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Maximum Power Point Tracking: Overview and Challenges

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Abstract— **The objective of this paper is to discuss some maximum power point tracking techniques which will work effectively in continuously changing atmospheric conditions. A maximum power point tracking algorithm is absolutely necessary to increase the efficiency of the solar panel as it has been found only 30-40% of energy incident is converted into electrical energy. The proposed research investigates the performance of the maximum power point tracking technique which will work efficiently to maximize the utilization efficiency of PV array efficiency. The suitable algorithm has to be chosen for good performance of PV array. For this purpose, comparison among all algorithms is given in discussion and summary.**

Keywords- Maximum power point tracking (MPPT), photovoltaic (PV) power system, maximum power point (MPP), switching mode DC-DC converter, MPPT Algorithms.

I. INTRODUCTION

As the conventional energy sources are rapidly depleting, the importance of solar photovoltaic (PV) energy has been emerging as replaceable energy resources to human being. Since it is clean, pollution-free, and inexhaustible, researches on the PV power generation system have received much attention, particularly, on many terrestrial applications. The main applications of photovoltaic (PV) systems are in either stand-alone (water pumping, domestic and street lighting, electric vehicles, military and space applications) [1-2] or grid-connected configurations (hybrid systems, power plants) [3]. Unfortunately, PV generation systems have two major problems: i.e. the conversion efficiency of electric power generation is very low (9-17%), especially under low irradiation conditions and the amount of electric power generated by solar arrays changes continuously with weather conditions. Moreover, the solar cell V-I characteristic is nonlinear and varies with irradiation and

temperature. In general, there is a unique point on the V-I or V-P curve, called the Maximum Power Point (MPP), at which the entire PV system (array, converter, etc.) operates with maximum efficiency and produces its maximum output power. The location of the MPP is not known, but can be located, either through calculation models or by search algorithms. Therefore Maximum Power Point Tracking (MPPT) techniques are needed to maintain the PV array's operating point at its MPP. Many MPPT techniques have been proposed in the literature; examples are the Perturb and Observe (P&O) methods [4-7], the Incremental Conductance (IC) methods [4-8], the Artificial Neural Network method [9], the Fuzzy Logic method [10], etc.These techniques vary between them in many aspects, including simplicity, convergence speed, hardware implementation, sensors required, cost, range of effectiveness and need for parameterization. In this paper, the effectiveness of these different control algorithms is thoroughly investigated via simulation.

However, efficient use of a PV panel includes some problems for the following two main reasons.

(1) Because of rotation of the world around the sun and itself ongoing, it may not have a fixed position to receive constant vertical solar radiation continuously. Thereby, PV systems may include some circuits to track the world movements depending on the sun consisting of stepper motor or other devices. These mechanisms are called the mechanical tracking systems and increase the amount of produced PV energy [11, 12].
(2) Due to nonlinear I-V curves of PV cells, output power depends on intersection point of load line with this curve. For solar radiation and cell temperature values taken as examples, there is only one point where maximum power is produced. Therefore, operation of the cell at this point is the right option. This process is called as electrical maximum power point tracking or simply MPPT [11].

II. MATHEMATICAL MODELLING

The simplest equivalent circuit of a solar cell is a current source in parallel with a diode. The output of the current source is directly proportional to the light falling on the cell (photocurrent). During darkness, the solar cell is not an active device; it works as a diode, i.e., a p-n junction. It produces neither a current nor a voltage. Thus, the diode determines the *I–V* characteristics of the cell.

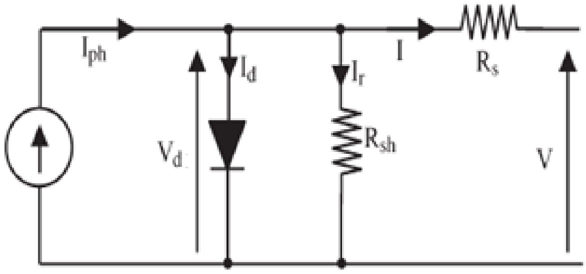


Fig 1: Equivalent electrical circuit of an SC.

The output current *I* and the output voltage of a solar cell are given by,

$$I = I_{ph} - I_d - \frac{V_d}{R_{sh}} \qquad (1)$$

$$I = I_{ph} - I_0\left(\exp\left(\frac{q.V_d}{n.k.T}\right) - 1\right) - \frac{V_d}{R_{sh}} \qquad (2)$$

$$V = V_d - R_s.I \qquad (3)$$

Here, I_{ph} is the photocurrent, I_0 is the reverse saturation current, I_d is the average current through the diode, n is the diode factor, q is the electron charge ($q = 1.6*10^{-19}$), k is the Boltzmann's constant ($k = 1.38*10^{-23}$), and T is the solar array panel temperature. Rs are the intrinsic series resistance of the solar cell; this value is normally very small. Rsh is the equivalent shunt resistance of the solar array, and its value is very large.

In general, the output current of a solar cell is expressed by,

$$I = I_{ph} - I_0\left(\exp\left(\frac{q}{n.k.T}(V + R_s I)\right) - 1\right) - \left(\frac{V + R_s I}{R_{sh}}\right) \qquad (4)$$

In (4) the resistances can be generally neglected, and thus, it can be simplified to

$$I = I_{ph} - I_0\left(\exp\left(\frac{q}{n.k.T}.V\right) - 1\right) \qquad (5)$$

If the circuit is opened, the output current I = 0, and the open-circuit voltage Voc is expressed by

$$V_{oc} = \left(\frac{n.k.T}{q}\right) In\left(\frac{I_{ph}}{I_0} + 1\right) \approx \left(\frac{n.k.T}{q}\right) In\left(\frac{I_{ph}}{I_0}\right) \qquad (6)$$

If the circuit is shorted, the output voltage V = 0, the average current through the diode is generally neglected, and the short circuit current Isc is expressed by using

$$I_{sc} = I = \frac{I_{ph}}{\left(1 + \frac{R_s}{R_{sh}}\right)} \qquad (7)$$

Finally, the output power P is expressed by

$$P = VI = \left(I_{ph} - I_d - \frac{V_d}{R_{sh}}\right).V \qquad (8)$$

III. ALGORITHM FOR FINDING MAXIMUM POWER POINT

The maximum power point tracking (MPPT) is a controlled dc–dc inverter that monitors a photovoltaic panel (PVP) to operate at its maximum power point (MPP) depending on the state of load, it is inserted between the pv array and its electric load to achieve the optimum characteristic matching, so that pv array is able to deliver maximum available power which is also necessary to maximize the photovoltaic energy utilization. Pv cell has a single operating point where the values of the current and voltage of the cell result in a maximum power output. These values correspond to a particular resistance, which is equal to v/i as specified by ohm's law. Also the pv cell has an exponential relationship between current and voltage, so the maximum power point (mpp) occurs at the knee of the curve, where the resistance is equal to the negative of the differential resistance (v/i = -dv/di). Additional current drawn from the array results in a rapid drop of cell voltage, thereby reducing the array power output. The aim of this MPPT sub-system is to determine just where that point is, and to regulate current accordingly and thus to allow the converter circuit to extract the maximum power available from a cell. The control methodology presented in this paper will adopt an approach in which designing of the power converter is done by using the relationship existing between the short-circuit current Isc and the MPP current Im. By simulating with various sample data for Isc and Im it is ascertained that the ratio of Im to Isc remains constant at 0.9. Initially the short circuit current Isc is measured and then the actual load current adjusted in such a way it is equal to a desired fraction value of 0.9Isc.

IV. DIFFERENT MPPT TECHNIQUES

There are different techniques used to track the maximum power point. Few of the most popular techniques are:-

- Perturbation and Observation method.
- Incremental conductance method.
- Hill climbing method.
- Fuzzy control method.
- Neural network Method etc.

The choice of the algorithm depends on the time complexity the algorithm takes to track the MPP, implementation cost and the ease of implementation.

I. PERTURB AND OBSERVE ALGORITHIM

P&O Algorithms are widely used algorithm to track the maximum power point due to its simplest structure and fewer required parameters. P&O method finds the maximum power point of the PV module by means of iteratively perturbing (i.e. Incrementing and decrementing), observing and comparing the power generated by the PV module. In this we use only one sensor, that is the voltage sensor, to sense the PV array voltage and so the cost of implementation is less and hence easy to implement[5,6].

In the P&O method, the load of the photovoltaic system is adjusted in order to change the terminal voltage and output power of the photovoltaic module.The variation of output voltage and power before and after change of load of photovoltaic system is observed and compared to the reference voltage and power for increasing and decreasing the load in the next step. If the power is increased, the perturbation will continue in the same direction in the next cycle, otherwise the perturbation direction will be reversed.That means the PV array terminal voltage is perturbed at every maximum power point tracking cycle. Therefore when maximum power point is reached, the P&O algorithm will oscillate around it, resulting in a loss of PV power, especially in case of constant or slowly varying atmospheric condition. It can be observed that regardless of the magnitude of sun irradiance(G) and terminal voltage(V) of PV modules, the maximum power point is obtained while the condition dP/dV= 0 is accomplished. The slope (dP/dV) of the power can be calculated by the consecutive output voltages and output currents. The basic operating procedure of P&O method is shown in figure 3.

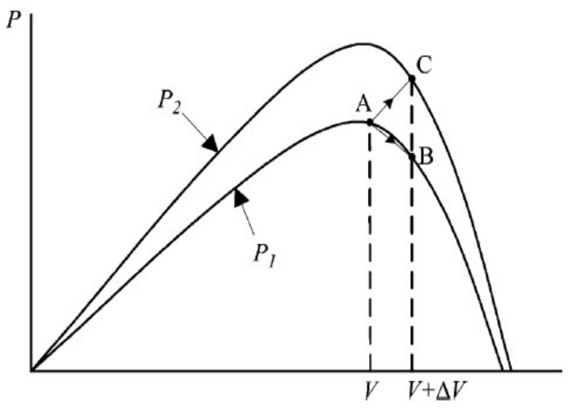


Fig. 3 Basic operating procedure of P&O method

Let Point –A be the starting point with voltage V at power P1.The load of the PV system is adjusted in order to change the terminal voltage and output power of the PV module.Let for a perturbation of Δ ,Operating point moves from point-A to point-B. Due to which there is a decrease in power of the PV system[7].

When weather condition is steady.If solar radiation increases in one sampling period, then the power curve Moves from P1-P2.and the operating point moves from A-D instead of A-B.Due to which power is increased but the voltage still moves towards the ΔV direction.

The operating point is further away from the maximum power point .i.e. point- C is the operating point but not the maximum power point.With increase in solar radiation, the change in voltage increases but the operating point shifts

away from the maximum power point which results in power loss of PV module and efficiency reduces. However the method does not take account of the rapid change of irradiation level (due to which MPPT changes) and considers it as a change in MPP due to perturbation and ends up calculating the wrong MPP. To avoid this problem we can use incremental conductance method.

Restrictions of Perturb & Observe algorithm:
In a situation where the irradiation changes quickly, the Maximum Power Point also moves on the right hand side of the curve. The algorithm takes it as a change due to perturbation and in the next iteration it changes the direction of perturbation and hence goes away from the MPP as shown in the figure.

Case	**Conditions**	**Position**	**Control Action**
1.	ΔPK>0, VK>0	Left of MPP	Increase δ
2.	ΔPK>0, VK<0	Right of MPP	Decrease δ
3.	ΔPK<0, VK>0	Right of MPP	Decrease δ
4.	ΔPK>0, VK<0	Left of MPP	Increase δ

The advantages of the P&O method are

- Simple structure, easy implementation and less required parameters.

The shortcomings of the P&O method can be summarized:

- The power tracked by the P&O method will oscillate and perturb up and down near the maximum power point. The magnitude of oscillations is determined by the magnitude of variations of the output voltage. There is a misjudgment phenomenon for the P&O method when weather conditions change rapidly.
- The PV system cannot always operate at the maximum power point due to the slow trial and error process, and thus the solar energy from the PVarrays are not fully utilized.

- The PV system may always operate in an oscillating mode even with a steady-state sunshine condition, leading to fluctuating inverter output
- The operation of the PV system may fail to track the maximum power point due to the sudden changes in sunshine.

Flow Diagram of Perturb & Observe algorithm:

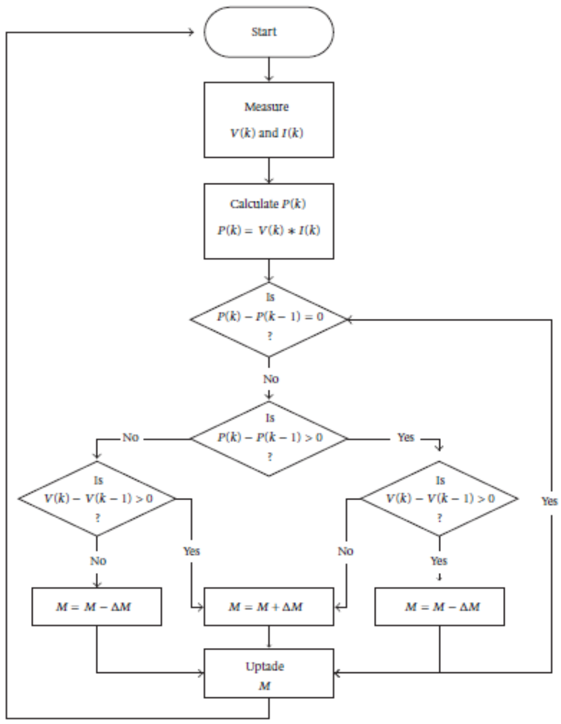


Fig.4. Flow diagram for P&O Method.

Summary of P&O Algorithm Cases

II. INCREMENTAL CONDUCTANCE ALGORITHM

Incremental conductance method uses two voltage and current sensors to sense the output voltage and current of the PV array. The incremental conductance method is to determine the variation direction of the terminal voltage for PV modules by measuring and comparing the incremental conductance and instantaneous conductance of PV modules. If the value of incremental conductance is equal to that of instantaneous conductance, it represents that the maximum power point is found.Incremental conductance method is used to overcome the disadvantages of P&O algorithm. The change in the array power is due to the change in array terminal voltage perturbation. In incremental conductance algorithm the array voltage is always adjusted according to its value relative to MPOP voltage[4,5].

The main difference between Incremental conductance algorithm and P&O algorithm is the judgment on determining the direction of voltage perturbation.When static conductance Gs is equal to dynamic Conductance G_d, the maximum power point is found.

Mathematically,

The output power from the source can be expressed as,

P = V.I

The fact that P = V.I and the chain rule for the derivative of products yields:-

dP/dV = d (V I) / dV

= I dV / dV + V dI / dV

= I + V dI / dV

(1/V) dP/dV = (I/V) + dI/dV (9)

Let's define the source conductance:

G = -I/V (10)

And the source incremental conductance:

ΔG = dI/dV (11)

In general output voltage from a source is positive. The Operating voltage is below the voltage at the maximum power point if the conductance is larger than the incremental Conductance, and vice versa. The job of this algorithm is therefore to search the voltage operating point at which the conductance is equal to the incremental conductance.

According to this algorithm,

if dP/dV > 0,then G >ΔG

if dP/dV = 0, then G =Δ G

if dP/dV <0, then G <ΔG

Tracking of MPP using Inc Conductance Algorithm

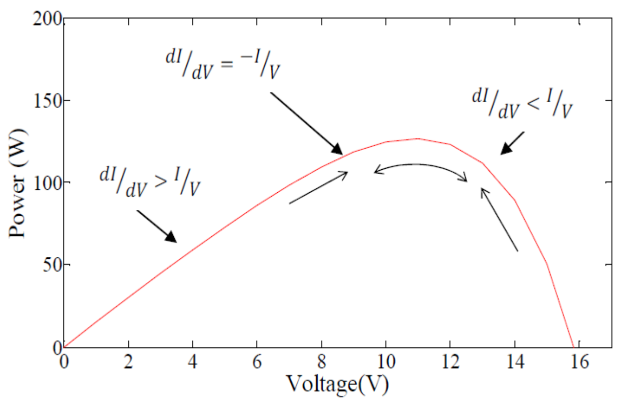


Fig.5. Schematic Diagram of IC method

When the operating behavior of PV modules is within the constant current area, the output power is proportional to the terminal voltage. That means the output power increases linearly with the increasing terminal voltage of PV modules (slope of the power curve is positive, dP/dV>0).When the operating point of PV modules passes through the maximum power point, its operating behavior is similar to constant voltage[6,7]. Therefore, the output power decreases linearly with the increasing terminal voltage of PV modules (slope of the power curve is negative, dP/dV<0).When the operating point of PV modules is exactly on the maximum power point, the slope of the power curve is zero (dP/dV= 0) and can be further expressed as,

$$\frac{dP}{dV}=\frac{d(VI)}{dV}=I\frac{dV}{dV}+V\frac{dI}{dV}=I+V\frac{dI}{dV} \quad (12)$$

By the relationship of dP/dV= 0, can be rearranged as follows,

$$\frac{dI}{dV}=-\frac{I}{V} \quad (13)$$

dI and dV represent the current error and voltage error before and after the increment respectively. The static conductance (Gs) and the dynamic conductance(Gd)incremental conductance) of PV modules are defined as follows,

$$Gs=-\frac{I}{V}$$
$$Gd=\frac{dI}{dV} \quad (14)$$

The maximum power point (operating voltage is Vm) can be found when,

$$Gd|_{V=Vm}=Gs|_{V=Vm} \quad (15)$$

However, the following situations will happen while the operating point is not on the maximum power point:

$$\frac{dI}{dV}>-\frac{I}{V};\left(G_d>G_s,\frac{dP}{dV}>0\right)$$

$$\frac{dI}{dV}<-\frac{I}{V};\left(G_d<G_s,\frac{dP}{dV}<0\right) \quad (16)$$

These equations are used to determine the direction of voltage perturbation when the operating point moves toward to the maximum power point. In the process of tracking, the terminal voltage of PV modules will continuously perturb, until the condition of $\frac{dI}{dV}=-\frac{I}{V}$ comes into existence.

The advantage of the incremental conductance method is that it can calculate and find the exact perturbation direction for the operating voltage of PV modules[8].

Flow Diagram of Incremental conductance Method.

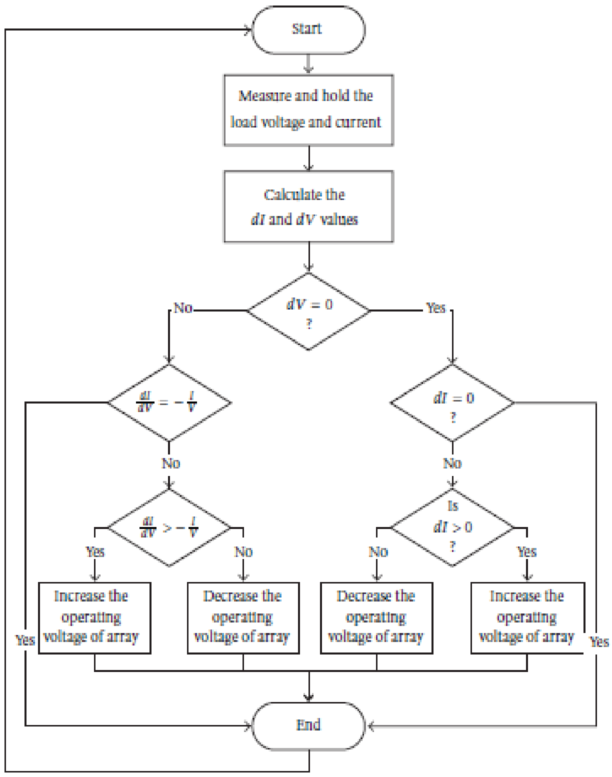


Fig 6. Flow diagram for IC method.

III. FUZZY LOGIC CONTROL METHOD:-

Fuzzy logic control method is one of the popular MPPT technique of artificial intelligence. Fuzzy logic controllers have the advantages of working with imprecise inputs, not needing an accurate mathematical model, and handling nonlinearity [10].

The basic scheme of a fuzzy controller for DC-DC converters is shown in figure. The fuzzy controller is divided into 5 modules: Fuzzifier, database, rule base, decision-making and defuzzifier.

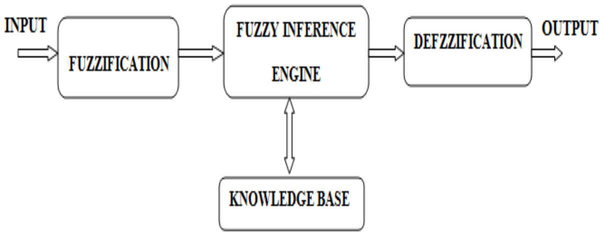


Fig. 9 Fuzzy Logic Controller

FUZZY INPUT VARIABLES

The inputs of the fuzzy controller are the error ‘e’ and one level error difference Δe. One level error difference is conventionally called as change of error (ce). The input variables are normalized using appropriate scaling factors (n_e for e and $n_{\Delta e}$ for Δe). The values of these normalization factors will be different for each type of converter. The inputs e and Δe are defined as:

$$e(k) = Vo - Vref$$

$$\Delta e(k) = e(k) - e(k-1) \quad (17)$$

Dividing e(k) by n_e will give the normalized value, P_o is the present PV Power output ,P_{ref} is the reference Power which is the PV output Power from previous iteration and k denotes the values taken at the beginning of the k^{th} switching cycle. The output of the fuzzy controller is the change of duty cycle defined as δd_k .

The duty cycle at kth switching cycle is given by

$$d_k = d_{k-1} + \eta * \delta d_k \quad (18)$$

Where δd_k the inferred change of duty cycle by the fuzzy controller at the k^{th} sampling time and η is the gain factor of the fuzzy controller. Adjusting η can change the effective gain of the controller.

MEMBERSHIP FUNCTION

During fuzzification, numerical input variables are converted into linguistic variables based on a membership function**.** The fuzzy control implemented here uses triangular membership functions. The triangular shape of the membership function of this arrangement presumes that for any particular input there is only one dominant fuzzy subset. Each universe of discourse is divided into 7 fuzzy subsets NB (negative big), NM (negative medium) ,NS (negative small) , ZO (zero), PS (positive small), PM (positive medium), PB (positive big). The partition of the fuzzy subsets and the shape of the membership functions are shown. For any combination of e and Δe a maximum of four rules are adopted. The computation time can thus be reduced. For instance if e is 0. 1 and Δe is -0.7 only (ZE, NS), (ZE, NB), (PS, NS) and (PS, NB) are in effect all other combinations will have zero weighting factor. That is the inferred grades of membership of the rest of the rules are zero.

RULE BASE

The control rules that associate fuzzy input to fuzzy output are derived from the general knowledge of system behaviors. The derivation of the fuzzy control rules is heuristic in nature and based on the following criteria,

1. When the output of the converter is far from the set value the change of duty cycle must be large so as to bring the output to the set point quickly.
2. When the output of the converter is approaching near the set point, a small change of duty cycle is necessary.
3. When the output of the converter is near the set point is approaching it rapidly the duty cycle must be kept constant so as to prevent overshoot.
4. When the set point is reached and the output is still changing the duty cycle must be changed a little bit to prevent the output from being moving away.
5. When the output is above the set point the sign of the change of the duty cycle must be negative and vice-versa.

FUZZY INFERENCE MECHANISM

The error e and Δe can be a member of more than one fuzzy set for a given singleton value. For e = 0.1L and Δe = -0.7 respectively, e is a member of both (ZE and PS) and Δe is a member of both (NB and NS). This means that for a particular input pair of values (e and Δe), more than one rule is activated and fired. In fuzzy logic terms, the compositional operation is the mechanism by which such task can be performed. This is given in detail earlier. The inferred output of each rule is calculated from the equation

$$z_i=\min\{\mu_e(e_0),\mu_{ce}(\Delta e_0)\}*c_i \quad (19)$$

Where z_i denotes the change of duty cycle inferred by the i^{th} rule. Since the inferred output is a linguistic result a defuzzification is performed next to obtain crisp result.

DEFUZZIFICATION

In the defuzzification stage, the fuzzy logic controller output is converted from a linguistic variable to a numerical variable still using a membership function. This provides an analog signal that will control the power converter to the MPP. MPPT fuzzy logic controllers perform well under varying atmospheric conditions. However, their effectiveness depends a lot on the knowledge of the user in choosing the right error computation and coming up with the rule base table. Defuzzification operation can be performed by a number of methods of which the center of gravity method is the most popular one. The center of gravity method selects the crisp output value corresponding to the center of gravity of the output membership function which is given by expression:

$$z = \delta dk = \frac{\sum_{i=1}^{N} z_i}{\sum_{i=1}^{N} w_i} = \frac{\sum_{i=1}^{N} w_i * c_i}{\sum_{i=1}^{N} w_i} \quad (20)$$

The effective change of duty cycle at the k[th] sampling time is therefore z*η. The relationship between the output variable δd_k and the inputs e and Δe can be expressed approximately as:

$$\eta * \delta d_k = \frac{e(k)}{\eta_e} + \frac{\Delta e(k)}{\eta_{ce}} \qquad (21)$$

This is in incremental form. Converting incremental form to direct form the above equation can be written as:

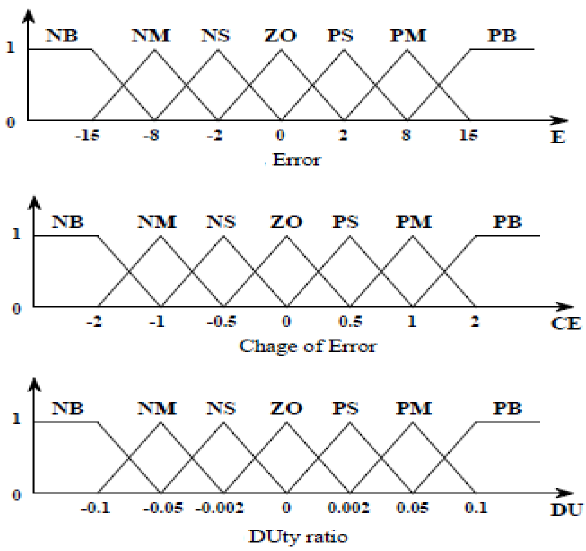
$$\eta * d_k = \frac{e(k)}{n_e} + n_{ce}\int e(k) \qquad (22)$$

$$d_k = \frac{1}{(\eta * n_e)}\left[\frac{e(k)}{n_e} + \left(\frac{n_e}{n_{ce}}\right)\int e(k)\right] \qquad (23)$$

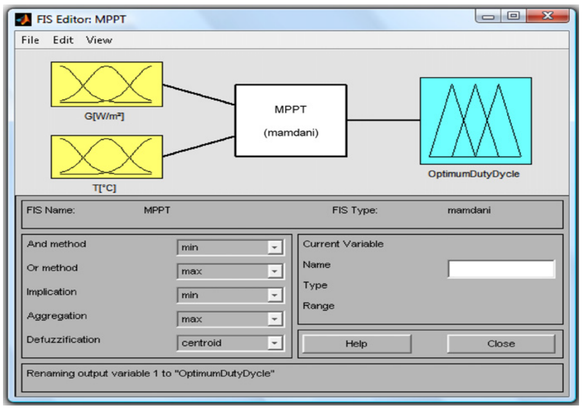
FUZZY RULE BASE TABLE

E \ CE	NB	NM	NS	ZO	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	ZO
NM	NB	NB	NM	NM	NS	ZO	PS
NS	NB	NM	NS	NS	ZO	PS	PM
ZO	NB	NM	NS	ZO	PS	PM	PB
PS	NM	NS	ZO	PS	PS	PM	PB
PM	NS	ZO	PS	PM	PM	PB	PB
PB	ZO	PS	PM	PB	PB	PB	PB

MEMBERSHIP FUNCTION



MATLAB WINDOW OF THE FUZZY LOGIC CONTROLLER.



RESULTS

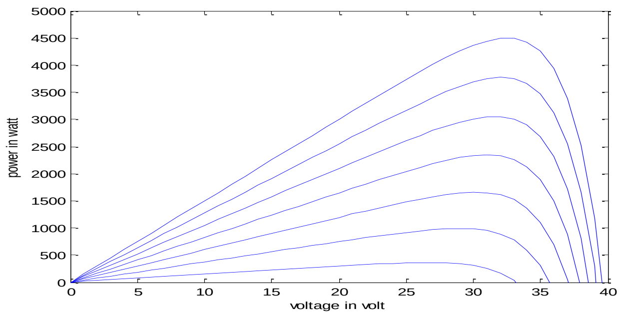


Fig.10.VI char for different insolation values

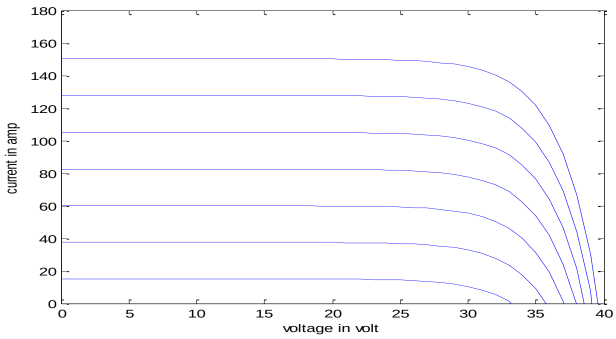


Fig.11. PV char for different insolation values

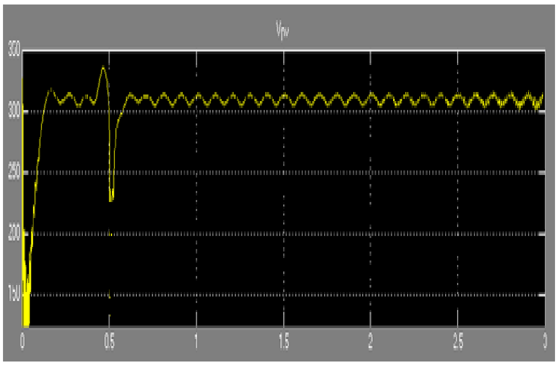


Fig.12. V-I curve of an P&O Method.

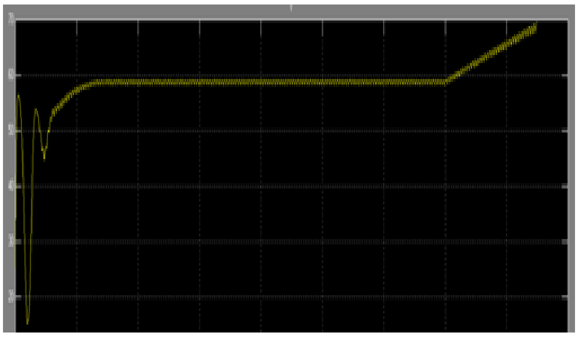


Fig.13. V-I curve of an IC Method.

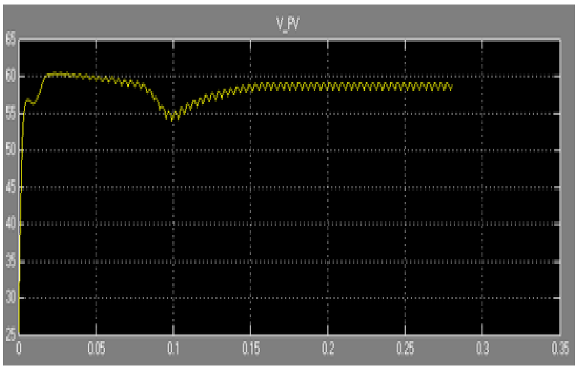


Fig.14. V-I curve of an Fuzzy Logic Control

CONCLUSION

This paper has presented a comparison among three different Maximum Power Point Tracking techniques in relation to their performance and implementation costs. In particular, different types of solar insulation are considered, and the energy supplied by a complete PV array is calculated; furthermore, regarding the MPPT implementation costs, a cost comparison is proposed taking into consideration the costs of sensors, microcontroller and additional power components. The results, indicate that the P&O and IC algorithms are in general the most efficient of the analyzed MPPT techniques.

DISCUSSION & SUMMARY

The Characteristics of different MPPT techniques are summarized in Table.

	Convergence speed	***Efficiency***	***Complexity***	***Periodic tuning***	***Sensed parameters***
P&O Method	Varies	81.5–85	Low	No	Voltage, current
I &C Method	Varies	73–85	Medium	No	Voltage, current
Fuzzy logic control	Fast	>95	High	Yes	Varies
Neural Network	Fast	>95	High	Yes	Varies

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