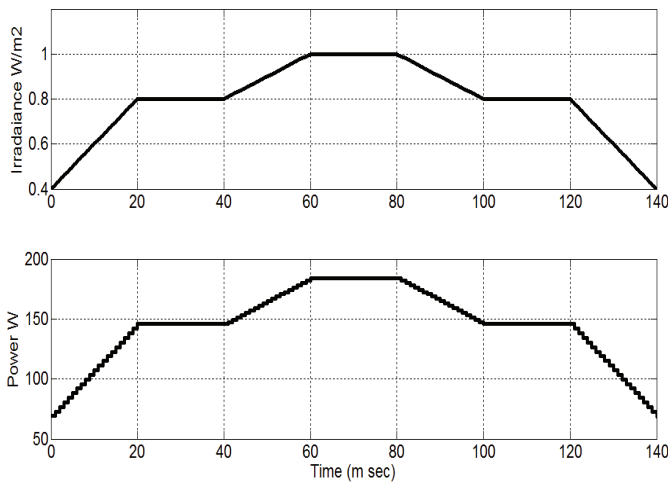


Fig. 12. Power response under variable irradiance

In the literature, the change in the converter duty cycle may be used as a third input for the fuzzy agent in order to improve the power response of the PV module but with more complexity. The tracking speed of the proposed technique is even better than the other traditional MPPT techniques like that in [2] which has a searching time of about 20 m sec. A comparison between the traditional MPPT techniques and the newly adapted fuzzy technique based on [1] is given in table 3 where New fuzzy represents the developed technique.

TABLE III. COMPARISON BETWEEN MPPT TECHNIQUES

MPPT Technique	Module - dependent	True MPP	Tracking speed	Tracking accuracy	Atmospheric effect
Fractional V_{oc}	Yes	No	Medium	Low	High
Fractional I_{sc}	Yes	No	Medium	Low	High
P & O	No	Yes	Varies	Varies	High
Inc. Cond.	No	Yes	Varies	Varies	Low
Fuzzy	Yes	Yes	Fast	High	Low
New Fuzzy	Yes	Yes	Very Fast	Very High	Low

IV. CONCLUSION

The fuzzy agent with two input parameters, which are $E = \Delta P / \Delta V$ and its change ΔE , enhanced by an initial estimation for the MPP voltage V_{MPP} using the fractional open circuit voltage technique leads to a good power response. This technique achieves the maximum possible output power from the PV module (185 W) without any steady state error in a small searching time (10 m sec). The improvement achieved by the proposed technique compared to the traditional fuzzy technique appears in the small searching time of the MPP by reducing the searching time to 20% from its traditional value. The developed MPPT technique shows a good response even under variable atmospheric conditions depending on the temperature adaptation of the initial estimation of V_{MPP} and the closed loop advantage of the fuzzy control scheme. Adaptation of the fuzzy agent may be done by giving the fuzzy agent inputs different weights causing a smaller settling

time (2 m sec) and high accuracy thus leading to a newly developed efficient technique. The proposed technique has the advantages of fast settling, accurate tracking, and simple implementation. Moreover, it is faster than the traditional MPPT techniques. Also, the technique is a closed loop control system which is able of avoiding aging effects of the PV module which is not available in feed forward MPPT systems.

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