A Comprehsive Review on MPPT Techniques used for Photovotaic Energy Conversion System

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***Abstract*—**This paper propose a comparative study of different MPPT techniques like Perturb & Observe, Incremental Conductance, Three Point Method, Fuzzy Logic Control, Artificial Neural Network, Constant Voltage, Fractional Open Circuit Voltage, Fractional Short Circuit Current, and Temperature Method with the parameter like convergence speed, implementation complexity and sensed parameter with the help of Simulation results of the proposed system are obtained using MATLAB/Simulink software. Photovoltaic array output characteristic is nonlinear that changes with solar irradiation and the cell's temperature. Hence, a Maximum Power Point Tracking (MPPT) technique is necessary so that it can draw peak power to maximize the power output to produce energy. The maximum power is tracked using both the MPPT techniques under Standard Test Condition (STC) and by varying solar irradiance and ambient temperature.

Keywords*—Maximum Power Point Tracking (MPPT), Comparative study, PV convertor, Maximum Power Point (MPP).*

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I. INTRODUCTION

Solar energy is considered to be one of the most important renewable/non-conventional energy resources. As compared to conventional resources such as coal, petroleum etc.., solar energy is considered to be clean, inexhaustible, free of cost and abundantly and easily available in nature. One of the main applications of photovoltaic energy conversion systems is that in either grid-connected configurations (power plants, hybrid systems) [17] or stand-alone (domestic and street lighting, electric vehicles, water pumping, military and space applications) [76], [77]. Photovoltaic energy takes the importance and attention by the researchers due to its numerous advantages and applications.

There are two most common problems which are broadly discussed one of which is the low conversion efficiency of electric power generation (9-16%), especially under low irradiation condition. Electric power generated by solar array changes with the change in weather condition. Furthermore, the V-I characteristic of solar –cell is nonlinear and changes with irradiation and temperature. Simply, there is a unique point on the V-I or V-P curve, that unique point is called as Maximum Power Point (MPP) and at the selected point in the given PV system (array, converter, etc….) operates with maximum efficiency and produces its maximum power output. The point of location of the MPP is unknown, but it can be located, either using calculation models or by search algorithms. Maximum Power Point Tracking (MPPT) techniques are used to maintain the PV array operating point at its MPP. There are different MPPT techniques which have been proposed in this literature; they are Perturb & Observe (P&O) method [4-7], Incremental Conductance (IC) method [4-8], Artificial Neural Network (ANN) method [9], Constant Voltage [13], Fractional Open Circuit Voltage [15], Fractional Short Circuit Current [14], Temperature Method [16], etc…are used to find out the MPP for the PV system. P&O and IC techniques are most widely used for MPPT in PV system. The MPPT techniques and their performance will be compared by using MATLAB tool Simulink, assuming different types of insulation, temperature variations and solar irradiance variations. The partially shaded condition will not be considered; the irradiation is assumed to be uniformly spread over the PV array.

II. IDENTIFICATION OF THIS SYSTEM

The system is composed of a PV generator, a MPPT power adapter, a DC/DC converter and a load.

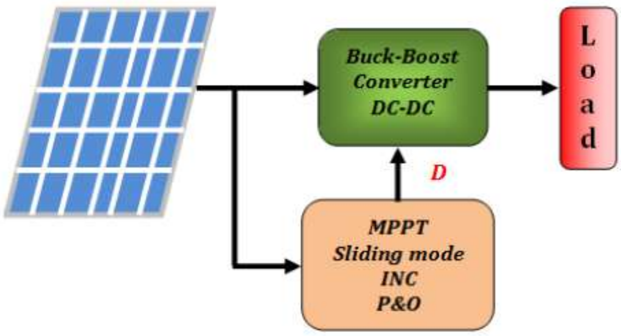

Fig.1 Schematic diagram of the PV Energy Conversion system

III. MODELLING OF PHOTOVOLTAIC CELL

The PV cell can be simulated using the single diode model; the general formula of the PV characteristic is represented in fig. 2.

A. Photovoltaic Array

Light energy is converted into electrical energy using PV cells. PV cell is formed by the combination of many solar cell connected in series and in parallel to form PV array, according to the requirement of voltage and current. As the sunlight strikes the surface of the solar cell, the incident light energy directly converted into electrical energy without any mechanical effort.

B. Electrical Circuit for PV Module

Consider a model of single diode, a solar cell which is configured as shown in figure (2). This model offers a good compatibility between simplicity and accuracy with a basic structure consisting of a current source and a parallel diode, series resistance Rs and parallel diode

Rsh where I_{ph} represents the cell photocurrent while R_{sh} and R_s are the intrinsic shunt and series resistances of the cell [1].

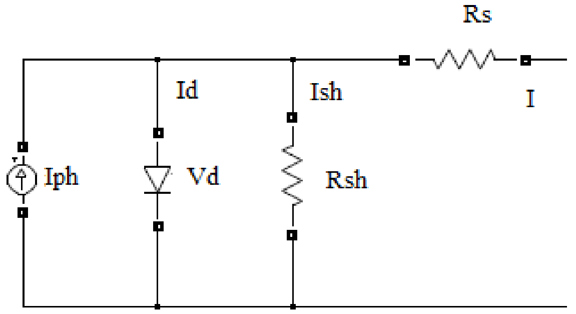

Fig. 2 Schematic diagram of single diode solar cell

C. Equations of the PV cell

When numbers of PV cells are connected in larger units they are called as PV modules, which are further interconnected in series and in parallel mode to form PV arrays. The followings are the basic equations from the theory of semiconductors and photovoltaic that mathematically described the I-V characteristic of photovoltaic cell and module [1], [37], [38].

D. Photo Current

It is well known that, the PV cell photocurrent I_{ph} depends linearly on solar irradiation and it is also affected by temperature according to (1).

$$I_{ph} = [I_{sc} + K_i(T_c - T_{ref})] * H \tag{1}$$

Where

I_{ph} = Nominal generated current at 25^{0}C and 1kW/m^2

I_{sc} = Cells short-circuit current at 25^{0}C and 1kW/m^2

K_1 = Cells short-circuit current per temperature coefficient (0.0017A/K)

T_{ref} = Cell's reference temperature

H = Solar isolation in kW/m^2

E. PV Module Reverse Saturation Current

PV module reverse saturation current, I_{rs}, is given by-

$$I_{rs} = \frac{I_{sc}}{\left[\exp\left(\frac{qV_{OC}}{N_S kAT}\right) - 1\right]} \tag{2}$$

Where

q = Electron charge ($1.6 \times 10^{-19} C$)

V_{OC} = PV module open-circuit voltage (22.3V)

N_S = No. of cells connected in series (36)

k = Boltzmann constant ($1.3805 \times 10^{-23} J/K$)

A = Ideal factor (1.6)

F. PV Module Saturation Current

The PV module saturation current I_0 varies with the cell temperature and is given by (3).

$$I_0 = I_{rs} \times \left(\frac{T}{T_r}\right)^3 \times \exp\left[\left(\frac{q \times E_{go}}{A \times k}\right) \times \left(\left(\frac{1}{T_r}\right) - \left(\frac{1}{T}\right)\right)\right] \tag{3}$$

Where

E_{go} = Band gap energy of semiconductor (1.1eV for Si at 25^{0}C)

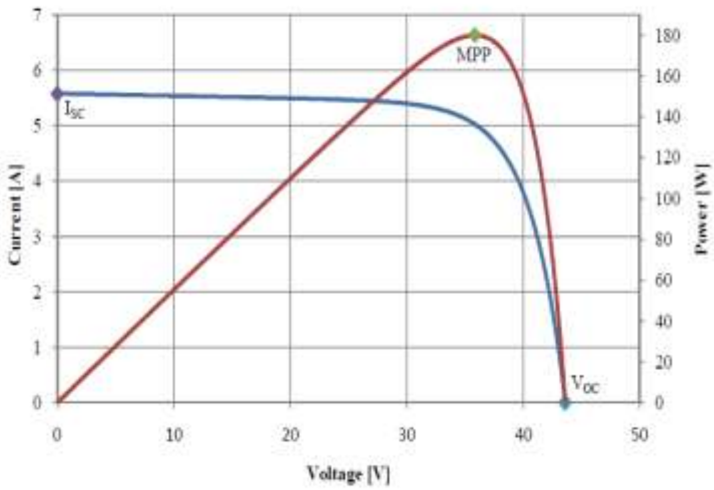

Fig. 3 I-V and P-V characteristic curve of penal

G. Module Output Current

One of the basic equation that describes the current output of the PV module I_{PV} of a single diode model is presented in *figure (2)* is given by (4) [37-40].

$$I_{PV} = N_P I_{ph} - N_P I_0 \left[\exp\left(\frac{q(V_{PV} + I_{PV} R_S R_S)}{N_S kAT}\right) - 1\right] - \frac{V_{PV} + I_{PV} R_S}{R_{sh}} \tag{4}$$

Where

N_P = No. of parallel connection of cells

N_S = No. of series connection of cells

$V_{PV} = V_{OC}$ = Open circuit voltage (22.3V)

R_S = Equivalent series resistance of module

R_{sh} = Equivalent parallel resistance of module

H. Effect of Parallel Resistance

The effect of parallel resistance on the device, when parallel resistance is sufficiently small, is to reduce the open-circuit voltage. Short-circuit current does not effected by R_{sh}. The value of parallel resistance R_{sh} is generally high and hence neglected to simplify the model as given by (5). The series resistance R_S (0.1Ω) is the sum of several structural resistances of PV module and its influence is stronger, especially near the MPP region. Equation (4) for the current output of PV module can be simplified as shown in (5).

$$I_{PV} = N_P I_{ph} - N_P I_0 \left[\exp\left(\frac{q(V_{PV} + I_{PV} R_S R_S)}{N_S kAT}\right) - 1\right] \tag{5}$$

I. *Convertor Topology for the MPPT*

There are basically five types of DC-DC converter circuit arrangements shown in the literatures named as:

1. BUCK Convertor
2. BOOST Convertor
3. Buck-Boost Converter
4. CUK Converter
5. SEPIC Convertor

J. *Selection of MPPT Converter*

When we proposing a maximum power point tracking (MPPT), the major job is to select and design a highly efficient converter which is supposed to operate as the main part of the MPPT. The selection of DC-DC converter based on the desired output voltage from the MPPT in term to ensure the PV module that will operate at the maximum point. The selection of MPPT converter is based upon the application where it is being used. Most of the literatures used Boost converter while comparing with the different MPPT techniques and so as in this review all the MPPT techniques is discussing based upon the Boost converter[165].

TABLE 1
COMPARATIVE STUDY OF DIFFERENT TYPE OF MPPT CONVERTER

Conv-erter	R_{in}	θ	**Switching loses**	η	**Application**
Buck	$\frac{1}{D^2} * R_L$	$0 \le \theta \le \phi$	High	Low	Low load-high module voltage
Boost	$(1-D)^2 * R_L$	$\phi \le \theta \le 90^0$	High	Low	High load-low module voltage
Buck-Boost	$\frac{(1-D)^2}{D^2} * R_L$	$0 \le \theta \le 90^0$	Low	High	Nearly matched battery and module voltage
CUK	$\frac{(1-D)^2}{D^2} * R_L$	$0 \le \theta \le 90^0$	Low	High	Same rating battery and module voltage
Sepic	$\frac{(1-D)^2}{D^2} * R_L$	$0 \le \theta \le 90^0$	Low	High	Higher rating battery and module voltage

Abbreviation used:

D-Duty cycle; R_L -Load Resistance; θ -convergence angle; R_{in} -Input Resistance; $\phi = \tan^{-1}\left(\frac{1}{R_L}\right)$

IV. MPPT TECHNIQUES

Many methods are available for tracking the maximum power point, were developed to allow the system to extract the maximum power from photovoltaic generator. Among the techniques, we have;

A. *Perturb and Obersve Method(P&O)*

This method is the simplest method of MPPT among the other developed methods. The result of operating of P&O algorithm is periodically achieved by incrementing or decrementing (i.e. perturbing) the PV array output terminal voltage or terminal current and analyzing the PV output power with that of the previous perturbation cycle [47]. If the PV array operating voltage changes and power increases $(dP/dV_{PV} > 0)$, the control moves the PV array operating point in that direction. On the other way if it decreases $(dP/dV_{PV} < 0)$, the operating point moves in the opposite direction. In the next perturbation the algorithm continues in the same way. Fig.4. show the algorithm flowchart of the P&O method [19], [20].

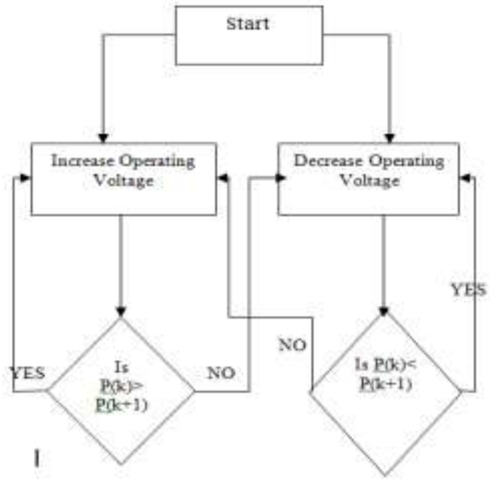

Fig. 4 P&O method algorithm flowchart

The only advantage of the P&O method is it's easiness to implement. However, it has some limitations like oscillations around the MPP in steady state operation, slow response speed and even tracking in wrong way under rapidly changing atmospheric conditions [20].

A most common problem in P&O algorithm is that the array terminal is perturbed in every MPPT cycle even through the MPP is reached to a unique point; the output power oscillates around the maximum MPP point. This results in power loss in PV system. In this case, it is especially true with constant or slow varying atmospheric conditions. Furthermore, P&O method is not suitable under rapidly changing atmospheric conditions [76-111].

B. *Incremental Conductance Method*

The Incremental Conductance algorithm is procured by differentiating the PV array power with respect to voltage and setting the result equal to zero. This is shown in equation (6).

At the MPP-

$$\frac{dP}{dV} = \frac{d(VI)}{dV} = I + V\frac{dI}{dV} = 0 \qquad (6)$$

After rearranging the above equation it should be as follow.

$$-\frac{I}{V} = \frac{dI}{dV} \qquad (7)$$

It is important to note that the L.H.S of equation (7) represents the opposite of the instantaneous conductance of the PV array, while the R.H.S represents the incremental conductance. Thereupon, at the MPP, these two quantities needed to be equal in magnitude, bur opposite in sign.

If the operating point is away from the MPP, a set of inequalities can be derived from equation (7) that indicates whether the operating voltage is above or below the voltage at MPP. Fig.5

shows the algorithm flowchart of the Incremental Conductance method [19], [47].

$$\frac{dI}{dv} = -\frac{I}{V}; \frac{dP}{dV} = 0, \text{ at MPP} \tag{8}$$

$$\frac{dI}{dV} > -\frac{I}{V}; \frac{dP}{dV} > 0, \text{ left of MPP} \tag{9}$$

$$\frac{dI}{dV} < -\frac{I}{V}; \frac{dP}{dV} < 0, \text{ right of MPP} \tag{10}$$

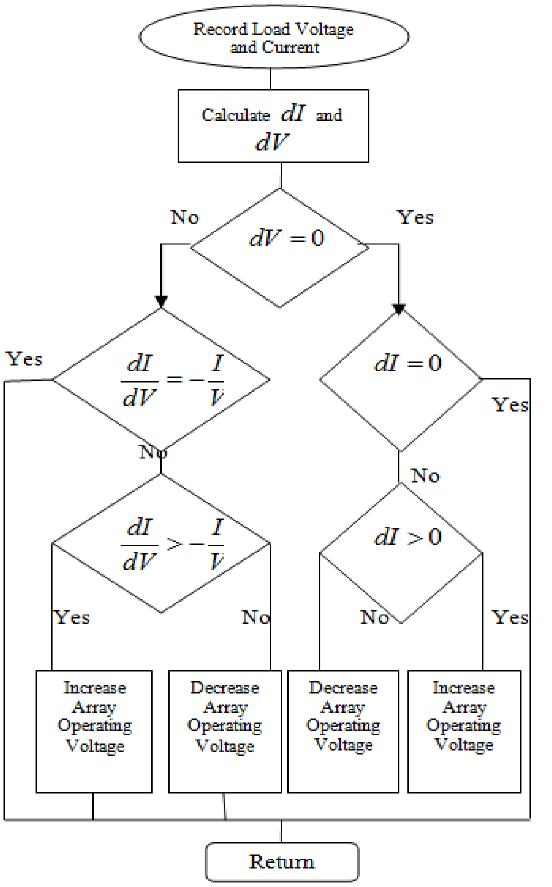

Fig.5 Incremental Conductance Method algorithm flowchart

Equations (9&10) are used to determine the direction in which a perturbation must occur to move the operating point towards the MPP. The perturbation is repeated until the Equation (8) is satisfied.

A primary and the main difference between Incremental Conductance and the P&O algorithm is that the Incremental Conductance possibly can calculate the direction of penetration of perturb so that array's operating point reach the MPP and can determine when it is actually reach the MPP. Therefore, under rapidly changing conditions, MPP should not track in wrong direction, as in case of P&O and it should not oscillate about the MPP once it reaches that point [112-133].

C. *Three Point Method*

Three point method is considered to be the extended technique of the P&O method. The P&O algorithm only correlate with two points, which are termed as the current operating point and the subsequent perturbation point. It then observes their changes which are in terms of power and thus decide whether to increase or decrease the solar array voltage.

The Three Point method is proposed to avoid the necessity of oscillating the operating point rapidly, when the solar radiation is varying quickly. The MPPT is able to trace accurately when the solar irradiance is stable and power loss is low [18].

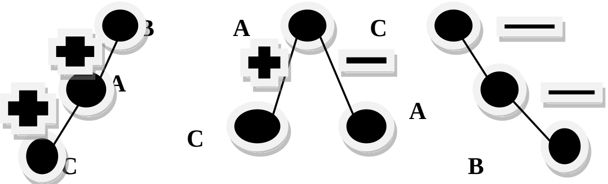

Fig.6 Possible cases in a constant irradiance case

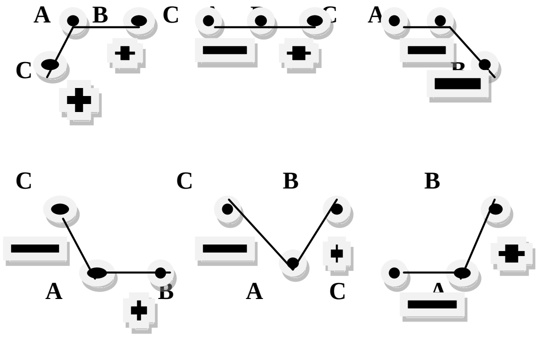

Fig.7 Possible cases in varying irradiance levels

The algorithm which is required to be used in the Three Point method runs periodically with continuously perturbing the solar array terminal voltage and examining the PV output power. This method measures the output power over the three points on the P-V curve. The three points are the current operating point A, a point B, perturbed from point A, and a point C, perturbed in the opposite direction from point A [75].

D. *Fuzzy Logic Control*

The various stages of P&O MPPT method using Fuzzy Logic Control (FLC) is shown in Fig.8. The input variables of the FLC are ΔP and ΔI, While the output variables of the FLC is the variable step-size ΔD of the P&O algorithm [21], [26].

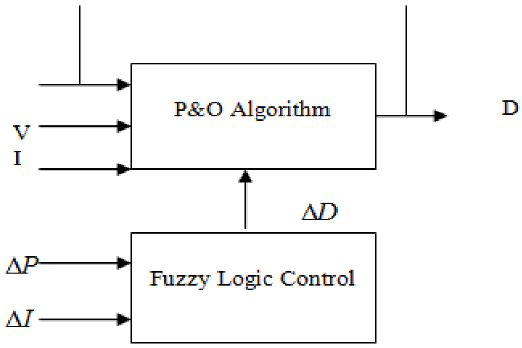

Fig. 8 Variable step-size P&O based Fuzzy Logic Control

The input variables ΔP and ΔI can be calculated from equations (10) to (12).

$$P(n) = V(n) \times I(n) \tag{10}$$

$$\Delta P(n) = P(n) - P(n-1) \tag{11}$$

$$\Delta I(n) = I(n) - I(n-1) \tag{12}$$

Where $P(n)$, $I(n)$ and $V(n)$ are the power, current and voltage of the PV system respectively.

The mostly used functions in this technique are expressed by triangular functions. This consists of five fuzzy subsets which are denoted by NB (Negative Big), NS (Negative Small), ZZ (Zero), PS (Positive Small) and PB (Positive Big). The fuzzy based rules consist of 25 rules which are illustrated in table I, to determine ΔD the output of the controller. These rules are framed based on the logic that if the operating point is far away from MPP, then step-size of perturbation should always become zero so that the stability in the power can be achieved. The output of the FLC is defuzzified using the method of center of gravity to calculate ΔD [21-25], [56-66].

ΔI	ΔP				
	NB	NS	ZZ	PS	PB
NB	NB	NS	NS	ZZ	ZZ
NS	NS	ZZ	ZZ	ZZ	PS
ZZ	ZZ	ZZ	ZZ	PS	PS
PS	ZZ	PS	PS	PS	PB
PB	PS	PS	PB	PB	PB

E. Artificial Neural Network

Artificial Neural Network (ANN) is an efficient computing system. ANNs are also named as "artificial neural systems," or "parallel distributed processing systems," or "connectionist systems." ANN acquires a large collection of units that are interconnected in some pattern to allow communication between the units. These units, also referred to as nodes or neurons, are simple processors which operate in parallel. Identification and development of adaptive controllers makes them most important for PVP energy applications in order to track the maximum power point of PVP. Now-a-days, a multilayer perception network mainly created for the back propagation method. Whereas, the nonrecurring multi-layer network is been developed to measure the DC/DC optimal duty cycle taking into account the ambient temperature variation and the irradiation. ANN is consisting of three different layers- input, hidden and output layers. The inner most layers contain two neurons as it takes two inputs (solar radiation and ambient temperature). The middle layer i.e. the hidden layer consist of five neurons; this number is selected because of the execution of empirical rules which includes starting with a high number of neurons and eliminating the unnecessary ones on the condition to reach network stability and output accuracy. The output layer consist one neuron that corresponds to the optimal duty cycle. Figure (9) this depicts the architecture of this network.

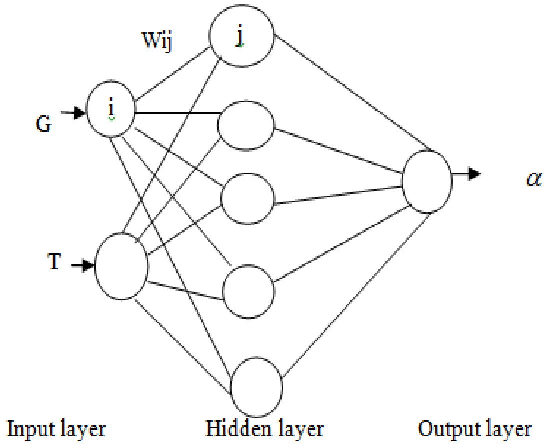

Fig. 9. The Neural Network architecture

The thresholds of the ANN and the connection weight value are chosen randomly during the starting of the training process and then at the time of training they are fixed so as to make minimum square error between estimated and training data. Many processes are available for training purpose. In this case, we used the retro propagation method, this is the most common and most used method. The training algorithm consists of minimizing the total error E defined by the equation (13) [29].

$$E = \frac{1}{2}\Sigma\left(O_n - t_n\right)^n \qquad (13)$$

Where O_n is the n^{th} measures read by the network and t_n is the n[th] target (the estimated output). Hence each input/output pair consists of some training sample. The retro propagation algorithm derives the error E and then distributes it back from output towards the input neurons through the hidden neurons using equation (14).

$$\Delta w_n = \delta \Delta w_n - \eta \frac{\partial E}{\partial w} \qquad (14)$$

Where

$w =$ Weight between any two neurons

$\Delta w_n =$ Changes of these weights for n iterations

$\delta =$ Speed term

$\eta =$ Training rate

The training rate determines the size of the changed weight that is caused due to the effect of the total error. The term speed which is used to avoids the oscillations of weight during the training iterations and it accelerates the training on the error surface. The number of the neurons selected from the hidden layer determines the degree of training. This number is calculated by the empirical formula, equation (15).

$$N_h = \frac{1}{2}\left(N_1 + N_0\right) + \sqrt{N_E} \qquad (15)$$

Where

$N_h =$ Number of hidden neurons

$N_1 =$ Number of input neurons

$N_0 =$ Number of output neurons

$N_E =$ Number of training samples

For the accurate system network, the latter is continuously adjusted after passing the testing data set to the trained ANN model and recording the results. Then, it is compared to measures. In case of convergence, the network performance is emulated by computing a performance factor. Likewise, considering the network performance to be stable on both sides of the validation sample and the test sample, we can say that the network is ready to generate the correct duty cycle (α) while excited by any (G, T) Inputs (Fig.10) [27-29], [67-71].

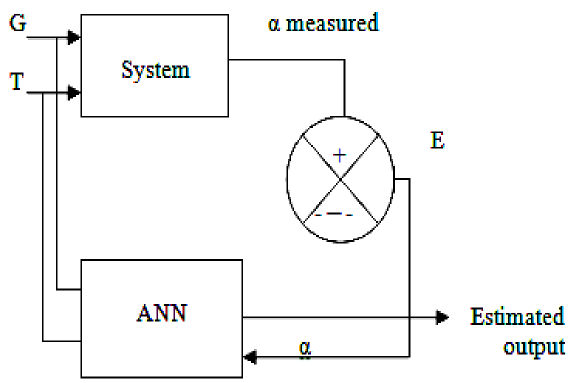

Fig.10 RNN approach

F. *Constant Voltage Method*

One of the simplest MPPT control method is constant voltage (CV) control algorathim. The PV array is kept near the operating point of MPP by regulating the array voltage and matching this point to a fixed reference voltage equal to the V_{MPP} of the PV panel. This assume that temperature variations and individual insulation on the array are insignificant and the constant reference voltage is an adequate approximation of the true maximum power point.

This method does not require any input. However, voltage V_{PV} measurment is necessary in order to set up the duty cycle for the DC/DC converter. It is necessary to observe that when the PV panel operate at low insulation conditions, the CV technique is more effective as compared to either the P&O or IC method [13], [72].

G. *Fractional Open Circuit Voltage*

This method basically operate on linear relationship between the open circuit voltage and MPP voltage (V_{MPP}), which varies directly with the irradiance and temperature [30].

$$V_{MPP} \approx k_1 V_{OC} \qquad (16)$$

Where k_1 is the constant integer depending on the the PV array characteristics and it needed to be determined before determining the V_{MPP} and V_{OC} at different levels of irradiation and temperatures. The value of constant k_1 has set to be between 0.71 to 0.78 [30]. Once the constant of proportionality, k_1 is known, the MPP voltage V_{MPP} can be determined by measuring V_{OC}. To measure V_{OC} the power converter is required to be shut down momentarily, so as to reduce the power loss in each measurement . Second problem of this method is important because it is incapable of tracking the MPP under irradition slopes, hence the observation of V_{MPP} is not continuous. One more disadvantage of using this technique is that the MPP reach is not the observed one because the relationship is only an approximation. In order to overcome these drawbacks, some of the solutions have been proposed, as is reported in [30]. For example, pilote cells are the solar cells that can be used to obtain V_{OC}. They represent the PV array cells and which are not used to produce electricity but to obtain characteristic parameters such as V_{OC} without interfering with the power converters. These pilot cells have to be specifically chosen and placed in order to represent the PV array characteristics and the solar irradiation conditions. Cost of the system is increased which is one of the drawback of using the PV array.

Depending on the application and implementation, this techniqe is very popular because it is very easy to impliment and is cheap also. It does not require DSP microcontroller to control and only one voltage sensor is required [30]. However, according to [30] this method, it is not a valid partial shading of the PV array because then the constant k_1 changes. To update k_1 a voltage sweep which is proposed though this to increases the complexity of the system, the cost increases and there are more power losses during the sweep[42-50].

H. *Fractional Short Circuit Current*

Just like in the above used fractional open circuit voltage method, there is a relationship, under varying atmospheric conditions, between the MPP current, I_{MPP} and the short circuit current I_{SC}, as it shown by:

$$I_{MPP} \approx k_2 I_{SC} \qquad (17)$$

K2 is used as the coefficient of proportionality which has to be determined according to each PV array, as in the previous method happened with k_1. According to [30] the constant k_2 has been reported to be between 0.78 and 0.92 [51-55]. It can be a problematic situation measuring the short circuit current while the system is operating. It usually requires adding an additional switch to the power converter to periodically short the PV array and measure I_{SC} [31]. We can measure I_{SC} by shorting the PV array with an additional field effect transistor added between the PV array and the DC link capacitor. One other option is shown in [32]: a boost converter is used to switch off the converter use to short the PV array. If we short circuit the PV array then it may lead also leads to a power loss. The last problem exists when the real MPP is not achieved because the proportional relationship is an approximation. Moreover, due to shaded or surface contamination, the PV array is partially shaded then k_2 changes. To overcome this problem, there is an online process to tune k_2 and [33] a periodical sweep of a PV voltage from open circuit to short circuit to update k_2 and this guarantee that the real MPP is reached at multiple maxima which absolutely increases the performance as well as complexity of the system. Most of the literature using this MPPT technique uses a DSP as controller [30].

I. *Temperature Methods*

The open circuit voltage V_{OC} of the solar cell varies mainly with the cell temperature, whereas the short circuit current is directly proportional to the irradiance level and relatively steady over cell temperature changes. The open circuit voltage V_{OC} can be described through the following equation (18):

$$V_{OC} = V_{OC \cdot STC} + \frac{dV_{OC}}{dT}\left(T - T_{STC}\right) \qquad (18)$$

Where

$V_{OC \cdot STC}$ = Open circuit voltage under standard test conditions (21.8V)

$\frac{dV_{OC}}{dT}$ = Temperature gradient (-0.08V/K)

T_{STC} = Cell temperature under STC

On the other hand, the optimal voltage is described through the following equation (19):

$$V_{OP} = \left[\left(u + S \cdot v\right) - T \cdot \left(w + S \cdot y\right)\right] \cdot V_{MPP \cdot STC} \qquad (19)$$

Where

$V_{MPP \cdot STC}$ = Open circuit voltage under standard test conditions (21.8V)

S = irradiance level

There are two different temperature methods available in the literature. The Temperature Gradient (TG) algorithm uses the temperature T to determine the open circuit voltage V_{OC} from equation (18). The optimum operating voltage V_{OP} is determined by open circuit technique, avoiding power losses. TG requires the

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measurement of the temperature T and a measurement of the voltage V_{PV} . The Temperature Parametric equation method (TP) adopts equation (19) and determines the optimum operating voltage V_{OP} instantaneously by measuring T and S. TP requires, in general, also the measurement of solar irradiance S [16], [117].

J. *Hill Climbing Method*

In this method 'hill' represents a unique photovoltaic power versus voltage or current curve in which power is varied by varying the Duty cycle of the converter/inverter being used. This method is somewhere identical to P & O method in which we have to focus on dP/dD instead of dP/dV .

The MPP's are available at these points where dP/dD is equal to zero. In every sampling period the duty cycle is determined by the comparing the power at present time and at previous time. If the incremental power $dP > 0$, the duty cycle should be increased in order to make $dD > 0$ .If $dP < 0$, the duty cycle is then reduced to make $dD < 0$ [134].

K. *Extremum Seeking Control Method*

This is a real-time optimization methodology which involves a nonlinear dynamic system with adaptive feedback. This ESC method is successfully implemented in various systems such as power reduction maximization of a flight, traction maximization in antilock braking for a car, autonomous vehicle target tracking, PID tuning pressure rise, maximization of an aero engine compressor. This method has also been specifically adapted for PV systems in order to track MPP [135–142].

Let a small sinusoidal current is represented by $\Delta I = a\sin\omega t$, is added as a perturbation to the reference current (I_{ref}). This leads to the flow of a ripple power (ΔP), having phase and amplitude that are dependent on the relative location of the operating point relative to the MPP. The sinusoidal current perturbation will be added to the reference current, and applied to the P-V system. If the resulting ripple in the current is in phase with the output power ripple, the output power will fall to the left of MPP, and the reference current will be less than I_{MPP} , therefore the controller will increase the reference current. If, on the other hand, the ripple in the current is out of phase with that in the output power, the output power will fall to the right of MPP, and the reference current will be larger than I_{MPP} . The controller will, therefore, decrease the reference current until MPP is reached. By passing the output through a high-pass filter, the ripple power (DP) can be extracted. The ripple power is then demodulated through multiplication by $\sin\omega t$. The resulting signal, zeta is either positive or negative depending on the position in the power output curve. Zeta is then applied to an integrator to modify the I_{ref} value in order to reach MPP. In the case where the operating point falls on MPP, the amplitude of the ripple will be very small and the frequency of the output power ripple will be twice to that of the current ripple.

L. *Particle Swarm Optimization Method*

This method is useful for more than one variable. The PSO algorithm can maintains a swarm or privacy of the individuals which is also called as particles, where each particle represented as individual maxima. Many local maxima are assumed to exist under partial shading conditions. The advantage of PSO is that it helps to tracking the global maximum point and leaves the other maximum points. Such that all the particles should attain the global best solution. It can also track without oscillating around MPP [143].

M. *Parasitic Capacitance Method*

In Parasitic capacitance method there is an inclusion of parasitic junction capacitance of the P-V cell. This method is a replica of Incremental Conductance with parasitic junction capacitance taken into account parallel to those with p-v cell.

$$I = I_{SC} - I_0 \exp\left\{ q\left(V + \frac{IR_S}{nkT} \right) + C_P \frac{dV}{dt} \right\} \qquad (20)$$

And hence MPPs can be calculated by using incremental conductance method i.e. $dP/dV = 0$ or otherwise $dI/dV = -(I/V)$ hence by every individual switching ripple perturb the array. And hence by using suitable filters and multipliers we can first calculate the conductance of the system and hence can calculate the MPPs accordingly by using above said equations [144-146].

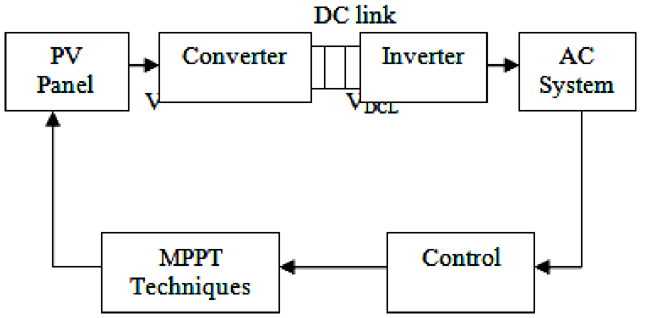

Fig.11. Capacitor Droop Control with DC Link connection

N. *DC Link Capacitor Droop Control Method*

This method is confined to parallel connected ac systems to P-V array (Fig.11). The Duty cycle of the boost converter can be given as

$$D = 1 - \frac{V}{V_{DCL}} \qquad (21)$$

Where V_{DCL} = DC link voltage

V= Voltage comes from the PV panel

Thus by varying the duty cycle keeping dc link voltage DCL V so as the current comes out to be maximum from inverter and therefore power comes out to be maximum from boost converter and get the maximum power from P-V array. In case of the deviation from MPPs to the dc link voltage gets decreases and therefore to retain the maximum current from inverter the controlled command transfer to dc link so as to maintain the voltage with the help of controller [145][147-150].

O. *Look-Up Table Method*

In Look-Up table method of MPPT, several MPPs are calculated by taking all the probable atmospheric conditions like solar irradiance, temperature, insulation etc. and store to the main memory of the controller being used and these data can be fetch out in the form of look up table whenever required for the same condition [151][152].

P. *Sliding Mode Method*

Sliding mode MPPT method is based upon the trajectory of a higher system which is being used and makes it into first order system. Sliding mode control uses discontinuous feedback control laws to force the system state to reach, and finally to remain on a fixed surface within the state space (the so called sliding or switching surface). The system is dynamic when fixed to the sliding surface as described in ideal sliding motion and represents the controlled system behavior [148]. If a higher order system kept under the switching surface and by using sliding mode control we can get the corresponding first order system so that the voltage and current of P-V array compare to the change in voltage and current. This change in voltage and current get utilize in every step by controlling the switching control signal to the dc-dc converter and thus the converter is forced to operate in MPP [153].

This method is used for the DSP, microcontroller, FPGA, etc. and for variable operating frequency processors, PWM-sliding mode or discrete switching mode can be used [154] [154].

Q. Curve-Fitting Method:(offline)

Curve fitting method is an analytic approach to get the MPPs. It is purely based upon the hit and trial method and apply the suitable mathematical equation to get the approximate equation which relates the P-V characteristic of a PV cell illustrated in Fig. 3. Once we get the suitable equation in P and V then apply $dP/dV = 0$ and hence can get the MPPs.

A third order equation relates to the P-V characteristic given as:

$$P = a + bV + cV^2 + dV^3 \qquad (22)$$

$$\frac{dP}{dV} = b + 2cV + 3dV^2$$

$$\frac{dP}{dV} = 0$$

$$b + 2cV + 3dV^2 = 0$$

$$V = \frac{-c \pm \sqrt{\left(c^2 - 3bd\right)}}{b}$$

And hence by sampling the constants a, b, c and d in regular intervals, we can calculate the V_{MPP} by using above equations [156].

R. Current Sweep Method

In this method of finding MPPs in the P-V array, a current sweep waveform is used in the I-V characteristic and is updated at the regular time interval.

For a current sweep waveform the current is taken as the time function which is proportional to its derivative such as

$$i(t) = k_1 \frac{di}{dt} \qquad (23)$$

Where

k_1 = Constant of proportionality

The solution of first order differential Equation.23 is

$$i(t) = c_1 e^{-\frac{t}{k_1}} \qquad (24)$$

Where c_1 takes the value of I_{MPP}

And thus power is given by

$$p(t) = v(t) * i(t)$$

At MPP

$$\frac{dp(t)}{dt} = \frac{d(v(t) * i(t))}{dt} = v(t)\frac{di(t)}{dt} + i(t)\frac{dv(t)}{dt} = 0$$

Or $$(v(t) + k_1 \frac{dv(t)}{dt}) * \frac{di(t)}{dt} = 0$$

Since for current sweep waveform, the time derivative of current function is non-zero i.e.

$$\frac{di(t)}{dt} \neq 0$$

It implies that

$$\frac{dp(t)}{dt} = v(t) + k_1 \frac{dv(t)}{dt} = 0 \qquad (25)$$

Equation.25. gives the V_{MPP} which reaches the value of I_{MPP} from Eqn.23. The current sweep waveform takes about 50 ms, implying some loss of available power [157] [158].

S. Ripple Correlation Control Method

Ripple Correlation Control Method uses power converter for finding the switching ripples. The voltage and current ripples of the PV system is being utilized to perform MPPT. In this method the first derivative of voltage or current can correlate with the first derivative of the power in the time varying domain of P-V array to drive the power gradient to zero so as reaching the MPP. In *figure (3)*

Assume $\dot{p} = \frac{dp}{dt}; \dot{v} = \frac{dv}{dt}; \dot{i} = \frac{di}{dt}$

If $\dot{v} > 0$ (or) $\dot{i} > 0$ and $\dot{p} > 0$ then $V < V_{MPP}$ or $I < I_{MPP}$

And if $\dot{v} > 0$ (or) $\dot{i} > 0$ and $\dot{p} < 0$ then $V > V_{MPP}$ or $I > I_{MPP}$

From the above observations, we can clearly see that $\dot{p}\dot{v}$ or $\dot{p}\dot{i}$ are positive to the left side of the MPP, negative to right side of the MPP, and zero at the MPP [159].

Power converter used is a boost converter in which as we increase the duty ratio the inductor current also increases which is same as PV array current but PV array voltage decreases, therefore the duty ratio control input is calculated which is given by equations as follows:

$$d(t) = -k \int \dot{p}\dot{v}\, dt \qquad (26)$$

Or

$$dt = -k \int \dot{p}\dot{i}\, dt \qquad (27)$$

Where, k is a positive integer. It is concluded that by controlling the duty ratio the MPP will be continuously tracked, making RCC a true MPP tracker [147] [165].

T. Beta Method

This is one of the MPPT method in which a constant β is selected as such

$$\beta = \ln \frac{I_{PV}}{V_{PV}} - \left(\frac{q}{kT\eta}\right) * V_{PV} \qquad (28)$$

Where,

I_{PV} = Current of PV array

V_{PV} = Voltage of PV array

k = Boltzmann constant

T = Ambient temperature of PV array

η = Diode quality factor

q = Electric charge

In the equation.28 it clearly seems that β depends upon the temperature while independent to that of solar irradiance [160] [161].

U. Feedback Voltage or Feedback Current Control Method

This method is adopted in the system having no battery. The voltage of the bus kept constant and by varying the duty cycle of the converter such that the PV panel voltage is varied. A controller is designed such that the feedback through it gets continuously compare the PV panel voltage with the bus voltage and for some iteration for the duty cycle we can get the MPPs. The method is low cost, computationally simple, and only uses one feedback control loop. However, it does not consider the effect of variations in temperature and irradiation [162-165].

V. CONCLUSIONS

In this paper, most of the MPPT techniques were reviewed. For simplicity, effectiveness and performance reasons P&O, IC and FLC were taken for further analysis. The performances of the mostly used MPPT techniques like modified P&O, IC algorithm and the fuzzy logic were compared with the help of Table shown below, and based on the performance of the dynamic efficiency test, it was concluded that the modified hill climbing algorithm show better characteristic than the FLC. The advantages of FLC cannot be mentioned, because the author is not an expert in tuning fuzzy systems. There are various different techniques for obtaining maximum power point tracking of photovoltaic PV systems. As shown in the table. There are 9 different methods which have been introduced in the literature, with several variations on implementations.

S. No.	MPPT technique	Convergence speed	Implementati on complexity	Sensed parameters	Cost
1	P&O	Varies	Low	Voltage, Current	High
2	Incremental Conductance	Varies	Medium	Voltage, Current	High
3	Three Point Method	Varies	Low	Voltage, Current	Low
4	Fuzzy Logic Control	Fast	High	Varies	High
5	Neural Network	Fast	High	Varies	High
6	Constant Voltage	Medium	Low	Voltage	Low
7	Fractional V_{oc}	Medium	Low	Voltage	Low
8	Fractional I_{sc}	Medium	Medium	Current	Low
9	Temperature method	Medium	High	Voltage, Irradiance, Temperatur e	Low
10	Hill Climbing Method	Varies	Low	Voltage, Current	High
11	Extremum Seeking Control Method	Fast	Medium	Current	High
12	Particle Swarm Optimization Method	Fast	Medium	Voltage, Current, Irradiance, Temperatur e	High
13	Parasitic Capacitance Method	Varies	Low	Voltage	High
14	DC Link Capacitor Droop Control Method	Medium	Low	Voltage	High
15	Look-Up Table Method	Medium	Low	Voltage, Current, Irradiance, Temperatur e	Low
16	Sliding Mode Method	Fast	High	Voltage, Current	High
17	Curve-Fitting Method:(offli ne)	Fast	Low	Voltage	Low
18	Current Sweep Method	Slow	High	Voltage, Current	High
19	Ripple Correlation	Fast	Low	Voltage, Current	High
21	Beta	Fast	High	Voltage, Current	High
22	Feedback Voltage/ Current	Fast	Low	Voltage, Current	Low

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