International Journal of Engineering Research
Volume No.5, Issue No.6, pp : 539-545

ISSN:2319-6890)(online),2347-5013(print)
1 June 2016

A Review of Maximum Power Point Tracking Techniques for Photovoltaic System

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Abstract : The consumption of electrical energy is increasing and due to limited supply of fossil fuel, the only option left is the renewable energy (RE). In last few years there has been an increase in attention towards the use of solar energy. The power-voltage characteristic of photovoltaic cell is non-linear. To get the maximum output power from photovoltaic system, the maximum power point (MPP) must be continuously tracked. The maximum power point tracking (MPPT) algorithms enhance the efficiency of PV system. The Maximum Power Point (MPP) of a photovoltaic system varies with irradiance, temperature and load connected to the (PV) system. In literature we have found large no. of MPPT algorithms categorized on the basis of complexity, cost, number of sensor required. This paper comprehends the most commonly implemented algorithms such as P&O, Incremental Conductance, Ripple Correlation Control, Current sweep and also some intelligent control algorithm such as ANN & Fuzzy logic. The MPPT algorithms are defined and compared in a tabular form.

Keywords- Maximum Power Point Tracking (MPPT) Technique, Solar Cell, PV System.

Introduction

In present time many renewable energy sources are available such as solar energy, wind energy, biomass energy, fuel energy etc. Solar energy is one of the most convenient & popular form of renewable energy because of the possibility of its direct conversion into electrical energy using Photo Voltaic (PV) system. Another major advantage of solar energy is that it is maintenance free [1]. In many countries PV system have been commercialized as it is environmental friendly [2]. The high installation cost has been a factor against implementation of this technology.

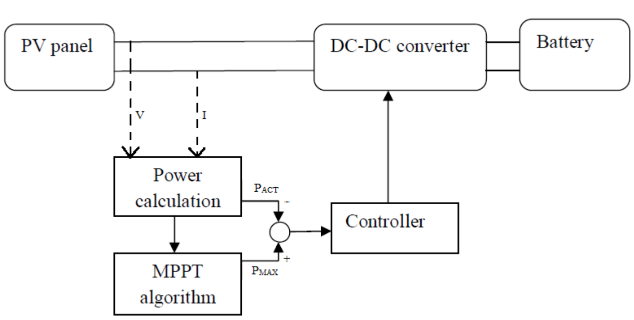

Fig. 1. Block diagram of PV system

The PV system comprises of PV (Photo Voltaic) module, DC to DC converter, controllers and batteries as shown in Fig. 1. The PV module consists of many solar cells connected in series. The electrical equivalent circuit of solar cell is shows in Fig. 2. Usually, for small system, batteries are connected directly as load, whereas for large systems, synchronized line inverters are used for direct interfacing with mains grid. In simple systems a switching device is used to stop the charging when the battery is fully charged. The sensing of full charge status is determined by the battery voltage. To attain maximum efficiency, MPPT charge controllers are used in PV system. In order to achieve maximum efficiency, MPPT charge controllers are used [3].

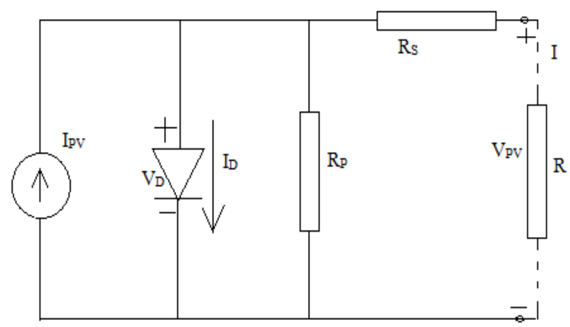

Fig. 2. Equivalent Electrical circuit of Solar Cell

In the above figure V_{PV} and I are the output voltage and current, R_S is series resistance of the solar cell, it is equivalent to contact resistance between silicon and metal contact, R_P is parallel resistance which come in the appearance due to manufacturing defect. In ideal condition R_S and R_P are zero and infinite respectively. The output current is determined by the (1).

$$I = I_{PV} - I_o\,[exp((V + IR_S)/aV_T) - 1] - (V + IR_S)/Rp \qquad (1)$$

In the above equation I_{PV} is the photocurrent produced by constant current source, I_o is reverse saturation current, a is the diode quality factor (ideality factor), V_T is temperature equivalent voltage, R_S and R_P are the series and parallel equivalent resistance of the solar cell. This expression also betell the I-V characteristic of solar panel or solar cell, as in [4].

The output power of photovoltaic array mainly depends on solar irradiance, panel temperature and the load impedance [5]. The solar irradiance and temperature is subject to atmospheric changes, and thus, is not fixed but unpredictable to a large extent. The output power obtained varies depending on the above factors. The output voltage and current must be fixed for higher efficiency [6,7]. The solar PV system is not so popular because of its low efficiency and high cost. There are primarily three factors that affect the efficiency of a PV system. These are the efficiencies of the solar PV panel, MPPT charge control system and the inverter.

The installation cost of a PV system is very high. The total investment in the SPV (solar PV) system constitutes of the following, PV array around 60%, battery 25%, charge controller, inverter and other installation costs around 15% [8]. The effective cost can be reduced by improving the efficiency of the PV system. There is a balance to be maintained between the cost and efficiency. Any improvement in the efficiency of the PV panel and the inverter is difficult because it depends on available technology, but improvement in the tracking algorithm is easier [9].

It was briefly mentioned above that MPPT are required to guarantee the maximum power output. It is necessary to implement MPPT algorithms as can be seen from the Power - Voltage curve below. The P-V curve is non-linear and hence maximum power output can be obtained by selecting the maximum power point in the output characteristics of SPV [10]. For a 24V system, maximum power point would be around 37V.

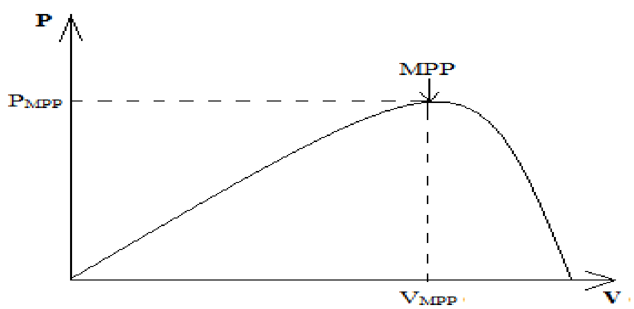

Fig. 3. P-V characteristic of solar cell

The point depicted in the above figure is called a MPP (Maximum Power Point) and it is determined mainly by temperature of panel and irradiance condition. The irradiance may change frequently due to clouds or shadow of any object and fluctuate the MPP. An algorithm which continuously computes the operating point of the solar panel is used to fix this dynamic operating point at the maximum power point. These are called MPPT (maximum power point tracking) algorithms [11]. To obtain maximum available power, the operating point must be tracked accurately in all condition by using MPPT algorithm. In [12], the MPPT not only increases the power delivered to the load but also increases the life span of the PV system. In the MPPT system, the duty cycle of PWM based dc-dc converter adjusted to obtain the maximum power point.

In last few years numbers of MPPT algorithms have been published, they differ on the basis of complexity, sensor required, cost or efficiency, convergence speed, range of effectiveness and implementation hardware. T. Esram and P. L. Chapman [13] has compiled about 90 papers with brief discussion and categorization.

Maximum Power Point Tracking (MPPT) Techniques

Perturb and observe (P & O) algorithm – The most commonly used algorithm to find MPP is perturb and observe (P&O) resulting in the ease of its practical implementation with the advantages of low cost and high speed [14]. In this technique, as the name says, one perturbs or produces an infinitesimal change in output voltage to observe the change in power(ΔP). If $(\Delta P > 0)$ the next perturbation should be in same way to get the MPP and if $(\Delta P < 0)$ then direction of perturbation is reversed, as shown in Fig.3. In other words we can say that if due to increment in voltage , the power increases it shows that the actual operating point is at the left side of the MPP [15]. This process is repeated at some fix intervals until the MPP is achieved, this is also summarized in Table.1.

The P&O technique tracks the MPP in wrong direction if irradiance changes frequently. In this technique the operating point of the system oscillates about the MPP and never reaches the actual MPP [16]. The oscillation may be reduced by decreasing the perturbation size but it also delays the tracking process. A strategy is proposed in [17, 18] to overcome this contradictory problem by using perturbation of variable size, that reduces if operating point is closer to MPP.

The P&O and Incremental conductance algorithm are examples of hill climbing algorithm. The P&O involves a perturbation in the operating voltage (V) of the PV array and Hill climbing involves a perturbation in the duty ratio of power converter [19, 20].

Table. 1. Summary of P& O algorithm

Perturbation	Change in power	Next perturbation
Positive	Positive	Positive
Positive	Negative	Negative
Negative	Positive	Negative
Negative	Negative	Positive

In [21] algorithm is proposed that tracks in two stages, the faster but possibly less precise tracking algorithm to get closer to the MPP as stage one and finer tracking to reduce the oscillation as stage two. The idea of finer tracking to reduce the oscillation of P&O algorithm is also proposed in 2010 [22], where a MPPT algorithm is presented which uses biological swarm chasing procedure. In this method (to find out the direction of tracking correctly) a system is proposed in which tracking of MPPT is based on the samples taken from each PV module individually and also collectively as an array, so as to optimize power obtained from each PV module as well as the array. The MPP is considered as moving target. Thus every PV

International Journal of Engineering Research
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ISSN:2319-6890)(online),2347-5013(print)
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module can chase the MPP automatically. This technique increases the efficiency by 12-19 % of P&O algorithm. In [23], Fuzzy logic control is used to optimize the magnitude of the next perturbation.

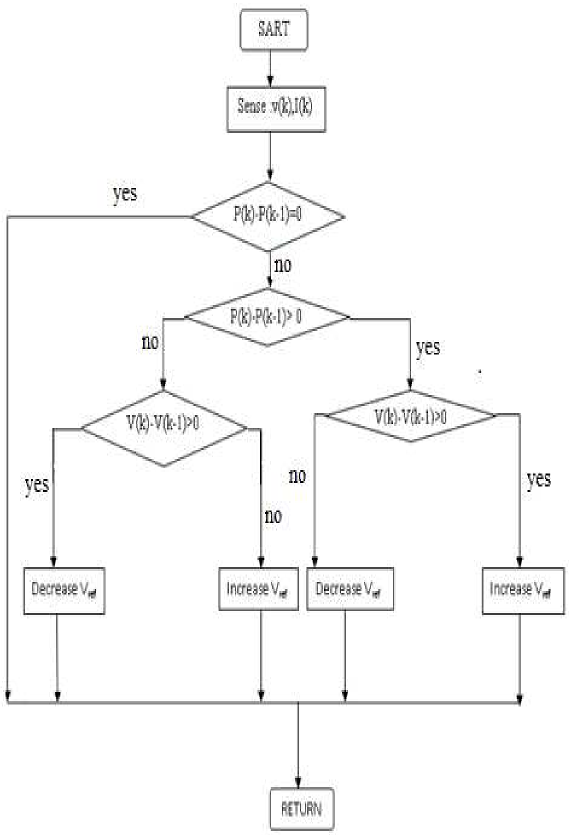

Fig. 4. Perturbation and Observation algorithm

Incremental conductance (I.C) algorithm – IncCond. technique is based on power- voltage characteristic, the slope of P-V curve is zero at the MPP, positive on the left side and negative on the right side [24]. The drawback of the P&O method (i.e, oscillation of operating point in varying irradiance condition) is eliminated by IncCond. method. This is a further improvement on the P&O algorithm. The IncCond. technique acknowledges that the MPPT has reached at MPP and stops perturbing the output voltage [25]. The PV array operation is maintained at this point until output current (ΔI) is unchanged. In this technique to track the new MPP, the V_{ref} is increases or decreases [26, 27].

$$dP/dV = d(V.I)/dV = I + V\,dI/dV = 0 \qquad (2)$$

$$\begin{cases} dp/dv = 0 \\ dp/dv > 0 \\ dp/dv < 0 \end{cases}$$

$$\begin{cases} \Delta I/\Delta V = -I/V & \text{At MPP} \\ \Delta I/\Delta V > -I/V & \text{Left of MPP} \\ \Delta I/\Delta V > -I/V & \text{Right of MPP} \end{cases} \qquad (3)$$

Thus MPP can be achieved by comparing the instantaneous conduction (I/V) to the incremental conductance $(\Delta I/\Delta V)$. In this method the array terminal voltage is adjusted according to the MPP voltage, It is based on the incremental and instantaneous conductance of the PV module [28].

In both P&O and IncCond. schemes, time taken to track the MPP depends on the size of the increment of the reference voltage (V_{ref}). For fast tracking the large increment size is used but then the system will not operate exactly at the MPP and will oscillate about the MPP which means that the full efficiency of the system is never reached. The perturbation size problem is same in P&O and I.C. This can be solved by variable perturbation size [29], in which the first stage pushes the operating point close to MPP and then uses IncCond. for reaching at MPP exactly, but this algorithm requires complex and costly control circuit. The IncCond. algorithm has higher efficiency than P&O in frequently changing irradiance condition.

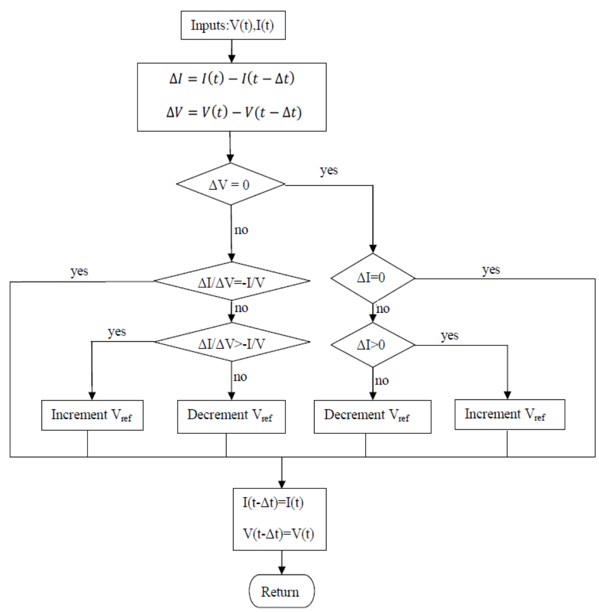

Fig. 5. Incremental conduction algorithm

Open Circuit Voltage (OCV) method - This method uses the characteristic of PV array of approximate linear relation between V_{MPP} and open circuit voltage V_{OC} [30-32].

$$V_{MPP}/V_{OC} \approx k_1 < 1 \qquad (4)$$

k is the constant of proportionality and its value depends upon the characteristic of the solar panel. It is calculated in advance

ISSN:2319-6890)(online),2347-5013(print)
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for particular PV array by determining V_{MPP} and V_{OC} at different values of temperature and irradiance. The variable k could attain value between 0.71 and 0.78.

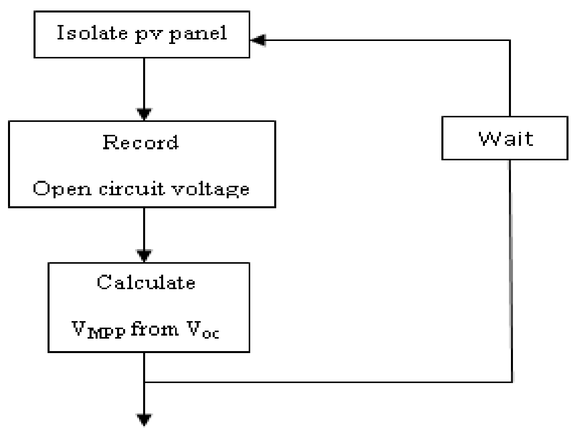

Fig.6. constant voltage algorithm

In this method the solar panel is isolated from MPPT unit temporarily the V_{OC} is measured as shown in Fig.6, and then V_{MPP} is calculated from Eq. 4. The array output voltage is adjusted for the calculated V_{MPP} and hence the module is operated at MPP. This process of measuring V_{OC} and adjusting of V_{MPP} is repeated at fixed interval until MPP is attained. The continuous tracking of MPP is not performed as PV arrays is isolated at the time of measuring V_{OC} , which also causes power loss. due to this power loss also occurs. One more drawback of this method is, the MPP reached is not a true MPP because it is based on approximation. The above listed disadvantages aside, this technique is very simple and cost effective to implement.

Short circuit current (SCC) method – This technique is also based on the fact that the current correspond to MPP (I_{MPP}) is related to short circuit current (I_{SC}) ,as in (5).

$$I_{MPP}/I_{SC} \approx k_2 < 1 \qquad (5)$$

The value of k_2 is depends on characteristic of PV module, it is known as coefficient of proportionality. It is calculated for particular PV array under different atmospheric condition in a way similar to that of k_1 as in constant voltage method by measuring (I_{MPP}) and (I_{SC}) [31]. The value of coefficient k_2 is generally found to be between 0.78 and 0.92. The main problem with this method is to measure the short circuit current (I_{SC}) when system is operating. The additional switch is used to short PV array periodically and current sensor then measure $(I_{SC})$and hence (I_{MPP}) is calculated each time. In literature different technique are discussed to measure(I_{SC}), in [33] the field effect transistor is used as additional switch, in [34] a boost converter with a switch is used for shorting the PV array, but it's increases the component, complexity and hence implementation cost increase. This is also approximation based method so true MPP is not achieved.

Ripple correlation control (RCC) technique – In PV system, PV array is directly connected to a power converter, which is basically a switching device. The switching action of the converter imposes voltage and current ripples on the PV array. Hence, we can say, that the power generated from PV array is related to ripples. In [35, 36], the Ripple correlation control method ripple are utilized to track MPP. The switching converter has ripple naturally so that there is no need to generate perturbation artificially.

RCC correlates time derivative of power dp/dt with either time derivative of time varying PV current di/dt or voltage dv/dt to drive the power gradient to zero to get MPP. The derivatives are nonzero due to the natural ripple that occurs because of the high converter switching frequency. Thus the name "ripple correlation control". The role of RCC is to force this ripple to zero and ultimately drag the PV panel voltage and current to that of MPP.

$\frac{dv}{dt} > 0$ or $\frac{di}{dt} > 0$ and $\frac{dp}{dt} > 0$, then the operating point is below the MPP $(V < V_{MPP} \; or \; I < I_{MPP})$

$\frac{dv}{dt} > 0$ or $\frac{di}{dt} > 0$ and $\frac{dp}{dt} < 0$, then the operating point is above the MPP $(V > V_{MPP} \; or \; I > I_{MPP})$

Combining these observations, we see that $\frac{dp}{dt}\frac{di}{dt}$ or $\frac{dp}{dt}\frac{dv}{dt}$ are positive to the left of the MPP, negative to the right of the MPP and zero at the MPP.

In the boost converter case, the inductor current include a dc component (I_L) and a ripple component $(\tilde{i}_L)$. We can correlate the inductor current (i_L) and array power (p) in order to figure out whether(I_L) is right side or left side of (I_{MPP}). When (I_L) is left of (I_{MPP}), a current ripple imposed along the curve leads to an in-phase power ripple. This implies that the product of the time derivative of (i_L) and the time derivative of power (p) is positive. When (I_L) is right side of (I_{MPP}), the current ripple and power ripple are out of phase, and the product of the time derivative of $(i_L)$and the time derivative of power (p) is negative.

$\frac{di_L}{dt}\frac{dp}{dt} > 0 \qquad \approx \; i_L < I_{MPP}$, left of the MPP

$\frac{di_L}{dt}\frac{dp}{dt} < 0 \qquad \approx \; i_L > I_{MPP}$, right of the MPP

By adjusting the duty ratio d, the value of i_L can be adjusted. The value of d can be calculated as

$$d = k\int \frac{di_L}{dt}\frac{dp}{dt}dt \qquad k \text{ is constant.} \qquad (6)$$

ISSN:2319-6890)(online),2347-5013(print)
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The Convergence rate is limited by switching frequency and controller gain. RCC is suitable for the system where high rate of convergence is required, such as moving systems. That encounter rapidly changing irradiance condition like solar cars.

Current sweep technique – In this technique the sweep waveform of PV array current is used to obtain I-V characteristic of PV array. The voltage V_{MPP} can be calculated from I-V curve. The sweep waveform is updated to track MPP at fixed time interval, hence characteristic curve is also updated periodically. The V_{MPP} is determine each time at the same interval. In [37, 38], the function chosen for current sweep waveform is directly proportional to its derivatives.

$$i(t) = k_1 \frac{di}{dt} \qquad (7)$$

$$i(t) = k_2 e^{\frac{t}{k1}} \qquad (8)$$

k_2 is taken as I_{MPP} at MPP.

$$\frac{dp(t)}{dt} = \frac{d\,(v(t)i(t))}{dt} = i(t)\,\frac{dv(t)}{dt} + v(t)\,\frac{di(t)}{dt} = 0 \qquad (9)$$

From equation (7) and (9)

$$\frac{dp(t)}{dt} = \left(k_1\,\frac{dv(t)}{dt} + v(t)\right)\frac{di(t)}{dt} = 0 \qquad (10)$$

Where $i(t)$ can be calculated using Eq. (8) and V_{MPP} using Eq. (10). The current in Eq. (8) can be obtained by the current discharging through a capacitor. In this technique sweep is updated periodically, during the interval between two updates the operating point is different from MPP which results in power loss. The practical implementation cost and complexity is high, both voltage and current measurement is required. This technique is worth if the power consumed by tracking unit is less than the power increased by PV system. The actual MPP can be found by this method.

DC-link capacitor droop control technique – This technique is developed for the system where PV system is parallel connected with AC system line [39, 40]. The duty cycle of boost converter is defined as in (12).

$$D = 1 - V/V_{link} \qquad (12)$$

Where V is the output voltage of PV array and V_{link} is the voltage across the DC link. In this technique for fixed DC link voltage V_{link} , the output power of boost converter increases by increasing the current going in to the inverter and hence it will also increases the output power of PV array. The voltage V_{link} is maintain constant for increasing current until the power required by inverter is less than maximum power can provide by the PV array. If the required power by inverter is further increase and exceeded by the level of maximum power present at PV array. The V_{link} start to decrease, just before this condition the output current is at maximum value (I_{max}) and PV array is at MPP. The duty cycle of converter is set for (I_{max}) and AC system line current is fed back to avoid drooping of V_{link} , thus MPPT is performed.

Load current or load voltage maximization technique – In this technique the aim is to maximize the current or voltage at the load. When attempting to maximize output power of PV array, the output power of converter also gets maximized [41, 42]. In a similar fashion if we try to achieve maximum power at the load connected to the converter output, the PV array output power gets maximized, assuming converter is lossless. The loads are generally either voltage source type, current source type or resistive type. If the load is voltage source, the output voltage is fixed at load voltage. To maximize the output power, the load current I_{out} must be maximized. In the same way for current source type load, the output current is constant and to maximize the output power load voltage V_{out} must be maximized. This is also applicable to non linear load.

To understand we take a general case of PV system with battery as main load, battery can be considered as voltage source type load to maximize the power output the load current should be maximized. To maximize the output current so that output power is close to MPP, converter uses positive feedback. The drawback of this method is, system never track exact MPP because lossless converter is not possible.

Artificial Intelligence – An Artificial Intelligence (AI) MPPT technique in PV system achieve very good performance and fast responses especially for rapid temperature and irradiance variations. In present time AI technique is implemented in different areas**.** This paper considers only Artificial neural network (ANN) and Fuzzy logic (FL) method out of the many existing AI techniques for MPPT.

Artificial Neural Network – An Artificial neural network (ANN) consists of electrical neurons which are connected to each other depending on different topologies. An ANN uses non linear and complex function for identification and modeling of the system. Neural networks consists of three layers as shown in fig. 7. The PV data such as open circuit voltage (V_{oc}) and short circuit current (I_{sc}) or atmospheric irradiance and temperature may be used as input. The output signal is the duty cycle signal for power converter to operate at MPP. The exact knowledge of PV system parameter is not required, which is a major advantage of ANN [43-46].

The node *i* and node *j* are connected through weighted link W_{ij} as depicted in the figure 7. The weight W_{ij} must be determined carefully to track MPP precisely, using relations established between input and output of PV system through the process of training. The characteristic of PV module changes with time, so the weights must be updated accordingly to achieve MPP, and this process is termed as an adaption cycle. The closeness of operating point and MPP depends on the algorithm used by

ISSN:2319-6890)(online),2347-5013(print)
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hidden layer. The number of nodes in each layer depends on the user.

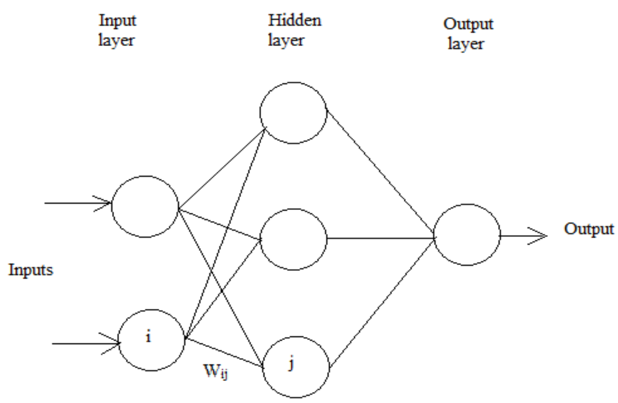

Fig. 7. Example of neural network

Fuzzy Logic based MPPT technique – The Fuzzy-Logic technique is used for complex and non-linear systems and in recent years has found application in MPPT system. The fuzzy logic based MPPT controllers, similar to ANN, can also work with imprecise inputs [47-50].

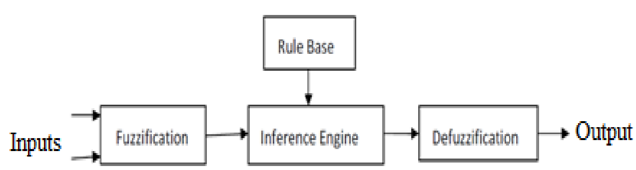

Fig. 8. Fuzzy logic controller

Normally fuzzy logic controller has two inputs and one output as discussed in [48]. The error signal $(E(n))$ and change in error $(\Delta E(n))$ as in (13) and (14) for n^{th} sampled time, are used as an inputs for the MPPT controller.

$$E(n) = \frac{P(n) - P(n-1)}{V(n) - V(n-1)} \qquad (13)$$

$$\Delta E(n) = E(n) - E(n-1) \qquad (14)$$

The input signals depends on the instantaneous values of output power and voltage which in turn depends on the atmospheric condition such as irradiance and temperature [49]. The Fuzzy logic controller performs operation in four stages as in Fig. 8. The first stage is fuzzification in which the membership function is used to convert the numerical values in to linguistic fuzzy sets and vice-versa. The rule base is a set of If-Then statements that contains information about controller parameter. Fuzzy inference engine provides result on the basis of fuzzy rule base, in the form of linguistic fuzzy set. Defuzzification is the last stage, during which the output of controller in the form of linguistic variable, is again converted into an actual variable in form of analog signal. The output analog signal could be duty cycle or change in duty cycle depending on Fuzzy logic system at hand. The analog output is used by power converter to drive the operating point to the MPP.

MPPT technique	PV array dependent	True MPPT	Analog or Digital	Periodic Tuning	Conversion speed	Implementation Complexity	Sensed Parameters
Hill-climbing/P&O	No	Yes	Both	No	Varies	Low	Voltage, Current
Incremental Conductance	No	Yes	Digital	No	Varies	Medium	Voltage, current
Open circuit voltage	Yes	No	Both	Yes	Medium	Low	Voltage
Short circuit current	Yes	No	Both	Yes	Medium	Medium	Current
RCC	No	Yes	Analog	No	Fast	Low	Voltage, current
Current sweep	Yes	Yes	Digital	Yes	Slow	High	Voltage, current
Dc Link Capacitor droop Control	No	No	Both	No	Medium	Low	Voltage
Load I or V maximization	No	No	Analog	No	Fast	Low	Voltage, current
ANN	Yes	Yes	Digital	Yes	Fast	High	Varies
Fuzzy logic control	Yes	Yes	Digital	Yes	Fast	High	Varies

Table. 2. Comparison of MPPT techniques [4, 13]

Conclusion - In this review paper, most widely used MPPT technique are discussed such as perturb & observe, incremental conductance, fuzzy logic control, artificial intelligence etc. All discussed MPPT technique are compared on the basis of complexity, cost, sense parameter and conversion speed in Table.2.

Out of these techniques, some are low in cost and complexity but also has less efficiency and others are expensive but has good efficiency. It is difficult to find out which method is best as each has its advantages and disadvantages, it's depends on the application and requirement. The comparison table must provide help in selecting an appropriate method for specific PV system.

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