Real world Maximum Power Point Tracking Based on Fuzzy Logic Control

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Abstract: - In the recent years, the solar energy becomes one of the most important alternative sources of electric energy, so it is important to improve the efficiency and reliability of the photovoltaic (PV) systems. Maximum Power Point Tracking (MPPT) plays an important role in photovoltaic power systems because it maximize the power output from a PV system for a given set of conditions, and therefore maximize their array efficiency. This paper presents a Maximum Power Point Tracker (MPPT) using fuzzy logic theory for a PV system. The work is focused on the well known Perturb and Observe (P&O) algorithm and is compared to a designed Fuzzy Logic Controller (FLC). The simulation work dealing with MPPT controller; a DC/DC Ćuk converter feeding a load is achieved. The results showed that the proposed Fuzzy Logic MPPT in the PV system is valid.

Key-Words: - Solar Energy, Photovoltaic system, Fuzzy Logic Control, Maximum Power Point Tracking (MPPT).

1 Introduction

In the last years global warming and energy policies have become a hot topic on the international agenda. Developed countries are trying to reduce their greenhouse gas emissions. Renewable energy sources are considered as a technological option for generating clean energy. Among them, photovoltaic (PV) system has received a great attention as it appears to be one of the most promising renewable energy sources. Photovoltaic power generation has an important role to play due to the fact that it is a green source. The only emissions associated with PV power generation are those from the production of its components. However, the development for improving the efficiency of the PV system is still a challenging field of research. MPPT algorithms are necessary in PV applications because the MPP of a solar module varies with the irradiation and temperature as shown in Fig. 1 and Fig.2, so the use of MPPT algorithms is required in order to obtain the maximum output power from a solar array [1]. When a PV module is directly coupled to a load, the PV module's operating point will be at the intersection of its V–I curve and the load line which is the V-I relationship of load.

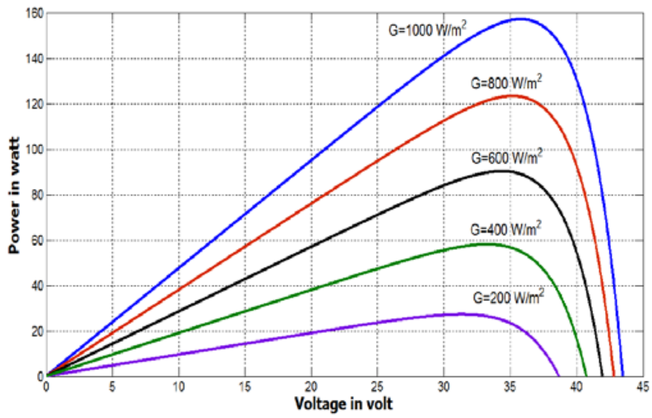

Fig. 1 PV module voltage–Power at different irradiance levels

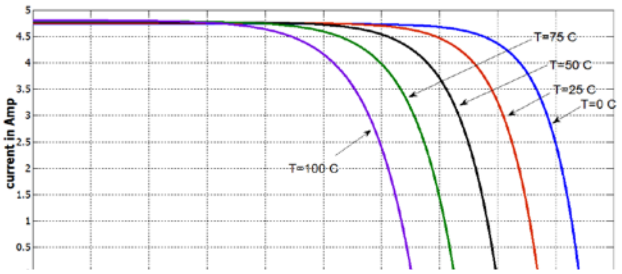

Fig. 2 PV module voltage–current at different temperature levels

In Fig. 3, a resistive load has a straight line with a slope of $1/R_{load}$ as shown in Fig. 4. In other words, the impedance of load dictates the operating condition of the PV module. In general, this operating point is seldom at the PV module's MPP, thus it is not producing the maximum power.

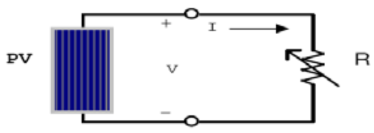

Fig. 3 PV module is directly connected to a (variable) resistive load

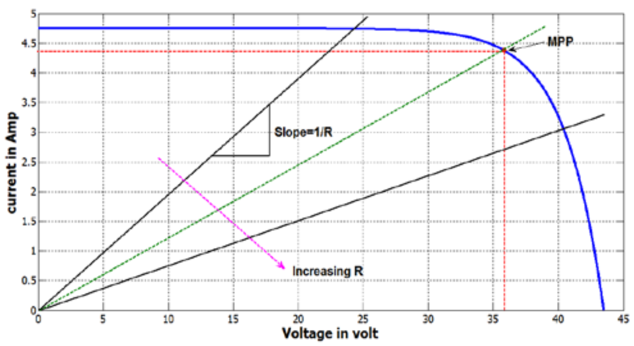

Fig. 4 V-I curve of PV module and various resistive loads

To mitigate this problem, a maximum power point tracker (MPPT) can be used to maintain the PV module's operating point at the MPP. MPPTs can extract more than 97% of the PV power when properly optimized [2]. A photovoltaic system for isolated grid-connected applications as shown in Fig. 5 is a typically composed of these main components:

1) PV module that converts solar energy to electric one,

2) DC-DC converter that converts produced DC voltage by the PV module to a load voltage demand,

3) Digital controller that drives the converter operation with MPPT capability.

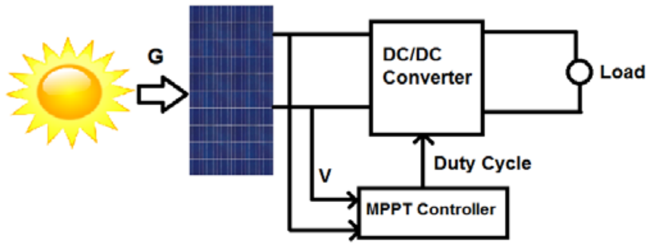

Fig. 5 Block diagram of the stand-alone PV system

In the literature, many maximum power point tracking (MPPT) techniques are proposed and implemented. The MPPT control method, which uses one estimate processes between every two Perturb processes in search for the maximum PV output (EPP) is proposed in [3]. An intelligent approach for MPPT DC/DC Boost converter focused on P&O algorithm and compared to a designed fuzzy logic controller is presented in [4]. A comparative study of two type of Maximum Power Point Tracking (MPPT) which are Perturb and Observe (P&O) and incremental conductance method is introduced in [5]. An Artificial Neural Networks is proposed in [6] to detect the atmospheric conditions variations in order to adjust the perturbation step for the next perturbation cycle. The presented tracking algorithm shows better steady state and dynamical performance than traditional P&O. The implementation of fuzzy logic controller based on the change of power and change of power with respect to change of voltage is studied in [7], fuzzy determines the size of the perturbed voltage. The performance of fuzzy logic with various membership functions (MFs) is tested to optimize the MPPT. Fuzzy logic can facilitate the tracking of maximum power faster and minimize the voltage variation. A novel intelligent fuzzy logic controller for MPPT in grid-connected photovoltaic systems based on boost converter and single phase grid-connected inverter is introduced in [8]. This is simple to be implemented on MCU chip and needs no memory space to save fuzzy rules, and that optimizing factor in the fuzzy inference equation can adjust fuzzy rules on-line automatically to improve system control effect, which provides the system with an intelligent characteristic. An intelligent control method for MPPT of a photovoltaic system under variable temperature and insolation conditions which uses a fuzzy logic controller applied to a DC-DC converter device is proposed in [9]. Results of this simulation are compared to those obtained by the perturbation and observation controller. A fuzzy logic control (FLC) is proposed in [10] to control MPPT for a photovoltaic (PV) system; this technique uses the fuzzy logic control to specify the size of incremental current in the current command of MPPT. This paper presents a Maximum Power Point Tracker (MPPT) using Fuzzy Logic for a PV system. The work focused on the well known Perturb and Observe (P&O) algorithm and compared to a designed Fuzzy Logic Controller (FLC). A simulation work dealing with MPPT controller, a DC/DC Ćuk converter feeding a load is achieved. The results will show the validity of the proposed fuzzy logic MPPT in the PV system. Most of the performed works in the literature reviews in this point is based on assumed not actual solar radiation data but this paper is used a real data for solar radiation measured by solar radiation and meteorological station located at National Research Institute of Astronomy and Geophysics Helwan, Cairo, Egypt which is located at latitude 29.87°N and longitude 31.30°E. The station is over a hil top of about 114 m height above sea level. Example of The daily recorded measured solar radiation is shown in Fig. 6.

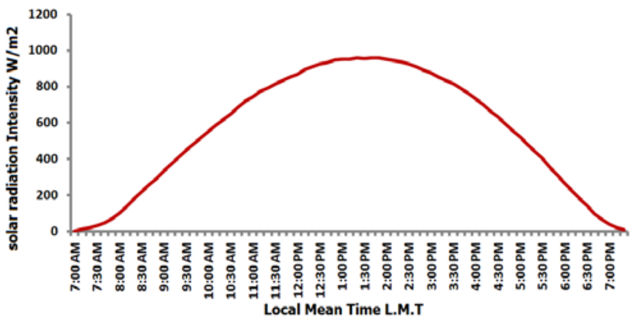

Fig. 6 Example of the Daily measured solar radiation Intensity at Helwan.

2 Mathematical Model

2.1 Modelling of PV cell and module

A PV cell can be simulated by a real diode in parallel with an ideal current source I_{SC} which depends on impinging radiation. The generalized equivalent circuit of the PV cell including both series and parallel resistances is shown in Fig. 7 [11-12].

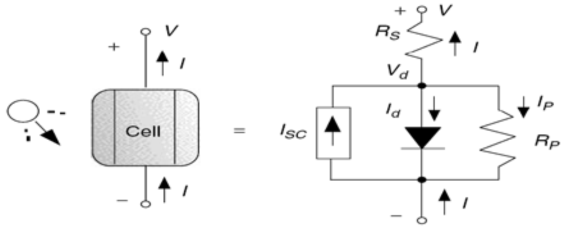

Fig. 7 The equivalent circuit for a PV cell

One can derive the following equation for current and voltage in one diode model:

$$I_{SC} = I + I_d + I_P \quad (1)$$

$$I = I_{SC} - I_0\left\{\exp\left[\frac{q(V+I.R_S)}{AkT}\right] - 1\right\} - \left(\frac{V+I.R_S}{R_P}\right) \quad (2)$$

$$I_0 = \frac{I_{SC}}{\left(e^{\frac{qV}{AkT}} - 1\right)} \quad (3)$$

The reverse saturation current is dependent on the temperature and is given by the following eqn.

$$I_0(T) = I_0(T_{ref}) * \left(\frac{T}{T_{ref}}\right)^3 * exp\left(\frac{qE_G}{AK}\left(\frac{1}{T_{ref}} - \frac{1}{T}\right)\right) \quad (4)$$

The short circuit current depends on the solar radiation and cell temperature as follows:

$$I_{SC} = \left[I_{SCr} + K_i\left(T - T_{ref}\right)\right] * G \quad (5)$$

Where I is the cell output current, I_{SC} is the short Circuit Current, I_o is the reverse diode saturation current, V is the cell output voltage, R_S is the cell series resistance (Ω), R_P is the cell parallel resistance (Ω), A is the diode ideality factor, K is the Boltzmann constant ($1.38e^{-23}$), T is the cell junction temperature (°C), T_{ref} is the reference temperature of the PV cell, $I_o(T_{ref})$ is the cell reverse saturation current at reference temperature, E_G is the band gap of semi conductor used in the cell, I_{scr} is the cell short-circuit current at reference temperature and radiation, K_i is the short circuit current temperature coefficient and G is the solar radiation in kW/m^2.

The PV module consists of n_S of series cells and $n_P$of parallel branches as shown in Fig. 8.

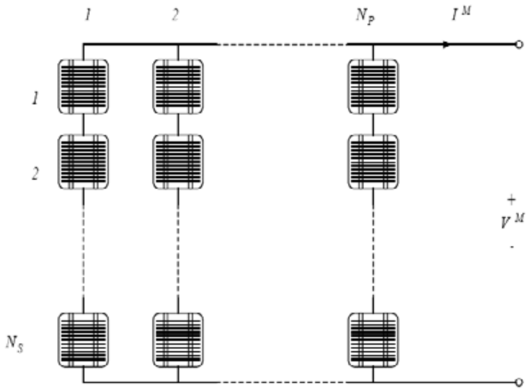

Fig. 8 The equivalent circuit for a PV module

The PV module's current I^M under arbitrary operating conditions can be described as:

$$I^M = N_p I_{SC} - N_p I_0 \left\{ \exp\left[\frac{q(\frac{V^M}{N_S} + I^M.R_S{}^M)}{AkT} \right] - 1 \right\} - \left(\frac{\frac{V^M}{N_S} + I^M.R_S{}^M}{R_P{}^M} \right) \quad (6)$$

$$R_S{}^M = \frac{N_S}{N_P} R_S{}^C \text{ And } R_P{}^M = \frac{N_P}{N_S} R_P{}^C \quad (7)$$

Where $R_S{}^C$ and $R_P{}^C$ are the series resistance and the parallel resistance of the cell respectively.

2.2 Modelling of DC/DC converter

The heart of MPPT hardware is a switch-mode DC-DC converter. It is widely used in DC power supplies and DC motor drives for the purpose of converting unregulated DC input into a controlled DC output at a desired voltage level [13]. MPPT uses the same converter for a different purpose: regulating the input voltage at the PV MPP and providing load matching for the maximum power transfer. The topologies of DC-DC converters are further categorized into three types: step down (buck), step up (boost), and step up & down (buck-boost). The buck topology is used for voltage step-down. In PV applications, the buck type converter is usually used for charging batteries and in LCB for water pumping systems. The boost topology is used for stepping up the voltage. The grid-tied systems use a boost type converter to step up the output voltage to the utility level before the inverter stage. Then, there are topologies able to step up and down the voltage such as: buck-boost, Cúk, and SEPIC (stands for Single Ended Primary Inductor Converter). The input current of the Cúk topologies is continuous, and they can draw a ripple free current from a PV array that is important for efficient MPPT. Fig. 9 shows a circuit diagram of the basic Cúk converter.

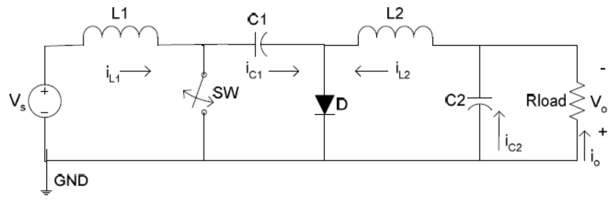

Fig. 9 Circuit diagram of the basic Cúk converter

Mode 1: When *SW* turns *ON*, the circuit becomes one shown in Fig. 10. The voltage of the capacitor (C_1) makes the diode (*D*) reverse-biased and turned off. The capacitor (C_1) discharge its energy to the load through the loop formed with *SW*, C_2, R_{load}, and L_2.

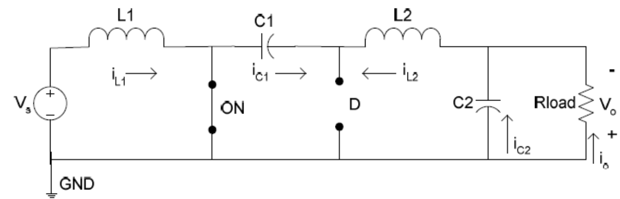

Fig. 10 Basic Cúk converter when the switch is ON

Mode 2: When *SW* turns *OFF*, the circuit becomes one shown in Fig. 11.

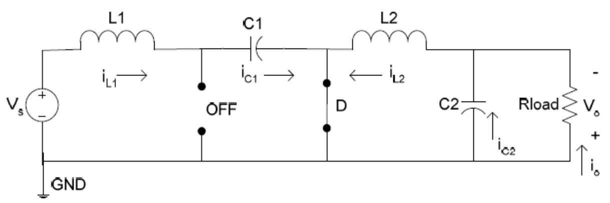

Fig. 11 Basic Cúk converter when the switch is OFF

The capacitor (C_1) is getting charged by the input (V_s) through the inductor (L_1). The energy stored in the inductor (L_2) is transfer to the load through the loop formed by *D*, C_2, and R_{load}. Thus, the following relationship is established [14]. Assuming that this is an ideal converter, the average power supplied by the source must be the same as the average power absorbed by the load.

$$P_{in} = P_{out} \quad (8)$$

$$V_S I_{L1} = V_o I_{L2} \quad (9)$$

$$\frac{I_{L1}}{I_{L2}} = \frac{V_O}{V_S} \quad (10)$$

Finally one can derive the following equation:

$$\frac{V_O}{V_S} = \frac{D}{1-D} \quad (11)$$

Where: D is the duty cycle ($0 < D < 1$)

The output voltage relation to the duty cycle (*D*) is:
- If $0 < D < 0.5$ the output is smaller than the input.
- If $D = 0.5$ the output is the same as the input.
- If $0.5 < D < 1$ the output is larger than the input.

3 Proposed Technique

3.1 Perturb and Observe Algorithm

Over the past decades many methods to find the MPP have been developed and published. These techniques differ in many aspects such as required sensors, complexity, cost, range of effectiveness, convergence speed, correct tracking when irradiation and/or temperature change, hardware needed for the implementation or popularity, among others. A complete review of 19 different MPPT algorithms can be found in [15]. The Perturb and Observe (P&O) algorithm is the most commonly used in practice because of its ease of implementation. This controller is introduced briefly in Ref. [16]. Fig. 12 shows the power voltage characteristic for the PV module at solar radiation=1000 W/m^2 and temperature 25^{o}C.

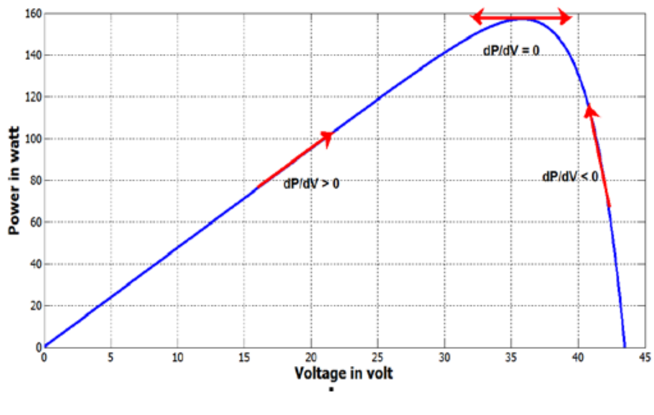

Fig. 12 the power voltage characteristic for the PV module at G=1000 W/m^2 and temperature 25^{o}C

In the P&O algorithm, the operating voltage of the PV array is perturbed by a small increment, and the resulting change in power, ΔP, is measured. If ΔP is positive, then the perturbation of the operating voltage moved the PV array's operating point closer to the MPP. Thus, further voltage perturbations in the same direction (that is, with the same algebraic sign) should move the operating point toward the MPP. If ΔP is negative, the system operating point has moved away from the MPP, and the algebraic sign of the perturbation should be reversed to move back toward the MPP. Fig. 13 shows the flowchart of this algorithm. P&O algorithm has some drawbacks which are in [3]; it cannot always operates at the maximum power point due to the slow trial and error process, and thus the solar energy from the PV arrays are not fully, the PV system may always operates in an oscillating mode and finally; the operation of PV system may fail to track the maximum power point.

3.2 Fuzzy Logic MPPT Controller

The use of fuzzy logic control has become popular over the last decade because it can deal with imprecise inputs, does not need an accurate mathematical model and can handle nonlinearity. Microcontrollers have also helped in the popularization of fuzzy logic control [15].

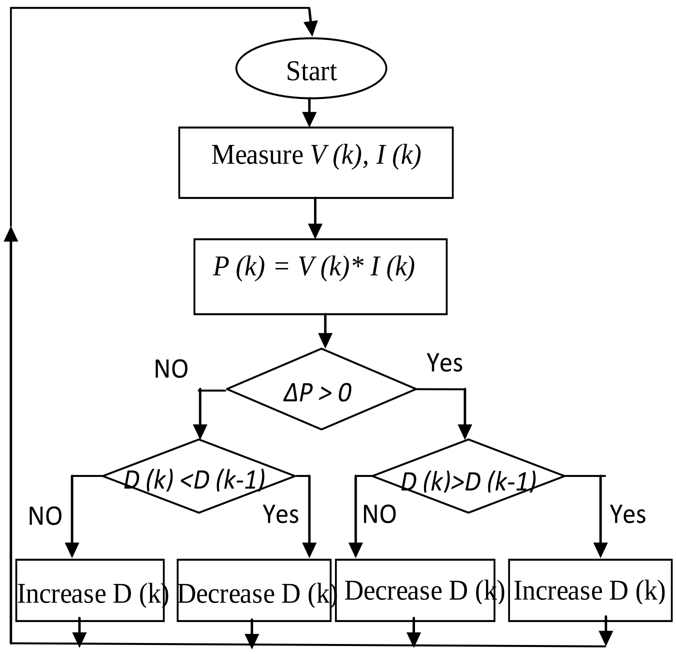

Fig. 13 Flow chart of P&O algorithm

The fuzzy logic consists of three stages: fuzzification, inference system and defuzzification.

Fuzzification comprises the process of transforming numerical crisp inputs into linguistic variables based on the degree of membership to certain sets. Membership functions are used to associate a grade to each linguistic term. The proposed MPPT sown in Fig. 14 based on Fuzzy Logic has two inputs which are the error E and change of error CE at sampled times k defined by:

$$E(k) = \frac{P(k) - P(k-1)}{V(k) - V(k-1)} \quad (12)$$

$$CE(k) = E(k) - E(k-1) \quad (13)$$

Where *P (k)* and *V (k)* are the instant power and voltage of the photovoltaic module respectively. The controller crisp value (dD) is the output of the fuzzy controller. The proposed membership functions for both inputs and outputs are NB (Negative Big), NM (Negative Medium), NS (Negative Small), NZ (Negative Zero), ZE (Zero), PZ (Positive Zero), PS (Positive Small), PM (Positive Medium) and PB (Positive Big). The proposed fuzzy rules which are carried out by using Madani's method are shown in Table 1. The defuzzification uses the centre of gravity to compute the output of this FLC:

$$D = \frac{\sum_{j=1}^{n} \mu(D_j) - D_j}{\sum_{j=1}^{n} \mu(D_j)} \quad (14)$$

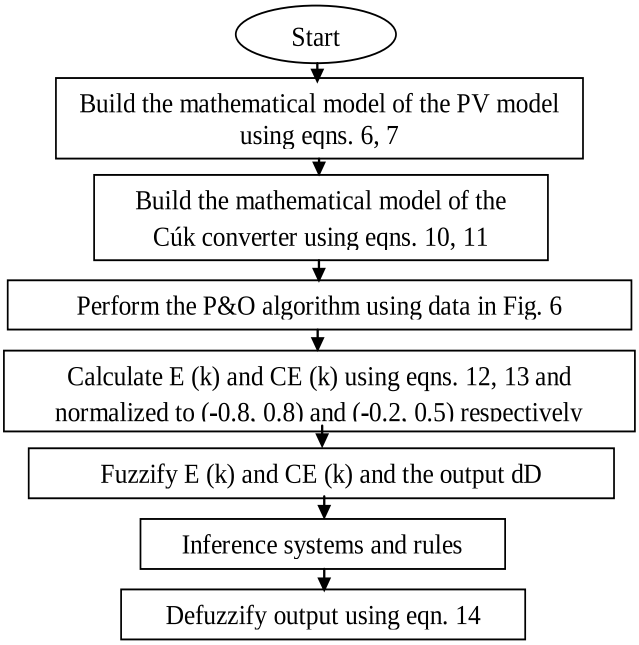

Fig. 14 proposed MPPT based on a fuzzy controller

Table 1 Fuzzy logic controller Rules base

E \ CE	NB	NM	NS	NZ	ZE	PZ	PS	PM	PB
NB	ZE	ZE	ZE	PB	PB	PB	PB	PB	PB
NM	ZE	ZE	ZE	PM	PM	PM	PM	PM	PM
NS	ZE	ZE	ZE	PS	PS	PS	PS	PS	PS
NZ	PS	PM	ZE	ZE	ZE	ZE	ZE	NM	NS
ZE	PS	PM	ZE	ZE	ZE	ZE	ZE	NM	NS
PZ	NS	NM	ZE	ZE	ZE	ZE	ZE	PM	PS
PS	NS	NS	NS	NS	NS	NS	ZE	ZE	ZE
PM	NM	NM	NM	NM	NM	NM	ZE	ZE	ZE
PB	NB	NB	NB	NB	NB	NB	ZE	ZE	ZE

If E is PB and EC is ZE then crisp dD is NB, its means that if the operating point is far away from the maximum power point (MPP) by the left side, and the variation of the slope of the curve is almost Zero; then increase the duty cycle (dD).

4 Numerical Analysis

The proposed technique in this paper uses bpsx150 PV module which has electrical characteristic shown in Table. 2 [17].

Table 2 Electrical characteristics of bpsx150 PV

Maximum power (Pmax)	150W
Voltage at Pmax (Vmp)	34.5V
Current at Pmax (Imp)	4.35A
Warranted minimum Pmax	140W
Short-circuit current (Isc)	4.75A
Open-circuit voltage (Voc)	43.5V
Maximum system voltage	600V
Temperature coefficient of Isc	(0.065±0.015)%/°C
Temperature coefficient of Voc	– (160±20)mV/°C
Temperature coefficient of power	– (0.5±0.05)%/ °C
NOCT	47±2°C

The bpsx150 PV module is simulated by Matlab program Version 7.10 and the power voltage characteristic at different solar radiation is shown in Fig. 1, also the current voltage characteristic at different solar radiation is shown in Fig. 2. The simulated bpsx150 PV module and the real measured solar radiation shown in Fig. 6 are used with another program that coupled the bpsx150 PV module with Cúk converter and the P&O algorithm is performed. The power-voltage and voltage-current characteristic and the voltage-current characteristic of P&O algorithm are shown in Fig. 15 and Fig. 16.

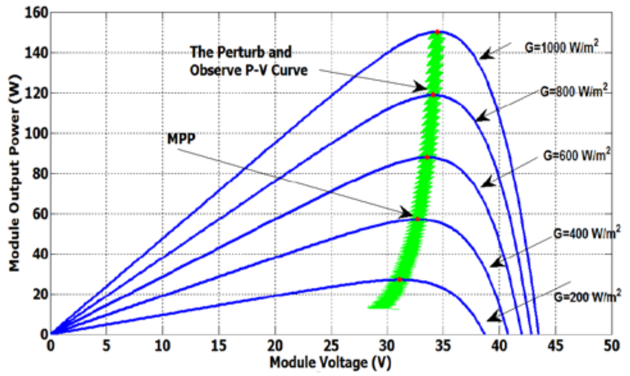

Fig. 15 The power-Voltage characteristic of the P&O algorithm

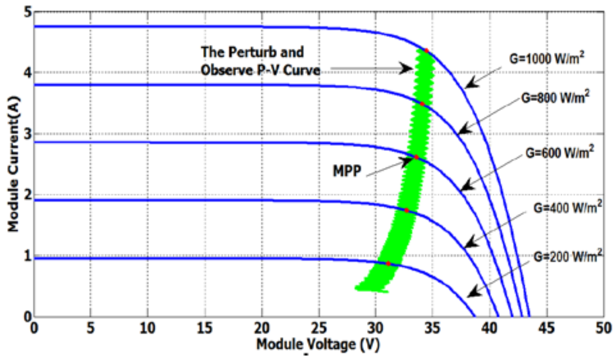

Fig. 16 the Voltage-Current characteristic of the P&O algorithm

The relationship between the output power of converter versus the duty cycle is shown in Fig. 17.

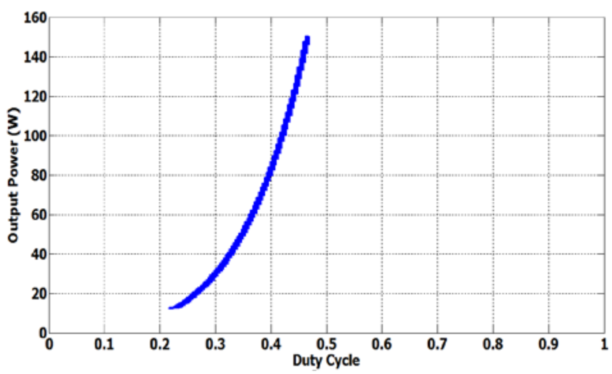

Fig. 17 The output power-Duty cycle characteristic

The output voltage versus the output current is shown in Fig. 18. After simulating the perturb and observe algorithm with Cúk converter the error E(k) is calculated and normalized between (-0.8 to 0.8), CE(k) is calculated and normalized between (-0.26 to 0.069) also the change in duty cycle dD is normalized between (-0.2 to 0.5). The fuzzy membership function used in this study is Gaussian surface.

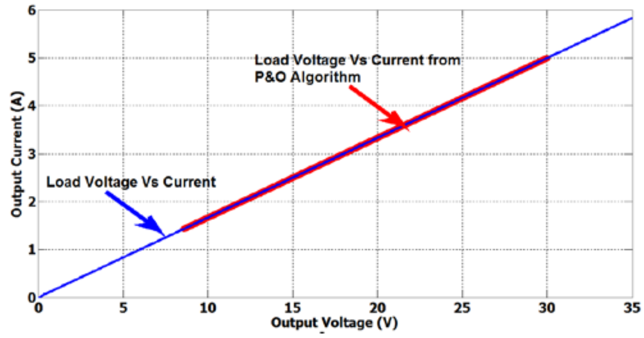

Fig. 18 The output voltage- output current characteristic

The fuzzy member ship functions for inputs and output are written as follows and are shown in Fig. 19, Fig. 20 and Fig. 21.

[Input1]

Name='Error'

Range= [-0.8 0.8]

NumMFs=9

MF1='NB':'gaussmf', [0.08493 -0.8]

MF2='NM':'gaussmf', [0.08493 -0.5]

MF3='NS':'gaussmf', [0.08493 -0.2]

MF4='NZ':'gaussmf', [0.0849 -0.0037]

MF5='ZE':'gaussmf', [0.08493 0]

MF6='PZ':'gaussmf', [0.0849 0.0034]

MF7='PS':'gaussmf', [0.0849 0.01]

MF8='PM':'gaussmf', [0.08493 0.5]

MF9='PB':'gaussmf', [0.08493 0.8]

[Input2]

Name='Error change'

Range=[-0.26 0.069]

NumMFs=9

MF1='NB':'gaussmf', [0.01746 -0.260356446370531]

MF2='NM':'gaussmf', [0.01746 -0.2]

MF3='NS':'gaussmf', [0.01746 -0.1]

MF4='NZ':'gaussmf', [0.01746 -0.009]

MF5='ZE':'gaussmf', [0.01746 0]

MF6='PZ':'gaussmf', [0.01746 0.009]

MF7='PS':'gaussmf', [0.01746 0.022]

MF8='PM':'gaussmf', [0.01746 0.05]

MF9='PB':'gaussmf', [0.01746 0.069]

[Output1]

Name='DeltaD'

Range= [-0.2 0.5]

NumMFs=9

MF1='NB':'gaussmf', [0.03716 -0.2]

MF2='NM':'gaussmf', [0.03716 -0.15]

MF3='NS':'gaussmf', [0.03716 -0.1]

MF4='NZ':'gaussmf', [0.03716 -0.009]

MF5='ZE':'gaussmf', [0.03716 0]

MF6='PZ':'gaussmf', [0.03716 0.009]

MF7='PS':'gaussmf', [0.03716 0.1]

MF8='PM':'gaussmf', [0.03716 0.2]

MF9='PB':'gaussmf', [0.03716 0.5]

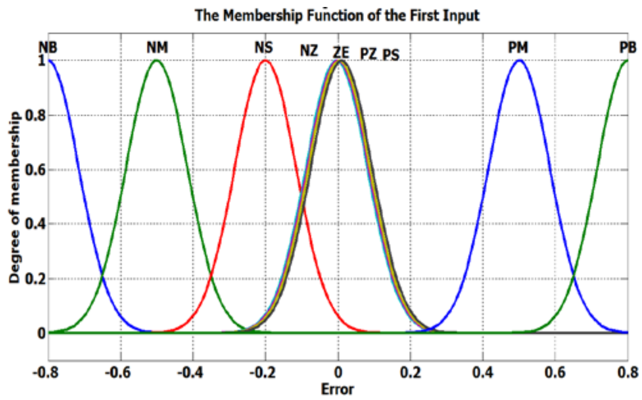

Fig. 19 The fuzzy member ship functions for input E(k)

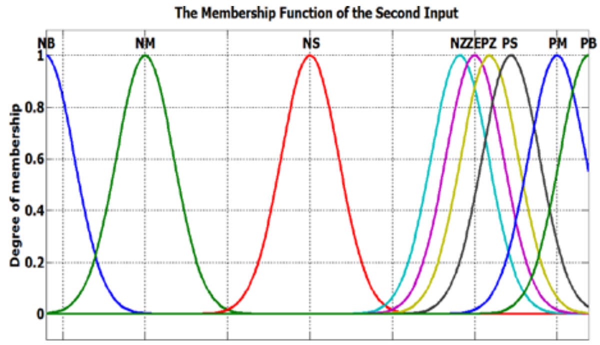

Fig. 20 The fuzzy member ship functions for input CE(k)

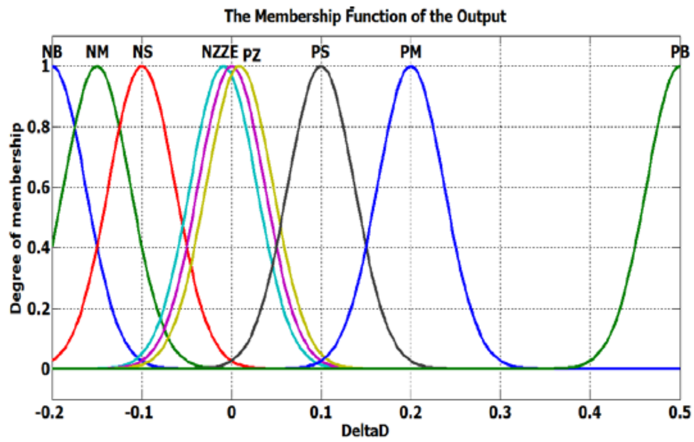

Fig. 21 The fuzzy member ship functions for output dD(k)

The fuzzy surface is shown in Fig. 22.

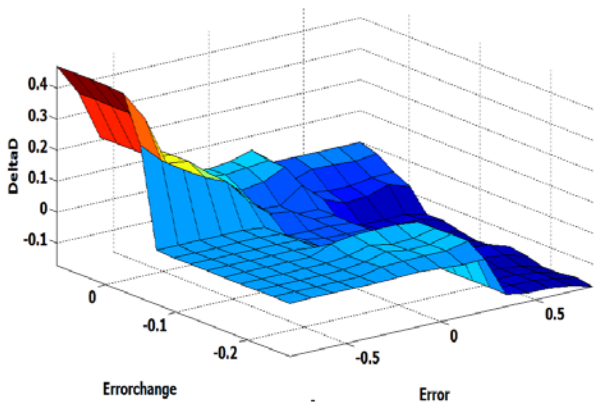

Fig. 22 The fuzzy rule surface

A comparison between P&O algorithm and the Fuzzy logic MPPT is performed in Figs. 23, 24.

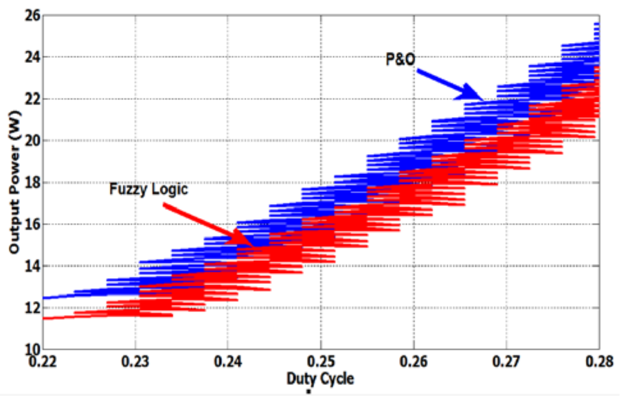

Fig. 23 Power versus duty cycle for both P&O algorisms and Fuzzy Logic

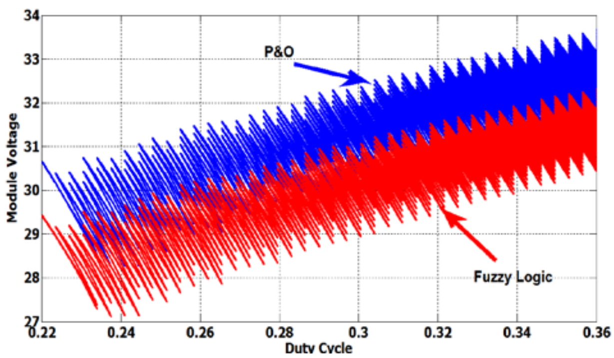

Fig. 24 Module voltage versus duty cycle for both P&O algorisms and Fuzzy Logic

5 Conclusions

Since the Maximum power point Tracking (MPPT) plays an important role in photovoltaic (PV) power systems because they maximize the power output from a PV system for a given set of conditions, and therefore maximize their array efficiency.

This paper presents a maximum power point tracker (MPPT) using fuzzy logic with Gaussian membership functions for a PV system based on real measuring data for solar radiation measured by meteorological station located at National Research Institute of Astronomy and Geophysics Helwan, Cairo, Egypt.

The work focused on the well known Perturb and Observe (P&O) algorithm and compared to a designed fuzzy logic controller (FLC). A simulation work dealing with MPPT controller, a DC/DC Ćuk converter feeding a load is achieved. The results showed the validity of the proposed fuzzy logic MPPT in the PV system.

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