A Review of Grid Connected Photovoltaic Systems

Tamanna Nazeer, Swastik Gupta, Shashi Bhushan Kotwal
Department of Electronics & Communication Engineering, Shri Mata Vaishno Devi University, Katra-182320, India

Abstract – Due to ever increasing power demand and the environmental concerns associated with it, the interest in distributed energy generation systems (DG systems) based on solar energy is increasing. Using Photovoltaic (PV) modules, solar energy can be directly converted to electrical energy. In PV modules, the output voltage is DC and has low amplitude. In order to be connected to the grid; the PV modules output voltage should be boosted and converted into an AC voltage. This task can be performed by one or more conversion stages. Different topologies are used for this purpose. Also voltage power characteristic of PV array is non-linear and the power characteristic varies with the level of solar irradiation and temperature therefore making the extraction of maximum power from the PV panel a complex task. Thus, in order to overcome this problem, several methods called Maximum Power Point Tracking (MPPT) techniques for extracting the maximum power have been proposed in the literature and a careful comparison of these methods can result in important information for the design of these systems. This paper presents an overview of the existing power inverter topologies that have found practical applications for grid connected PV systems. In addition, paper presents a comparison of various power point tracking (MPPT) techniques serving as a convenient reference for future work in PV power generation.

Index Terms – Photovoltaic (PV) generation system, inverter, Maximum Power Point Tracking (MPPT), Perturb & Observe (P&O).

1. INTRODUCTION

The growing energy demand and the increasing concern about environmental protection have led to the use of energy sources that are pollution free and are renewable. Among the various alternative natural energy resources, solar energy has received a greater interest since it is clean, renewable and pollution-free. Even though sunlight experiences the phenomenon of reflection and absorption by the atmosphere, but still the solar energy incident on the surface of the earth is on the order of ten thousand times greater than the world energy consumption [1]. Over the last decade, Photovoltaic (PV) technology has evolved as a renewable source for distributed generation systems due to their relatively small size, noiseless operation, simple installation and the possibility to put it close to the user [2]. There has been an exponential growth in the number of PV installations, mainly due to the governments and utility companies that support programs which focus on grid-connected PV systems [3]. Grid connected PV systems account for more than 99% of the PV installed capacity compared to stand-alone systems (which use batteries) [4].Grid-connected PV systems do not need batteries since all of the power generated by the PV plant is uploaded to the grid for direct transmission, distribution and consumption. In a conventional PV system, PV cells generate a DC that greatly depends on the solar irradiance, temperature and voltage at the terminals of the PV systems. The interface of the PV array to the grid is realized with a PV inverter which converts the DC power into the AC power. The two typical configurations of a grid-connected PV system are single or two stages. In a two-stage configuration, the first stage (DC-DC Converter) is used to boost the PV array voltage and track the maximum power and the second stage (DC-AC converter or inverter) ensures the conversion of this DC power into high-quality AC voltage [5]. This paper gives an overview of existing power inverter topologies for grid-connected photovoltaic systems.

Tracking the maximum power point (MPP) of a photovoltaic array is usually an essential part of a PV system. The voltage power characteristic of a PV array is nonlinear and time-varying because of the changes caused by the atmospheric conditions - irradiance and temperature. Thus the linear control theory cannot be easily used to obtain the maximum power point (MPP) of the PV array [6]. To overcome this problem, several methods have been developed to continuously track the MPP [6]-[16]. In fact, so many methods have been developed that it has become difficult to adequately determine which method, newly proposed or existing, is most appropriate for a given PV system. A careful comparison of these methods can result in important information for designing a given PV system.

2. STRUCTURE TOPOLOGIES FOR GRID CONNECTED PHOTOVOLTAIC SYSTEMS

PV systems normally consist of many cells that collectively form a module. From there, some modules connect to each other to make a PV panel. A group of such panels is called a PV array. These elements can be connected in series or parallel; the goal of this connection is to obtain higher output power from the PV system. There are different topologies available for grid-connected PV systems that are categorized based on the number of power stages.

2.1. Central Inverters

The centralized inverter technology, a past technology, illustrated in Fig. 1(a), was based on centralized inverters that interfaced a large number of PV modules to the grid [17]-[19]. The PV modules were divided into series connections (called a string), each generating a sufficiently high voltage to avoid further amplification. These series connections were then connected in parallel, through string diodes, in order to reach high power levels of 10–250 kW [19]. For this architecture, the PV arrays are connected in parallel to one central inverter. The main advantage of central inverters is the high efficiency (low losses in the power conversion stage) and low cost due to usage of only one inverter. This centralized inverter includes some severe limitations, such as high voltage DC cables between the PV modules and the inverter, power losses due to a centralized MPPT, mismatch losses between the PV modules, losses in the string diodes, and a non-flexible design where the benefits of mass production could not be reached. The failure of the central inverter results in that the whole PV plant fails to operate. The grid-connected stage was usually line commutated using thyristors, involving many current harmonics and poor power quality [20]-[25].

Centralized inverter configurations are mostly used to interface large PV systems to grid. The most common inverter topology found in practice is the 2L-VSI, composed of three half-bridge phase legs connected to a single dc link [4].

2.2. String Inverters

The string inverter shown in Fig. 1(b), is a reduced version of the centralized inverter, where a single string of PV modules is connected to the inverter [3], [17].The input voltage may be high enough to avoid voltage amplification. Compared to central inverters, in this topology, the PV strings are connected to separate inverters. The possibility of using fewer PV modules in series also exists, if a dc–dc converter or line-frequency transformer is used for voltage amplification. There are no losses associated with string diodes and separate MPPTs can be applied to each string; this increases the overall efficiency compared to the centralized inverter, and reduces the price, due to mass production [26].

The most common string inverter topology is the full- or half bridge inverter. The H-bridge with a grid-side low-frequency transformer features a simple power circuit, galvanic isolation and voltage elevation provided by the transformer, which enables a large range of input voltages[4].The transformer less H-bridge(H4 inverter) with a boost dc-dc stage gets rid of the low-frequency transformer by splitting the grid inductor into the phase and neutral wires of the system and using a bi-polar PWM to solve the problem of the switched common-mode voltage and leakage current and using boost stage for a wider input voltage range [4].

2.3. Multistring Inverters

The multi-string inverter depicted in Fig. 1(c) is the further development of the string inverter, where several strings are interfaced with their own DC–DC converter (separate MPP tracking systems) to a common DC–AC inverter [3], [17]. This is beneficial, compared to the centralized system, since every string can be controlled individually. Accordingly, a compact and cost-effective solution, which combines the advantages of central and string technologies, is achieved. This multi-string topology allows for the integration of PV strings of different technologies and of various orientations (south, north, west and east). These characteristics allow time-shifted solar power, which optimizes the operation efficiencies of each string separately. The application area of the multi-string inverter covers PV plants of 3–10 kW [17], [23], [27].

One of the first multistring inverters introduced in practice was the half-bridge inverter with boost converters in the dc–dc stage by SMA [76]. Other topologies that have followed include the H-bridge, the H5, the three-phase two-level voltage–source inverter (2L-VSI), the 3L-NPC, and the three-phase three-level T-type converter (3L-T) [4].

2.4. AC Modules

The AC module depicted in Fig. 1(d) is the integration of the inverter and PV module into one electrical device [3]. It removes the mismatch losses between PV modules since there is only one PV module, as well as supports optimal adjustment between the PV module and the inverter and, hence, the individual MPPT. It includes the possibility of a facilitated enlargement of the system, due to the structure. The necessary high voltage-amplification may reduce the overall efficiency and increase the price per watt, because of more complex circuit topologies. The present solutions use self-commutated DC–AC [17], [23].

A commercial AC-module topology is the interleaved flyback converter, developed by Enphase Energy [75] and currently commercialized by Siemens. The flyback converter performs MPPT and voltage elevation and provides galvanic isolation while the H-bridge inverter controls the dc-link voltage [4].

3. MAXIMUM POWER POINT TRACKING TECHNIQUES FOR GRID CONNECTED PHOTOVOLTAIC SYSTEMS

Tracking the maximum power point (MPP) of a photovoltaic (PV) array is usually an essential part of a PV system and task of MPP tracking techniques is to continuously tune the PV system so that it draws maximum power from the PV array.

The maximum power point of PV panels is a function of solar irradiance and temperature. Several methods for extracting the maximum power have been proposed in the literature .These methods vary in complexity, sensors required, convergence speed, cost, range of effectiveness, implementation hardware, popularity and in other respects.

3.1. Perturb and Observe (P&O)

P&O method involves the perturbation in the operating voltage of the PV array. The P&O method (Fig. 3) operates by periodically incrementing or decrementing the output terminal voltage of the PV cell and comparing the power obtained in the current cycle with the power of the previous one (performs dP/dV).

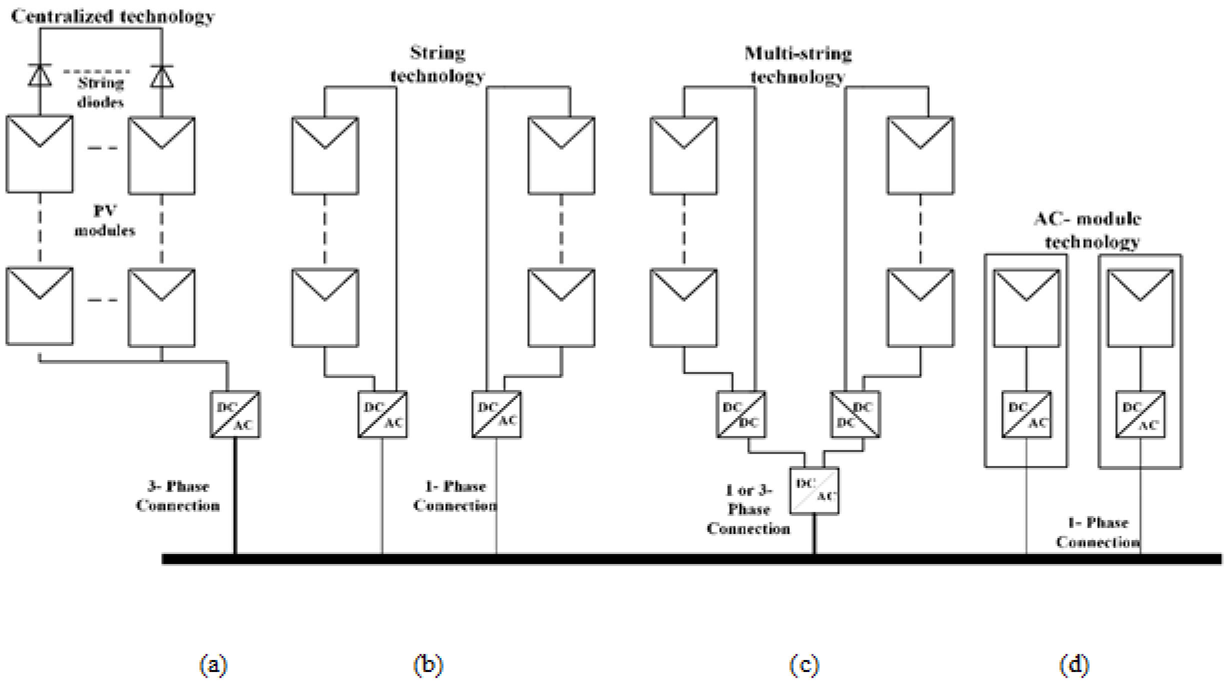

Fig. 1 PV Grid Connected System Configurations (a) Central Inverter (b) String Inverters (c) Multi-String Inverters (d) AC Module Inverters

PV Configuration	MPPT	Voltage Level	Diode Losses	Mismatch Losses
Centralized	NO	High	Yes	Yes
String	Limited	High	No	No
Multi-String	Yes	Low & High	No	No
AC-Module	Yes	Low	No	No

Table 1 Comparison of PV Configurations

If the voltage varies and the power increases, the control system changes the operating point in that direction; otherwise, it changes the operating point in the opposite direction. Once the direction for the change of voltage is known, the voltage is varied at a constant rate [1], [28]-[30]. It is often referred to as hill climbing method, because they depend on the fact that on the left side of the MPP, the curve is rising ($dP/dV > 0$) while on the right side of the MPP the curve is falling ($dP/dV < 0$) this is shown in Fig. 2.

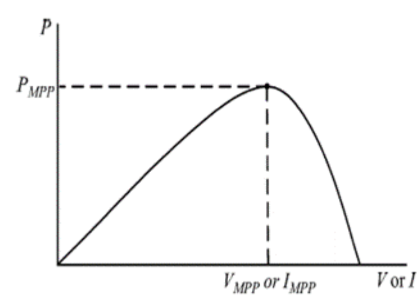

Fig. 2 Characteristic PV array Power Curve [52]

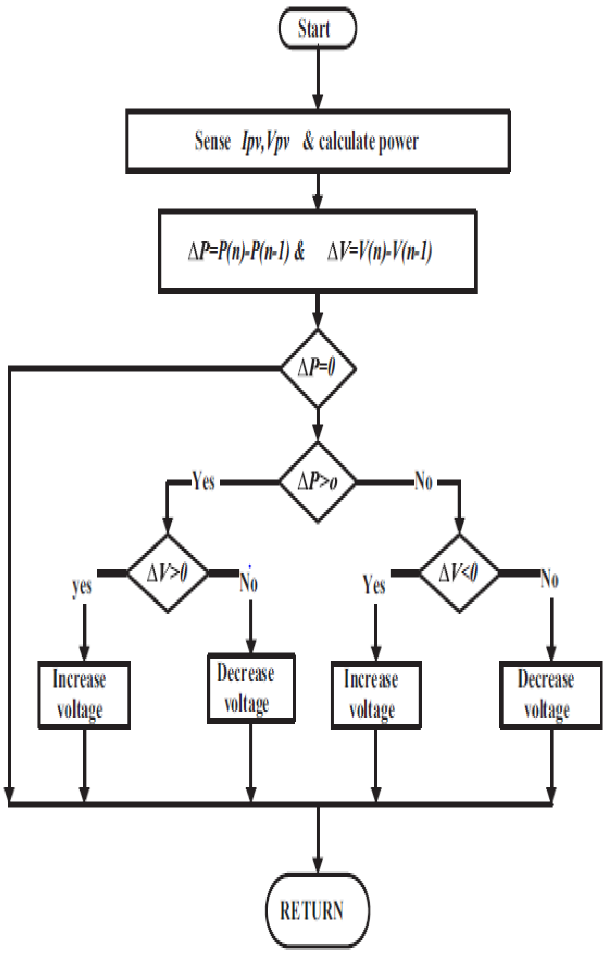

Fig.3 Flow chart of P&O algorithm [29], [30]

Perturb and observe methods have two primary drawbacks. The first is the oscillation around the MPP at steady state, which wastes energy [31]. The second disadvantage is the low quality tracking during rapidly changing weather conditions. The MPPT moves away from the real MPP due to the quick change in the weather conditions [12]. Improvements can be obtained through a digital controller, transforming the conventional P&O into an adaptive solution once different step sizes according to the distance of the MPP are performed. In steady state, the operation point is not altered unless changes in environmental conditions happen. The key idea is to reduce to zero the *dP/dV* using a closed-loop control performing the P&O based on PI [1].

3.2. Incremental Conductance (Inc Cond)

The incremental conductance (IncCond) [15],[32]–[37] method is based on the fact that the slope of the PV array power curve (Fig. 2) is zero at the MPP, positive on the left of the MPP, and negative on the right, as given by:

$$\left.\begin{aligned} \frac{dP}{dV} &= 0, \ at\ MPP \\ \frac{dP}{dV} &> 0, \ left\ of\ MPP \\ \frac{dP}{dV} &< 0, \ right\ of\ MPP \end{aligned}\right\} \qquad (1)$$

Since,

$$\frac{dP}{dV} = \frac{d(IV)}{dV} = I + V\frac{dI}{dV} \cong I + V\frac{\Delta I}{\Delta V} \qquad (2)$$

(1) Can be written as:

$$\left.\begin{aligned} \frac{\Delta I}{\Delta V} &= -\frac{I}{V}, \ at\ MPP \\ \frac{\Delta I}{\Delta V} &> -\frac{I}{V}, \ left\ of\ MPP \\ \frac{\Delta I}{\Delta V} &< -\frac{I}{V}, \ right\ of\ MPP \end{aligned}\right\} \qquad (3)$$

The MPP can thus be tracked by comparing the instantaneous conductance (*I/V*) to the incremental conductance (*ΔI/ΔV) as* shown in the flowchart in Fig. 4. *Vref* is the reference voltage at which the PV array is forced to operate. At the MPP, *Vref* equals to V_{MPP}. Once the MPP is reached, the operation of the PV array is maintained at this point unless a change in Δ*I* is noted, indicating a change in atmospheric conditions and the MPP. The algorithm decrements or an increment *Vref* to track the new MPP. The size of the increment or decrement determines how fast the MPP is tracked. Fast tracking can be achieved by applying larger increments, but the system may not operate exactly at the MPP and oscillations around the MPP may result. That is, use of the IncCond method involves a trade-off between speed of convergence and the likelihood of appearance of oscillations around the MPP. In [36] and [40], a method is proposed that brings the operating point of the PV array close to the MPP in a first stage and then uses IncCond to exactly track the MPP in a second stage.

The incremental conductance method demands two sensors to measure the instantaneous values for the voltage and current. Furthermore, this tracking method can be applied using a digital signal processor (DSP) and microcontroller, which have the ability to save the current and past values and make the proper decision based on the algorithm in Fig. 4 [15].

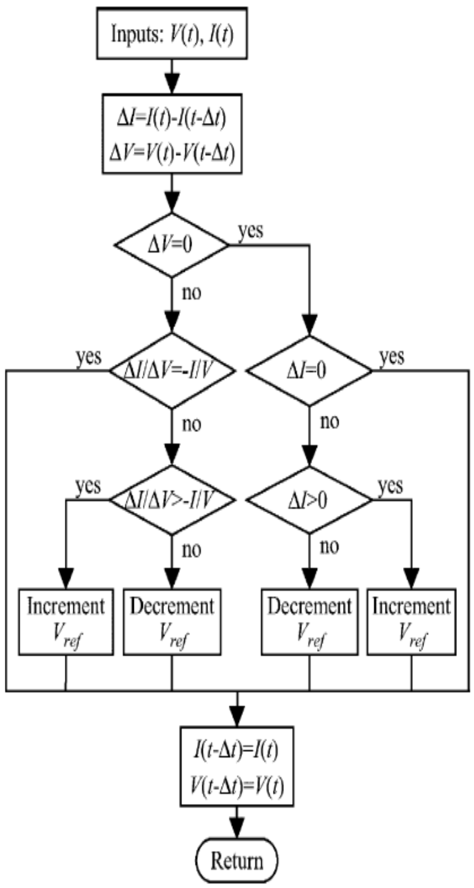

Fig. 4 Flow Chart of Incremental conductance method [14], [15], [16]

3.3. Fractional Open Circuit Voltage

The near linear relationship between V_{MPP} and V_{OC} of the PV array, under varying irradiance and temperature levels, has given rise to the fractional VOC method [38]-[42].

$$V_{MPP} = k_1 V_{OC} \quad (4)$$

where k_1 is a constant of proportionality. Since k_1 is dependent on the characteristics of the PV array being used, it usually has to be computed beforehand by empirically determining V_{MPP} and V_{OC} for the specific PV array at different irradiance and temperature levels. The factor k_1 has been reported to be between 0.71 and 0.78. Once k_1 is known, V_{MPP} can be computed using (4) with V_{OC} measured periodically by momentarily shutting down the power converter.

However, this has some disadvantages, including temporary loss of power [42]. To prevent this, [43] uses pilot cells from which V_{OC} can be obtained. These pilot cells must be carefully chosen to closely represent the characteristics of the PV array. In [40], it is claimed that the voltage generated by pn-junction diodes is approximately 75% of V_{OC}. This eliminates the need for measuring V_{OC} and computing V_{MPP}. Once V_{MPP} has been approximated, a closed-loop control on the array power converter can be used to asymptotically reach this desired voltage. Even if fractional V_{OC} is not a true MPPT technique, it is very easy and cheap to implement as it does not necessarily require DSP or microcontroller control. However, [41] points out that k_1 is no more valid in the presence of partial shading (which causes multiple local maxima) of the PV array and proposes sweeping the PV array voltage to update k_1. This obviously adds to the implementation complexity and incurs more power loss.

3.4. Fractional Short-Circuit Current

This method is based on the fact that the PVs' I_{MPP} and I_{SC} share a near-linear relationship even if the weather conditions are changing [43]. This relationship is defined by the following equation:

$$I_{MPP} = k_2 I_{SC} \quad (5)$$

Where k_2 is a constant that can be adjusted depending on the PV characteristics between 0.78 and 0.92. Measuring I_{SC} during operation is problematic. An additional switch usually has to be added to the power converter to periodically short the PV array so that I_{SC} can be measured using a current sensor. This increases the number of components and cost. In [48], a boost converter is used, where the switch in the converter itself can be used to short the PV array.

Another disadvantage of this method is that is the PV array will never operate at the MPP because (5) is an approximation. In [49], a method was invented to improve the accuracy of the I_{MPP} value by changing the rate of k_1 based on the current atmospheric conditions. To guarantee proper MPPT in the presence of multiple local maxima, [41] periodically sweeps the PV array voltage from open-circuit to short-circuit to update k_2. Most of the PV systems using fractional I_{SC} in the literature use a DSP. In [46], a simple current feedback control loop is used instead.

3.5. Fuzzy Logic Control

Microcontrollers have been made using fuzzy logic control [48]–[52] popular for MPPT over the last decade. This method has the advantage of being able to deal with nonlinear equations and operate with inaccurate inputs. The measurements needed for this method are error (E) and change of error (ΔE). On the other hand, the output is a change of the converter's control signal [52]. Fuzzy logic control generally consists of three stages: fuzzification, rule base table lookup, and defuzzification. During fuzzification, numerical input variables are converted into linguistic variables based on a membership function similar to Fig. 5 [53].

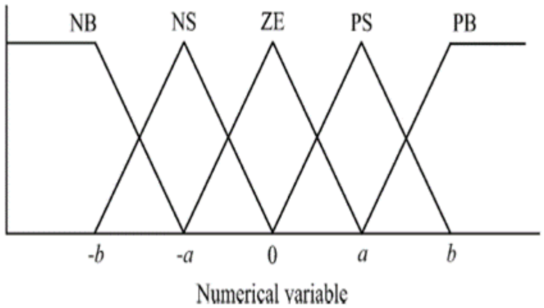

Fig.5 Membership function for inputs and output of fuzzy logic controller [53]

In this case, five fuzzy levels are used: NB (negative big), NS (negative small), ZE (zero), PS (positive small), and PB (positive big). In Fig. 5, *a* and *b* are based on the range of values of the numerical variable. The membership function is sometimes made less symmetric to give more importance to specific fuzzy levels as in [48], [51], and [52].

Based on the fact that at MPP *dp/dv=0*, the following equations have been adapted by [51]:

$$E(n) = \frac{P(n) - P(n-1)}{V(n) - V(n-1)} \tag{6}$$

$$\Delta E(n) = E(n) - E(n-1) \tag{7}$$

where ΔE and E are converted to linguistics variables in the fuzzification stage after calculation. In the second stage, the action required is taken based on a rule table (see Table 2). The controller output is a duty cycle change (ΔD) of the DC-DC converter [49].

The linguistic variables assigned to ΔD for the different combinations of E and ΔE are based on the power converter being used and also on the knowledge of the user. Table (2) is based on a boost converter. In the defuzzification stage, the fuzzy logic controller output is converted from a linguistic variable to a numerical variable still using a membership function as in Fig. 5. This provides an analog signal that will control the power converter to the MPP [53].

One of the main disadvantage of the fuzzy logic model is that successful implementation relies on the amount of knowledge of the expert who sets up the membership function and the rule-base table. In [54], an adaptive fuzzy logic controller was proposed based on a learning mechanism to regularly change the membership function and the rule base table; which showed higher performance than the conventional method. Another improved version adapts two different membership functions that experimentally show better tracking performance [52].

E \ **ΔE**	**NB**	**NS**	**ZE**	**PS**	**PB**
NB	ZE	ZE	NB	NB	NB
NS	ZE	ZE	NS	NS	NS
ZE	NS	ZE	ZE	ZE	PS
PS	PS	PS	PS	ZE	ZE
PB	PB	PB	PB	ZE	ZE

Table 2 Fuzzy Rule Base Table as Shown in [48]

3.6. Neural Network

Neural networks are another type of artificial intelligence MPPT technique which are also well adapted for microcontrollers [54]-[57]. As with a fuzzy logic controller, neural networks consist of three stages or layers: input, output, and hidden layers as shown in fig 6. The user has the flexibility to choose the number of nodes in each stage.

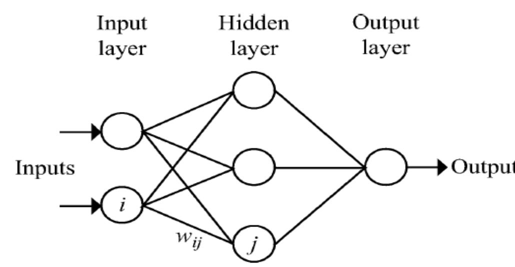

Fig.6 Example of neural network [52]

The input variables can be PV array parameters like V_{OC} and I_{SC}, atmospheric data like irradiance and temperature, or any combination of these. After these inputs are processed in the hidden stage, the output most likely is a duty cycle signal to control the power converter and change the operating voltage to be as close as possible to the MPP [52].

How close the operating point gets to the MPP depends on the algorithms used by the hidden layer and how well the neural network has been trained. This training happens on a long run where all the PV data is recorded continuously over months or even years into the neural network database. The links between the nodes are all weighted. The link between nodes *i* and *j* is labeled as having a weight of *wij* in Fig. 6. These *wij's* are carefully determined through a training process. Each PV array has its unique characteristics, so the neural network controller must be trained for each array separately. Moreover, the weather conditions and age of the PV array are changeable factors that affect the characteristic of the array; therefore, neural networks should be trained regularly to maintain high quality tracking [54], [56], [57].

3.7. Current Sweep

The current sweep [58] technique uses a sweep waveform for the PV array current such that the *I-V* characteristic of the PV array is obtained and updated at a constant time interval. The V_{MPP} can then be computed from the characteristic curve at the same intervals.

The chosen function for the current waveform is proportional to its derivative, as in:

$$i(t) = f(t) = k_3 \frac{df(t)}{dt} \tag{8}$$

Where k_3 is a constant.

The output power of the PV array is:

$$p(t) = v(t) \times i(t) = v(t) \times f(t) \tag{9}$$

At the MPP the derivative of *P* should equal zero:

$$\frac{dp(t)}{dt} = v(t)\frac{df(t)}{dt} + f(t)\frac{dv(t)}{dt} = 0 \tag{10}$$

By putting the value of *f(t)* into equation (10) so:

$$\frac{dp(t)}{dt} = \left(v(t) + k_3 \frac{dv(t)}{dt} \right) \frac{df(t)}{dt} = 0 \tag{11}$$

Assuming the derivative of *f(t)* does not equal zero on the sweep waveform and by dividing equation (11) by *df(t)/dt* so:

$$\frac{dp}{di} = v(t) + k_3 \frac{dv(t)}{dt} \tag{12}$$

the only solution for equation (8) is:

$$f(t) = Ce^{\frac{t}{k_3}} \tag{13}$$

Let *C* be equal to the maximum PV array current I_{max} and k_3 to be negative. The assumption results in a decreasing exponential function with a time constant $\tau=-k3$.Equation (13) leads to:

$$f(t) = I_{max} e^{-\frac{t}{\tau}} \tag{14}$$

The current in (14) can be easily obtained by using some current discharging through a capacitor.

This method cannot track the MPP continuously, but it does so periodically and the interval time can be adjusted as requested. The current sweep takes about 50ms, implying some loss of available power. In [59], it is pointed out that this MPPT technique is only feasible if the power consumption of the tracking unit is lower than the increase in power that it can bring to the entire PV system.

3.8. Ripple Correlation Control (RCC)

When a PV array is connected to a power converter, the switching action of the converter imposes voltage and current ripple on the PV array. That subjects ripple to the generated power of the PV system. In the RCC technique [60], this ripple is utilized by the PV system to perform MPPT. As the ripple is naturally available by using a switching converter, no artificial perturbation is required. RCC correlates *dp/dt* with either *di/dt* or *dv/dt* and hence using the equations below, the value of voltage and current of PV system are recognized whether more or less than that of MPP. The role of RCC is to force this ripple to zero and eventually drag the PV panel voltage and current to that of MPP [61].

$$\frac{dv}{dt} > 0 \; or \; \frac{di}{dt} > 0 \; and \; \frac{dp}{dt} > 0 \Rightarrow V < V_{mpp} \; or \; I < I_{mpp}$$

$$\frac{dv}{dt} > 0 \; or \; \frac{di}{dt} > 0 \; and \; \frac{dp}{dt} < 0 \Rightarrow V > V_{mpp} \; or \; I < I_{mpp}$$

In this technique, the time derivative of the time-varying PV array power $\dot{p}$ is correlated with the time derivative of the time-varying PV array current $\dot{i}$ or voltage $\dot{v}$ to drive the power gradient to zero, thus reaching the MPP [62]. When the power converter is a boost converter as in [61], increasing the duty ratio increases the inductor current, which is the same as the PV array current, but decreases the PV array voltage. Therefore, the duty ratio control input is:

$$d(t) = -k_4 \int \dot{p}\dot{v}\,dt \tag{15}$$

Or

$$d(t) = k_4 \int \dot{p}\dot{i}\,dt \tag{16}$$

Where k_3 is a positive constant [60].

Simple and inexpensive analog circuits can be used to implement RCC. An example is given in [62]. Experiments were performed to show that RCC accurately and quickly tracks the MPP, even under varying irradiance levels. The time taken to converge to the MPP is limited by the switching frequency of the power converter and the gain of the RCC circuit. Another advantage of RCC is that it does not require any prior information about the PV array characteristics, making its adaptation to different PV systems straightforward.

3.9. DC-Link Capacitor Droop Control

DC-link capacitor droop control technique [63] is designed to work with a PV system that is connected in parallel with an AC system line.

The duty ratio of an ideal boost converter is given by:

$$d = 1 - \frac{V}{V_{link}} \tag{17}$$

Where V is the voltage across the PV array and V_{link} is the voltage across the dc link. If V_{link} is kept constant, increasing the current going in the inverter increases the power coming out of the boost converter and consequently increases the power coming out of the PV array. While the current is increasing, the voltage V_{link} can be kept constant as long as the power required by the inverter does not exceed the maximum power available from the PV array. If that is not the case, V_{link} starts drooping. Right before the drooping point, the current control command of the inverter is at its maximum and the PV array operates at the MPP. The ac system line current is fed back to prevent V_{link} from drooping and d is optimized to bring I_{peak} to its maximum, thus achieving MPPT [61].

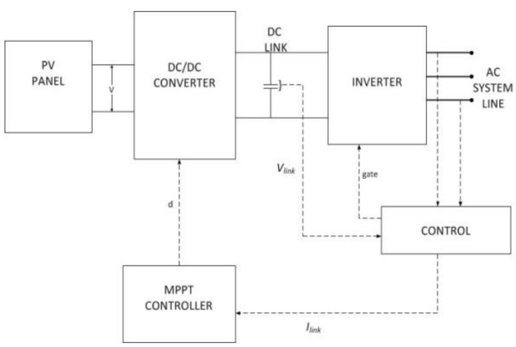

Fig. 7 Block diagram of dc-link capacitor droop technique [61].

3.10. Load Current or Load Voltage Maximization

This MPPT method is based on the fact that maximizing the power at the load maximizes the PV output power [52]. In [64], it is pointed out that most loads can be of voltage source type, current-source type, resistive type, or a combination of these. For a voltage-source type load, the load current i_{out} should be maximized to reach the maximum output power PM. For a current-source type load, the load voltage v_{out} should be maximized. For the other load types, either i_{out} or v_{out} can be used. This is also true for nonlinear load types as long as they do not exhibit negative impedance characteristics [65].Therefore for almost all kind of loads, it is adequate to maximize either the load current or load voltage to maximize the load power. In most PV systems, a battery is used as the main load or as a backup [65]–[67].For the battery as a voltage source, the voltage remains constant and the charging current must be maximized until the PV operates at the MPP. Usually a feedback controller is used with this technique to control the converter and the operation is near the MPP, but never at the MPP [67], [68].

3.11. *dP/dV or dP/dI* Feedback Control

This method benefits from the advantage of the microcontroller and DSP in dealing with complex calculations and provides a way of performing MPPT by computing the slope (dP/dV or dP/dI) of the PV power curve. MPPT can be conducted by feeding the curve back to the converter and applying some control to drive the slope to zero [68], [69]. Different techniques are used for computing the slope In [69], a few cycles are computed and stored; each cycle has a unique sign. Then, the MPP is reached after the controller optimizes the duty ratio depending on these signs ordering the converter to either increase or decrease.

In [70], a linearization-based method is used to compute dP/dV. In [72]–[74], sampling and data conversion are used with subsequent digital division of power and voltage to approximate dP/dV. In [74], the PV array voltage is incremented or decremented periodically and $\Delta P/\Delta V$ is compared to a marginal error until the MPP is reached. The tracking time is around 10 milliseconds [70].

MPPT TECHNIQUE	True MPPT	Regular Adjusting	Tracking Speed	Analog Or Digital	Complexity	Sensed Parameters
Perturb & Observe	Yes	No	Varies	Both	Low	V, I
Incremental Conductance	Yes	No	Varies	Digital	Medium	V, I

Fractional Open Circuit Voltage	No	Yes	Medium	Both	Low	V
Fractional Short Circuit Current	No	Yes	Medium	Both	Medium	I
Fuzzy Logic	Yes	Yes	Fast	Digital	High	Varies
Neural Network	Yes	Yes	Fast	Digital	High	Varies
Current Sweep	Yes	Yes	Slow	Digital	High	V, I
RCC	No	No	Fast	Analog	Low	V, I
Dc Link Capacitor Droop Control	No	Yes	Medium	Both	Low	V
Load I or V Maximization	No	No	Fast	Analog	Low	V, I
dp/dv or dp/dI Feedback Control	No	No	Fast	Digital	Medium	V, I

Table 3 Comparison of MPPT Techniques

4. CONCLUSION

This paper has presented different topologies of power inverter for grid connected photovoltaic systems with advantages and disadvantages attributed to each configuration. In this paper, the state of the art of MPP algorithms have also been reviewed It is shown that there are several other MPPT techniques than those commonly included in literature reviews. The concluding comparison table should serve as a guide in selecting the most suitable MPPT method for specific PV systems.

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Authors

Tamanna Nazeer received the B.Tech degree in Electronics and Communication Engineering from University of Kashmir, Jammu & Kashmir, India in 2014 and M.Tech. degree in Electronics and Communication Engineering from Shri Mata Vaishno Devi University, Jammu & Kashmir, India in 2017. Her research interests are photovoltaics, grid-connected power systems, renewable energy applications, and distributed power systems.

Swastik Gupta received the B.E degree in Electrical Engineering from University of Jammu, Jammu & Kashmir, India in 2007 and M.Tech degree in Electrical Engineering from Indian Institute of Technology (IIT), Kanpur, India in 2009. His research interests are power electronics, PV-Systems, low power networks, embedded systems, virtual instrumentation, and distributed control systems.

Shashi Bhushan Kotwal received the B. Tech degree in Electronics Engineering in 2002 and M. Tech degree in 2005. His research interests include modeling and simulation of systems, signal processing, sensor-networks and microprocessors.