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Conventional Maximum Power Point Tracking Techniques For Solar Photo Voltaic Systems: A Concise Review

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Abstract
Renewable energy systems in general, and particularly the Solar Photo Voltaic Energy Conversion Systems (SPVECS) have received worldwide attention in the recent decades. Among the various investigative thrusts carried out in respect of SPVECS the most recognized area of research is the 'extraction of maximum power from the Solar Photo Voltaic (SPV) system. Research in the direction of Maximum Power Point Tracking (MPPT) for extracting maximum power, for the given environmental conditions is very much appreciated and is a key phenomenon in developing efficient SPV systems. In this paper a review on the various MPPT techniques for SPV systems which have been adopted since the inception of the SPV systems up to the latest soft computing algorithms is presented. To date, there has been no critical analysis carried out on the various techniques of MPPT in terms of (1) Tracking speed, (2) Algorithm complexity, (3) Dynamic tracking under partial shading and (4) Challenges in Hardware implementation. In this work the authors have attempted to compile a categorical and comprehensive review of the various conventional and non intelligent MPPT techniques available, based on the above criteria. Further, it is envisaged that the information presented in this review will be a valuable gathering of information for practicing engineers as well as for new researchers.
Keywords: *Maximum Power Point Tracking, Photovoltaic, Power Electronics, Renewable Energy, Performance Comparisons.*

I. INTRODUCTION

With the modern lifestyles and the fast growth in industries the energy supply and demand chain has been subjected to remarkable strain. In addition, the issues of climate change and the need to diminish carbon footprints have added to the strong thrust for companies and nations to invest in alternate energy sources, particularly the renewable energy (RE) resources. Among the available RE resources, SPV source has emerged as one of the finest green energy resource and seen as a better replacement for conventional energy. The contribution of the energy harvested through the SPV systems had been significant in the past decade in meeting the national as well as international energy demands. In addition, the enhanced scale and eco-friendly nature of solar energy have attracted many researchers to propose scholarly research in this area. Even though numerous potential studies exist in SPVECS the major research areas are (i). Array reconfigurations and parameter evaluation [1-3], (ii). Modeling of solar cell characteristics with different climatic conditions [4-5] (iii) Assessment and estimation of MPPT techniques [6] (iv) PV Efficiency improvement [7-8] and (v). Interfacing with the national power Grid [9-13].

While massive amount of work has been carried out to improve the array configuration and parameter evaluation, equal importance has also been given to improve the power yield efficiency of PV system by improving its maximum power point tracking (MPPT) competence. MPPT is one of the most cost- effective ways to improve the overall PV system efficiency. Also MPPT improves the operating lifetime of the PV system [14]. In the conventional MPPT techniques, the power is calculated at any instant by sensing the voltage and current of the PV array and accordingly the duty cycle of the converter is adjusted to match the maximum power point. Depending upon the environmental conditions the location of the maximum power point (MPP) changes and is not known a priori, but can be located by calculation models or by search algorithms. The purpose or the role of various algorithms is to control the duty cycle (D) of the converter used. This is done in such a manner that the actual load line as seen by the PV array coincides with that of a load at which maximum power in extracted from the panel.

In the last few decades many research work on MPPT for solar PV system have been proposed and the methods developed so far can be broadly classified into (i) conventional techniques and (ii) Soft computing techniques.

The conventional MPPT methods include the Gradient Descent MPPT, Power Feedback MPPT, Curve Fitting based MPPT, Transient based MPPT, Current based MPPT, Voltage based MPPT, Constant voltage Controller MPPT, Ripple correlation MPPT, Sliding Mode MPPT, Incremental Resistance MPPT, Perturb & Observe MPPT, Incremental Conductance MPPT, Beta methodetc.,.

Most of the conventional methods as found in the literature exhibit the shortcomings of being less accurate and are applied to low power applications [15]. Comparative analysis of the two basic types of MPPT namely the Perturb and Observe (P&O) and the Incremental conductance (IC) method are presented in [15]. The P&O and the IC methods perform well for the conditions of uniform irradiance while they fail when irradiance becomes non uniform or the partially shaded condition [15]. The problems of these methods are, they exhibit high steady state oscillation, less convergence and slow tracking speeds in respect of changes in temperature and solar irradiance. This led to the algorithm called 'Improved Perturbs and Observe' or variable step size algorithm which overcomes the drawbacks of conventional P&O and IC algorithms. This algorithm has better efficiency and faster response rather than conventional P&O algorithm.

Table 1: List of MPPT methods

Constant parameter	*Measurement and comparison*	*Trial and Error methods*	*Mathematical calculation*
1. Current based 2. Voltage based 3. Gradient descent 4. PN junction drop voltage tracking technique	1. Lookup table 2. Voltage and current maximization 3. Linear current control method 4. State vector machine	1. PV output senseless control method 2. P&O 3. Three-point weight comparison method 4. On line MPP search algorithm 5. DC link capacitor droop control 6. Array reconfiguration method 7. MPPT with variable inductor	1. Curve fitting 2. Linear oriented co-ordinate method 3. Differential method 4. Slide control Ripple 5. One cycle control Technique 6. Current sweep method 7. Power feedback 8. Incremental resistance 9. Parasitic capacitance 10. Beta method 11. Ripple correlation method 12. Methods by modulation

$$I = n_s \{I_{pv} - I_{o1} [e^{\frac{V+IR_S}{a_1 V_t n_s}} - 1] - I_{o2} [e^{\frac{V+IR_S}{a_2 V_t n_s}} - 1]\} - (\frac{V+IR_S}{R_P}) \quad (3)$$

MODELING OF SOLAR PV

The electrical equivalent circuit or the electrical model of the solar cell shown in figure 1.

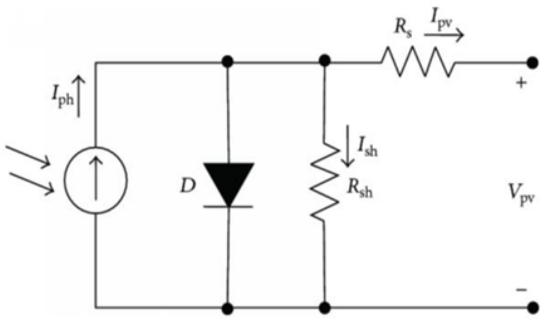

Fig.1: Equivalent circuit of a solar cell

The characteristic equation of the solar PV cell is expressed by,

$$I_{pv} = I_L - I_o (e^{\frac{q(V_{pv}-IR_S)}{AkT}} - 1) - \frac{V - IR_S}{R_{SH}} \quad (1)$$

where I and V are the solar cell output current and voltage respectively, I_o is the saturation current, charge of an electron is taken as q, A is the ideality factor of diode, k is the Boltzmann constant, T – temperature at absolute condition and R_S and R_{SH} are the series and shunt resistances of the solar photo voltaic cell. In an ideal case R_S would be zero and R_{SH} infinite.

A typical PV panel is composed of many solar cells, which are connected in series and parallel so that the output current and voltage of the PV panel are high enough to the requirements of the applications under consideration. The output current-voltage characteristic of a PV panel is expressed by equation (2), where *np* and *ns* are the number of solar cells in parallel and series respectively.

$$I \approx n_p I_L - n_p I_O \left(e^{\frac{q(V-IR_S)}{T n_s}} - 1 \right) \quad (2)$$

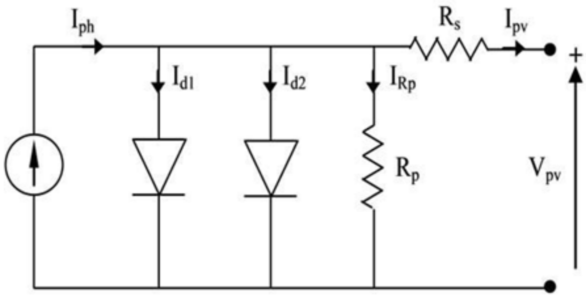

Fig.2: Equivalent circuit Double Diode model of a solar cell

IMPORTANCE FOR MAXIMUM POWER POINT TRACKING

Solar irradiation that hits the photovoltaic modules depends upon the geographical latitude, the orientation of the solar field, the season and hour of the day. During the course of a day, a shadow may be cast on the cell that may be foreseen, as in the case of a building near the solar field or unforeseeable as those created by clouds, birds etc. Also the energy produced by each photovoltaic cell depends on the irradiation and temperature, from these considerations, the necessity to identify instant by instant that particular point on the V-I characteristic of the PV generator in which there is the possibility of the maximum amount of power being transferred to the grid or load. During the course of operation, this MPP keeps shifting its position whenever the climatic or environmental conditions change. Hence MPPT controllers which have become an integral part of the solar PV system are designed to keep tracking MPP. The MPPT at the controller is logically placed in between solar PV panel and the power Electronic converter. The function of this controller is to effectively adjust the resistance as seen by the panel and operates the MPP. Also it alters the duty cycle of the DC-DC converters so as to to match output voltage of the PV generator with the battery voltage There are a number of DC-DC converters like the buck converter, the boost converter, buck- boost converter, fly back converter and the Z source DC-DC converter. Fig. 3 shows the basic block diagram of a DC-DC converter interfacing the solar PV panel with the load controlled by an MPPT controller [16].

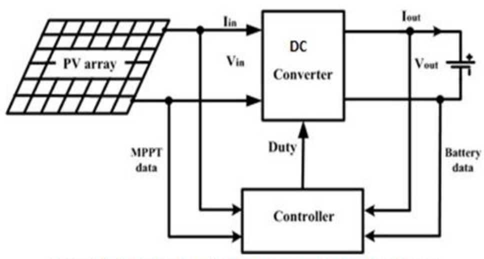

Fig.3: DC-DC converter with MPPT controller

CONSTANT PARAMETER

1) Gradient Descent

This method is useful to find the adjacent local MPP by calculating the gradient of the function. According to this principle, the maximum or the minimum points of the function occurs at some critical point. The local MPP can be constantly

tracked and updated to satisfy a mathematical equation: $\frac{dP}{dv} = 0$.

Using this method, the MPP is calculated using the function

$$v(t+1) = v(t) - \frac{dp/dv}{k_s} \quad (4)$$

Where, k_s is step-size corrector and decides the steepness of each step in the gradient direction. dp/dv is the deviation parameter and is calculated by using, $\frac{dp}{dv} = f(v(t), p(t))$

$$f(v(t), p(t)) = \frac{p(t+1) - p(t-1)}{2\Delta V} + O(\Delta V)^3 \quad (5)$$

Where, $(\Delta V)^3$ of second order accuracy and the local

truncation error for the centered differentiation.
In [17] the authors have proposed the Gradient Descent MPPT method using variable step sizes for faster and more precise tracking process and proved that this MPPT method is better in performance than the traditional strategies. A simple MPPT control structure is explained in [17] and proved with better efficacy. In order to achieve the maximum power output, the steepest descent optimization method which finds optimal value of step size is determined [17].

2 Voltage based MPPT Constant Voltage (CV)

The Constant Voltage technique is a simple MPP technique in which a constant reference voltage V_{ref} is considered adequate for the approximation of the true MPP for the given solar insolation and temperature.

In some other cases, this value is programmed by an external resistor connected to a current source pin of the control IC. For the CV method, therefore, the operating point is never exactly at the MPP and different data have to be adopted for different geographical regions. The CV method does not require any input. The CV technique works best at low irradiance levels, and so it is often combined together with other MPPT techniques.

Open Circuit Voltage (OCV) Method

It is the simplest offline method to control the MPPT where the ratio between MPP voltage to open circuit voltage is approximately constant whose value depends on temperature.

$V_{MPP} \approx kV_{OC}$. Where k is the constant which can be varied from 0.71 to 0.78. The figure. 4 explaining the method to calculate the V_{MPP} .

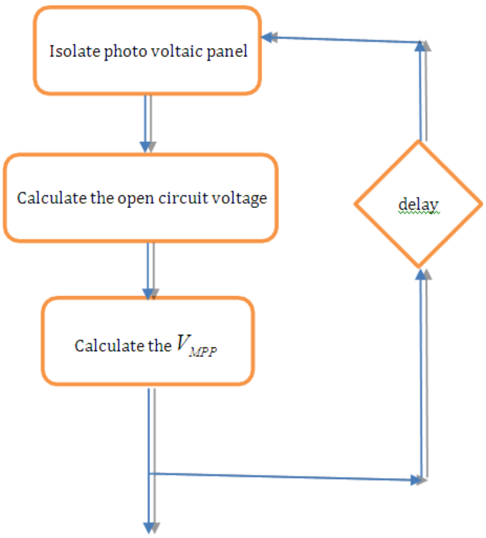

Fig. 4: Flow diagram of voltage based MPP method

However, this method has some disadvantages, like the MPP may not be tracked accurately leading to temporary loss of power. In order to prevent this power loss, pilot cells have been proposed to calculate V_{OC} . However, useful power is not produced by pilot cell because it is isolated from the PV panel. During open- circuit voltage measurements,To minimize the power loss the pilot cell is replaced by a semi-pilot cell. In addition, to overcome the power losses a more straightforward but approximate approach is proposed which involves measurement of the temperature and irradiance and estimation of the V_{OC} based on model governing equations.

3. Current based MPPT

Short Circuit Current Method (SCC)

Constant current method where the ratio between current at MPP and short circuit is maintained as constant which can be

expressed as $I_{MPP} = kI_{SC}$ where k is constant value

ranging between 0.8 to 0.9. To calculate I_{SC} the load should be shed in order to get more accurate results but the implementation cost is higher than OCV method. The short- circuit current needed for MPPT is provided by the switch in the boost converter itself. The flow chart of SCC shown in Figure 5.

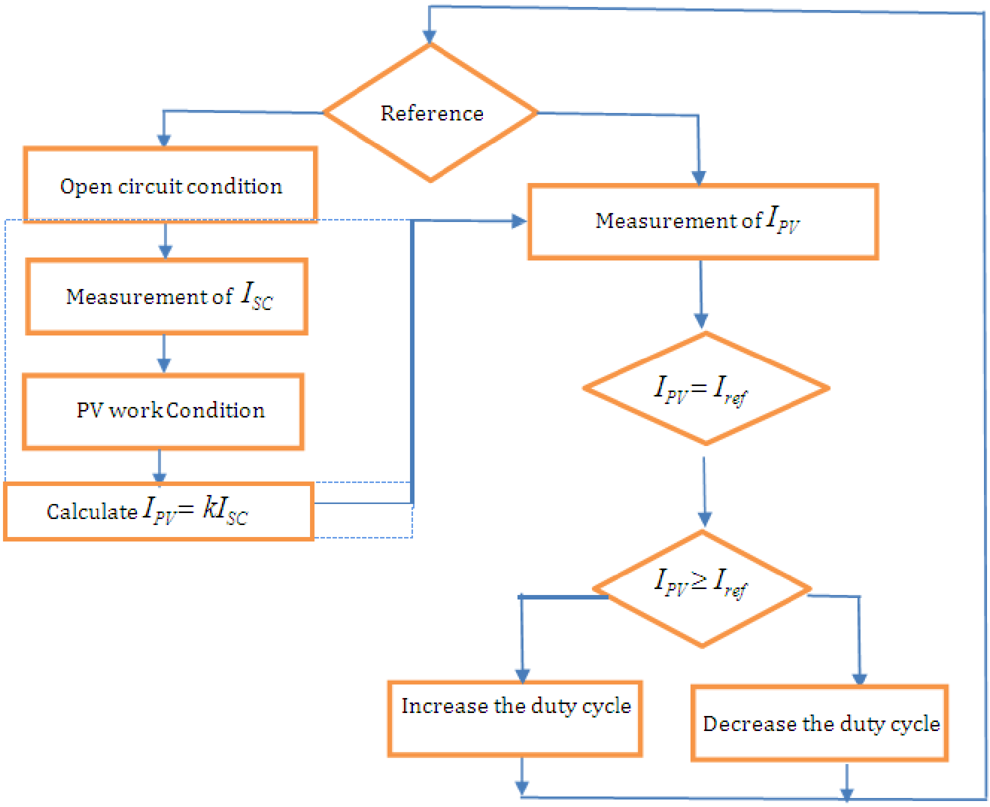

Fig.5: Flow Chart of SCC Method

Current Compensation Method

In this method a continuously changed reference current is produced by the voltage control loop and is considered for each switching cycle and this method shows up considerably less error in power harvest. To compensate the continuously changing current reference an Integrator is used in the current controller which is reset during each switching cycle.

Pilot Cell

A small solar cell known as the pilot cell having the same property of larger solar array is chosen for short circuit current or open circuit voltage measurement but this method the problem of a lack of a constant "K" value is still present. Again there was a logistical drawback of how best the pilot cell characteristics is mapping with larger solar array. Moreover, careful attention is needed to choose the pilot cell that closely represents the characteristics of the operational PV array.

However the SCC and OCV methods fails when the load interruption occurs while measuring the I_{SC} and V_{OC}. Also these methods cannot be considered as seeking the true MPP.

4. PN Junction Drop Voltage Tracking Technique

It is a simple and inexpensive but effective operating point tracker, in which, to track the excellent operating forward voltage drop of the p-n junction diodes is used as a reference voltage to track the excellent operating voltage. The detection error voltage of the proposed excellent operating tracker of the solar array is within 2.5%, and the detection error power is estimated to be negligibly small. This method is considered as a non-accurate method of MPP tracking since it considers only the temperature and neglects irradiance.

Table 2: Summary of MPPT based on Constant parameter

Tracking methods	*Cost*	*A/D*	*Sensors*	*Complexity*	*Accuracy*	*Speed*
Current based	*Cheap*	*A/D*	*I*	*Less*	*Medium*	*Medium*
Voltage based	*Cheap*	*A/D*	*V*	*Less*	*Medium*	*Medium*
Gradient decent	*Cheap*	*A*	*V*	*Medium*	*Medium*	*Less*
PN junction voltage drop	*Cheap*	*A*	*V*	*Medium*	*Medium*	*Fast*

Table 2: (Continued) Summary of MPPT based on Constant parameter

Tracking methods	*Application*	*Merits*	*Demerits*
Current based	*Stand-alone*	*Simple and Cheap*	*Requires periodic tuning*
Voltage based	*Stand-alone*	*Simple and Cheap*	*Requires periodic tuning*
Gradient descent	*Stand-alone*	*Suitable for fast changing environmental condition*	*Need higher sampling rate for accurate tracking*
PN junction voltage drop	*Grid Connected*	*Cheap and Fast convergence*	*Requires Tuning*

MPPT TECHNIQUE WITH MEASUREMENT AND COMPARISON

1)Lookup Table Method

The maximum power point voltages for various insolation levels are obtained from the experimental setup and are fed to the look up table [86]. From the look up table reference voltage for various insolation conditions is taken without many computations. The time taken for simulation is less than the conventional model, especially when interfaced with the power conditioning systems. Since force biasing is required for tracking very fast tracking is achieved. A three dimensional numerical array is required for each possible value of voltage, current and temperature hence number of sensors required also increases. This method does not render the exact maximum power point tracking but tracking is almost very close to the exact MPP.

2)Voltage and Current Maximization

The task of maximizing the power output of a PV panel is manipulated with the assumption that the power losses incurred in the power electronic converter is minimum. In case of voltage source, the load current IL should be maximized to reach the maximum output power similarly in a current source the voltage across the load should be maximized so that the power delivered is maximum. Therefore, in such cases only a single sensor is sufficient [89]. Therefore, the necessary and sufficient conditions are that for a voltage source the current should be maximized and for a current source the voltage across the load should be maximum. In most PV system, the battery is used as a voltage sink to maximize the load current which in turn make the PV module to operate close to the MPP.

3) Linear Current Control Method

In this method set of two algebraic equations is solved and the solution of intersecting points of two curves on the phase plane is used to track the MPP [18]. This is one of the easily implemented and instantaneously applied methods. The simplified P-V characteristics of a PV module is given by,

$$f(P_{Pv}, I_{pv}) = P_{pv} - \frac{1}{k} I \ln\left(\frac{I^2_{pv}/_{\kappa}}{(P_{Pv}-I^2_{pv}R_S)}\right) - I^2_{pv} R_s = 0 \tag{6}$$

This equation (6) can be approximated by a linear ramp as shown in fig.6.

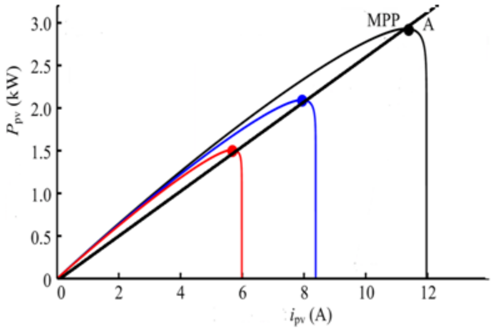

Fig.6: MPP location using Linear approximation method

4) State Vector Machine

State Vector Machine method is one of the robust and reliable which is insensitive to changes in system parameters by which MPPT is achieved even at changing atmospheric conditions. To track the MPP, state space vector model used to represent the PV in which dynamic non-linear controller is employed [19].

Table 3: Summary of MPPT based on Measurement and Comparison

Tracking methods	***Cost***	***A/ D***	***Sensors***	***Complexity***	***Accuracy***	***Speed***
Lookup table	*Cheap*	*D*	*I&T*	*Less*	*Less*	*Fast*
Voltage and current maximization	*Cheap*	*D*	*V*	*Less*	*Medium*	*Fast*
Linear current control method	*Cheap*	*D*	*I*	*Less*	*Medium*	*Fast*
State vector machine	*Expensive*	*A/ D*	*V&I*	*High*	*Medium*	*Fast*

Table 3: (Continued) Summary of MPPT based on Measurement and Comparison

Tracking methods	***Application***	***Merits***	***Demerits***
Lookup table	*State-alone*	*Offline method of fast tracking.*	*More sensors are involved hence less speed. Not a accurate method of tracking.*
Voltage and current maximization	*State-alone*	*Involves only one sensor. Convergence time is less with fewer oscillations*	*Costly method.*
Linear current control method	*State-alone*	*Very Lesser error*	*No experimental validation available.*
State vector machine	*Both*	*Robust and less sensitive with parameter variations.*	*No experimental validation available.*

MATHEMATICAL CALCULATION

1) Curve Fitting Method

To predict the PV curve of the SPV generator, a mathematical equation derived from two diode model of the PV panel [20] as represented by $P = aV_{pv}^3 + bV_{pv}^2 + cV + d$ where a, b, c and d are the coefficients determined by the sampling of PV Power, Voltage and Current at desired level. The power harvested becomes maximum when

$$V_{MPP} = \frac{-b\sqrt{b^2 - 3ac}}{3a} \quad (7)$$

However, this third order model of the PV generator may not be accurate, and going for the fourth order [21]

$$P = P_1V_{pv}^4 + P_2V_{pv}^3 + P_3V_{pv}^2 + P_4V_{pv} + P_5 \quad (8)$$

The calculation process should be repeated at a fast rate to get a higher tracking accuracy, But the control system requires a processor with faster calculation of mathematical equations.

2) Linear Oriented Co-ordinate Method

A non-traditional methodology which solves the MPP equation of the PV array iteratively, known as the linear reoriented co-ordinate method (LRCM) has been promoted by some authors. To find the solution of MPP equation, it requires a measurement of V_{oc} and I_{sc} and other parameters of PV panel. The maximum error in using LRCM algorithm approximates to 0.2% [22] but this result has been obtained by simulations and the proposed idea has not been validated with experimental results.

3) Differential Method

The MPP is based on the following equation

$$\frac{dP}{dt} = \frac{d(VI)}{dt} = V\frac{dI}{dt} + I\frac{dV}{dt} = 0 \quad (9)$$

To solve this equation requires eight steps,

S1. Measure the PV array voltage V
S2. Measure the PV array current I
S3. Measure change in voltage dV with respect to time.
S4. Measure change in voltage dI with respect to time.
S5. Calculate the product $V\frac{dI}{dt}$
S6. Calculate the product $I\frac{dV}{dt}$
S7. Sum the results of S5 and S6.
S8. Compare the result of S7 to zero to track the MPP.

However, this technique requires a powerful digital signal processor to solve above equations.

4) Sliding Mode Control

Due to the non-linear characteristics of PV cells, MPPT algorithm is adopted to maximize the output power with respect to voltage. In the Sliding Mode Controller (SMC) based MPPT technique a sliding surface is used to generate the pulses to the power switching device of the DC-DC converter.

Basically this technique uses maximum power

$$D = \frac{dP_{PV}}{dV_{PV}} = \frac{d(V_{PV}I_{PV})}{dV_{PV}} = I_{PV} + V_{PV}\frac{d(V_{PV})}{dV_{PV}} \quad (10)$$

Based on the slope of a V array curve the switch control signal D is generated and denoted as $\begin{cases} 1 \; for D < 0 \\ 0 \; for D > 0 \end{cases}$

6) Current Sweep Method

In this type of MPPT, the PV curves are automatically updated on the sweep waveform generated from the V-I characteristics curve at regular interval of time. The function of sweep current

$$i(t) = f(t) \quad (12)$$

Power of the panel

$$p(t) = v(t)i(t) = v(t)f(t) \quad (13)$$

At MPP $$\frac{dp(t)}{dt} = v(t)\frac{df(t)}{dt} + f(t)\frac{dv(t)}{dt} = 0 \quad (14)$$

This method is not suitable for practical implementation of tracking the MPP because of the need of complex data processing systems required.

7) Power Feedback

In this technique power variation is considered, in similarity with constant voltage and constant current techniques where voltage or current variations are considered. Here a slope of PV curve is calculated with respect to voltage or current and fed back to the converter and with the intention of making pushing it to zero [24]. As found in the literature this method has been implemented with a digital control system built around the digital microcontroller, Signal Processors etc. According to the sign of $\frac{dP}{dV}$ an incremental duty size is calculated which converge with speed. This method has not gained popularity due to the complexities involved in the real time implementation.

Typically, the Newton-Raphson algorithm $\frac{\Delta P}{\Delta V}$ is calculated and implemented using TMS320F2812 which provides quick and smooth response also less power loss than the P&O method.

8) Incremental resistance

An improved variable step-size algorithm has been implemented in [106] according to the slope of the Power Vs Duty cycle (P-D) curve

$$D(k) = D(k-1) \pm N\left|\frac{\Delta P}{\Delta D}\right| \quad (15)$$

Where N is a Scaling factor [106] and ΔD is the step variation of the duty cycle in the previous sampling period. To ensure the convergence of the MPPT rule, the variable step rule

According to [23] this method is fast but suffers from unstable switching frequency of switching components. In later stage, a fast current based MPPT techniques was proposed [23] and not mentioned about the THD of current.

5) One Cycle Control Technique

This is a nonlinear approach of MPPT. The proposed system has been demonstrated with a single stage photo voltaic inverter. The output power of inverter [23]

$$D = V_o I_o = \frac{V_o^2}{R_S}\left(C - \frac{V_m}{V_c}\right) \qquad (11)$$

C- Constant which is bounded to a value of output current, V_o grid AC voltage, V_c voltage across the capacitor, V_m constant across each line voltage

must meet inequality as $N\left|\frac{dP}{dV}\right| \leq \Delta D_{max}$ [25]. However, for highly varying irradiance nature the scaling factor is also needed to be changed and the dynamic change in scaling factor and its boundary values are evaluated using linear control theory. With the change in scaling factor the power linearization is also varied. This has been evaluated for a scaling factor of 0.38. Also in the small signal model of PV array to ensure the dynamic response and improved steady state performance, without any oscillations, an appropriate value of the scaling factor (N) is designed [26].

9) Parasitic Capacitance

This method is similar to INC method, for which the parasitic capacitance of the PV cells (used in charge storage in the p-n junction of the PV cell) is included for MPP Analysis.

$$I = F(V_P) + C_P \frac{dV_P}{dt} \qquad (16)$$

From equation (16) current have two components, one is a function of voltage and the other is function of current due to the parasitic capacitance. By multiplying Equation by the array voltage V_P to obtain array power and differentiating the result, the equation for the array power at the MPP is obtained

$$\frac{dF(V_P)}{dV_P} + C\left(\frac{\dot{V}}{V} - \frac{\ddot{V}}{\dot{V}}\right) + \frac{F(V)}{V_P} = 0 \qquad (17)$$

The Equation (17) represents the instantaneous conductance, the incremental conductance, and the induced ripple from the parasitic capacitance respectively.

10) Beta Method

By choosing an intermediate variable on the PV curve the point of maximum power is approximately chosen

$$\beta_{actual} = \ln\left(\frac{I_{pv}}{V_{pv}}\right) - CV_{pv} \qquad (18)$$

Where $C = \frac{q}{\eta K T N_s}$ is a diode constant. β_{actual} is calculated from the actual values of voltage and current of PV panel at any time. If this β_{actual} is within the specified range between β_{min} and β_{Max} then beta method turn into the next stage by calculating the new value of duty cycle D using P&O method. If this β_{actual} is not in specified range then new value of ΔD is manipulated using the $\Delta D = N(\beta_{actual} - \beta^*)$ where β^* is the β value calculated under STC as figure 7&8. N is the scaling factor. However this N is suitable for specific operating conditions only. Hence modified Beta is calculate the N value for the changes of β value during changes of irradiance and temperature. Two different values of scaling factors N_1 and N_2 are used (corresponding to β_{max} and β_{min}) to generate the variable step size ΔD

$$\Delta D = N_1(\beta_{actual} - \beta^*) \; for \; \beta_{actual} > \beta_{max}$$

$$\Delta D = N_2(\beta_{actual} - \beta^*) \; for \; \beta_{actual} < \beta_{max} \qquad (19)$$

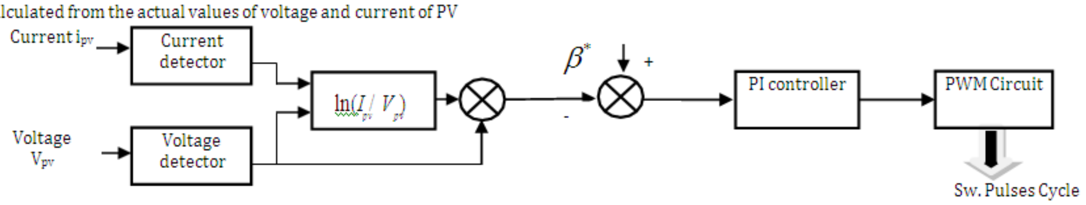

Figure 7: Generation of Duty cycle using Beta method

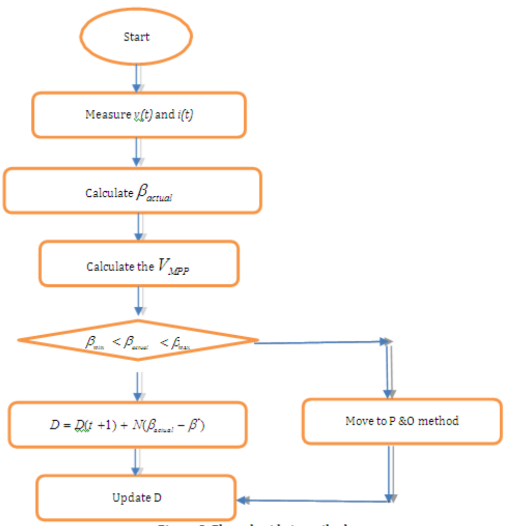

Figure 8: Flow chart beta method

6.11) Ripple Correlation Method

The Ripple Correlation Control (RCC) technique of MPPT results in fast and parameter insensitive MPPT of PV system [27] and further, this technique does not require any prior information about the PV array characteristics. Whenever a PV array is connected to a power converter, voltage and current ripples are produced

In this method, correlation of the derivative of power with respect to time & the derivative of voltage or current with respect to time is taken into account in order to drive the power gradient to zero.

$$\frac{dv}{dt} > 0 \text{ or } \frac{di}{dt} > 0 \text{ and } \frac{dP}{dt} > 0 \Rightarrow V < V_{MPP} \text{ or } I < I_{MPP} \quad (20)$$

$$\frac{dv}{dt} > 0 \text{ or } \frac{di}{dt} > 0 \text{ and } \frac{dP}{dt} < 0 \Rightarrow V > V_{MPP} \text{ or } I > I_{MPP} \quad (21)$$

The time taken to converge towards MPP is limited by the switching frequency of the power converter and the gain of the RCC circuit.

6.12) Methods by Modulation (Forced Oscillation Technique)

In this method of modulation, a small amount of voltage is added with operating voltage of PV array which results as a ripple power. The phase and amplitude of this power depends on the relative location of the operating point from the MPP. When the oscillation occurs on the left side of the MPP (region "X") (Fig. 9), the ripple voltage and the ripple power will be perfectly in phase, else it is 180° out of phase (region "Y"), the ripples of the voltage and power will be out of phase. The amplitude of the power ripple signal shrinks as the operating point gets closer to the MPP. Therefore, the analysis of the phase and the amplitude provides clear information on the location of the MPP. However, this method suffers from the complexity and the difficulty of implementation as well the analysis of the low voltage output signal.

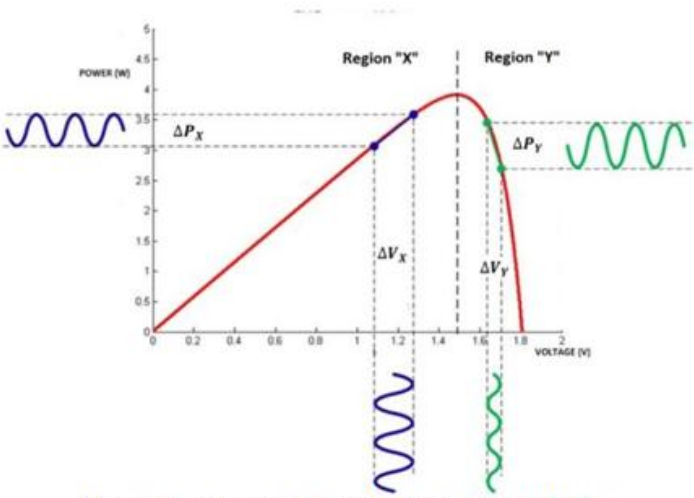

Figure 9: Power in ripple due to modulation

Table 4: Summary of MPPT based on Measurement and Comparison

Tracking methods	***Cost***	***A/D***	***Sensors***	***Complexity***	***Accuracy***	***Speed***
Curve fitting	*Cheap*	*D*	*V&I*	*Low*	*Low*	*Medium*
Linear oriented co-ordinate method	*Expensive*	*A/D*	*V &I*	*High*	*Low*	*Medium*
Differential method	*Expensive*	*A*	*V &I*	*Medium*	*Medium*	*Medium*
Slide control Ripple	*Expensive*	*D*	*V &I*	*High*	*High*	*Fast*
One cycle control Technique	*Cheap*	*A*	*V*	*Medium*	*Medium*	*Fast*
Current sweep method	*Expensive*	*A*	*V&I*	*High*	*Low*	*Low*
Power feedback	*Expensive*	*D*	*V&I*	*Medium*	*Medium*	*Fast*
Incremental resistance	*Cheap*	*D*	*V&I*	*High*	*Medium*	*Low*
Parasitic capacitance	*Expensive*	*D*	*V &I*	*Medium*	*High*	*High*
Beta method	*Expensive*	*D*	*V &I*	*Medium*	*High*	*Fast*
Ripple correlation method	*Expensive*	*D*	*V &I*	*Low*	*Medium*	*Fast*
Methods by modulation	*Expensive*	*A*	*V*	*High*	*Low*	*Slow*

Table 4: (Continued) Summary of MPPT based on Measurement and Comparison

Tracking methods	*Application*	*Merits*	*Demerits*
Curve fitting	*Stand alone*	*Simple method*	*Speed less, requires large memory, need mathematical calculation.*
Linear oriented co-ordinate method	*Grid Connected*	*Reduced Oscillation Robust*	*Speed less, high complex.*
Differential method	*Stand alone*	*Suitable for fast changing environmental conditions*	*Differentiation process under low levels of insulation results unsatisfactory*
Slide control Ripple	*Both*	*High precision, stable,Simple and robust*	*Slow transient response*
One cycle control Technique	*Both*	*Cheap and Fast converge speed.*	*Complex*
Current sweep method	*Grid Connected*	***This method is very much helpful when defective** module, Partial shadow, low irradiance etc.*	***Requires accurate knowledge and large memory** capacity for calculation of mathematical formulations.*
Power feedback	*Stand alone*	*Suitable for fast changing environments*	*Requires higher sampling rate for accurate tracking.*
Incremental resistance	*Both*	*High Efficiency, Faster Convergence rate*	*Implementation cost high*
Parasitic capacitance	*Stand alone*	*Reduced Oscillation Robust*	*Decrease in operating speed Increased complexity*
Beta method	*Both*	*Faster convergence rate during the atmospheric conditions*	*Implementation cost high*
Ripple correlation method	*Stand alone*	*Less expensive and Digital implementation*	*Larger inductor is needed to reduce the ripples*
Methods by modulation	*Stand alone*	***Very simple and** cheap*	***Requires** periodic tuning.*

TRIAL AND ERROR METHODS

1) PV output Senseless (or Sensor Less) Control Method

It is a simple maximum power tracking system as shown in figure 10, which is tracking the power by considering the current drawn from the PV or the current supplied to the converter by considering PWM signals. This technique is applied to huge power generating systems. The maximum current across constant voltage is approximately proportional to the maximum power [28].In this method load power is proportional to source power by changing the duty cycle. When the duty cycle is increased it causes the load current also to increase and this decreases the PV output voltage.

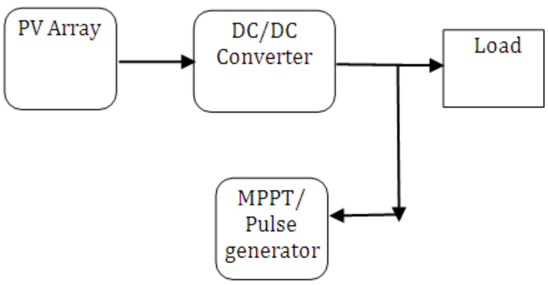

Figure 10: PV power output senseless control

2) P&O/ Hill Climbing Methods

The commonly used MPPT technique follows the Perturb-and-Observe (P&O) algorithm. The Hill Climbing (HC) algorithm and the P&O algorithm both have used nearly the same logic and can be said to be two different means of envisaging the same method. In this process a perturbation in the duty ratio of the power converter is involved, whereas P&O involves a perturbation in the operating voltage of the PV array. Since a power converter is generally used with a PV array, so perturbing its duty ratio will automatically perturb the working voltage and thus both the methods are almost same.

Where $$P(n) = V(n)I(n)$$

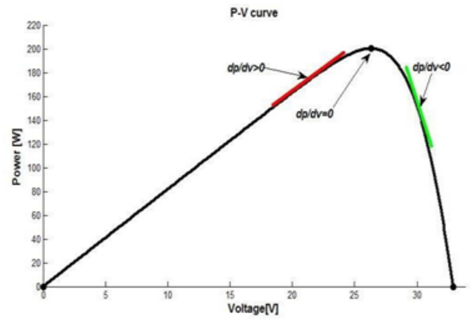

Figure 11: P-V characteristic of a PV module

In Figure 11, if the operating voltage of the PV array is perturbed in a given direction and $\frac{dP}{dV} > 0$, it is known that the perturbation moved the array's operating point toward the MPP. The P&O algorithm would then continue to perturb the PV array voltage in the same direction.

If $\frac{dP}{dV} < 0$, then the change in operating point moved the PV array away from the MPP, and the P&O algorithm reverses the direction of the perturbation. This algorithm is summarized in Table.1. The process is periodically repeated until the MPP is reached. A simple P&O algorithm as a flow chart is is shown in Fig.12.

Table 5: Summarized algorithm of P&O

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

According to the structure of the Hill Climbing or the P and O MPPT systems, the required parameters are only the voltage and current of PV array. Figure 11 shows the relationship between the terminal voltage and output power generated by a PV module. It can be experienced that in spite of the magnitude of suns irradiance and terminal voltage of PV modules, the MPP is obtained while the condition $\frac{dP}{dV} = 0$ is accomplished. The slope $\frac{dP}{dV}$ of the power curve can be forced to be zero by the successive output voltages and output currents, and can be expressed as follows,

$$\frac{dP(n)}{dV} = \frac{P(n) - P(n-1)}{V(n) - V(n-1)} \quad (22)$$

The advantage of the P&O method is that it is easy to implement. However, it has some restrictions, like oscillations around the MPP in steady state operation, slow response speed, and even tracking in wrong way under rapidly changing atmospheric conditions. The system oscillates around the MPP, which causes power loss. The oscillation can be minimized by decreasing the size of the perturbation. However, a too small perturbation considerably slows the tracking of the MPP. Then there is a compromise between accuracy and speed.

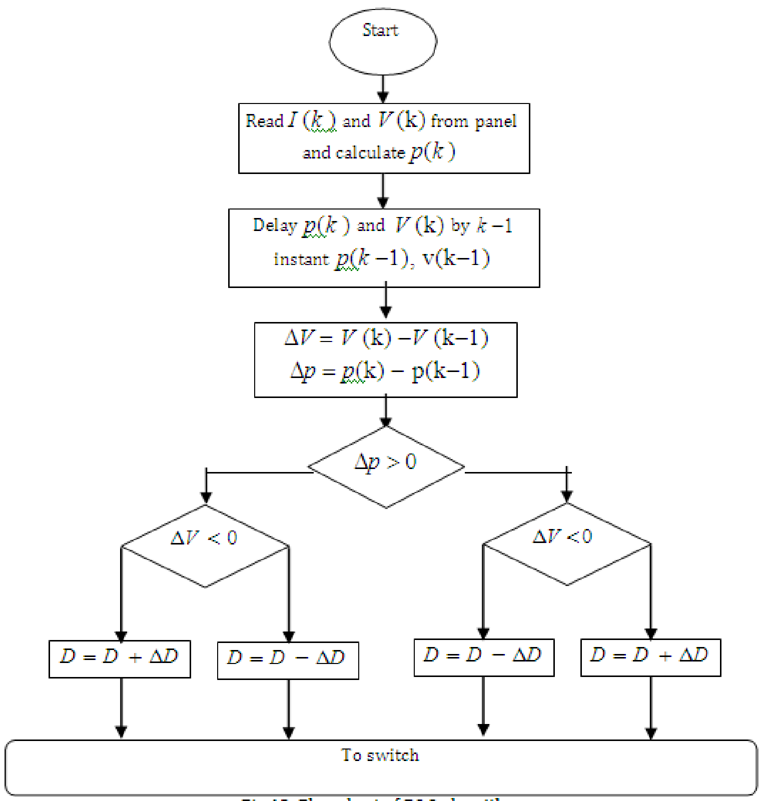

Fig.12: Flowchart of P&O algorithm

3) Incremental Conductance Algorithm

Incremental Conductance (INC) method utilizes the ratio of incremental conductance to instantaneous conductance value of the PV module. Based on this value, the slope of P-V characteristics is altered. In reference to the change in slope, duty cycle for converter is generated. The algorithm is derived by equating rate of change of power with respect to voltage to zero. $dp/dv = 0$ and rearranging it $\frac{-i}{V} = \frac{di}{dv}$

Where $\frac{-i}{V}$ is instantaneous conductance and $\frac{di}{dv}$ is incremental conductance, these two quantities must be equal in magnitude, but opposite in sign. The MPPT applying INC algorithm follow three steps.

Table 6: Incremental Conductance Algorithm Comparison

Case	*Condition*	*Decision*
$\frac{dp}{dv} = 0$	*Zero*	*MPP is achieved*
$\frac{dp}{dv} > 0$	Positive	MPP is dragged towards left side of the curve
$\frac{dp}{dv} < 0$	Negative	MPP is dragged towards right side of the curve

To reduce the tracking error in this method many ideas are proposed. An improved incremental conductance with variable step size is proposed in [29]. As like P &O method this technique employs a trade-off between the step size and the time between algorithm iteration, for faster tracking with accuracy [29].

4) Three-point Weight Comparison Method

This method reduces the oscillation problem caused by P& O algorithm which compares the two points *viz.* previous and present point. This algorithm is based on comparison between voltage and power of PV array. The algorithm of this method is explained in figure 13. [28]

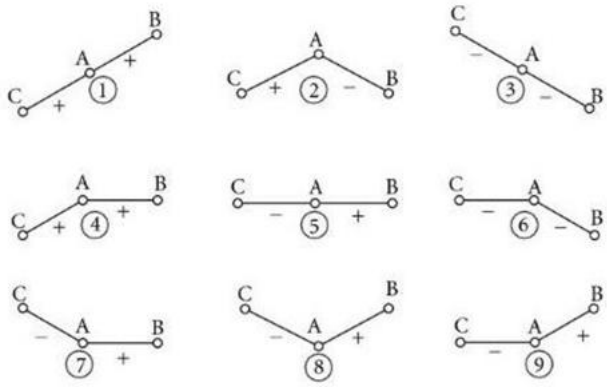

Figure 13: Nine possible cases for power variation for the three-point weight comparison algorithm

Different situation may

Case		*Decision*
$B \geq A$ $C < A$	*or*	*Positive*
$B < A$ $C \geq A$	*or*	Negative

5) On line MPP Search Algorithm

The main objective of online MPP algorithm is to determine the maximum power which is taken as reference value and compare reference value with obtained power. The difference between maximum and existing power is taken as error. The PV module is operating at MPP when there is zero error.

Online MPP algorithm is dependant of load operating power. If the load current is very small, then this algorithm cannot be used to determine the MPP, but additional load can be connected to the PV module current which will make the PV module to operate at MPP.

6) DC Link Capacitor Droop Control

Dc link capacitor droop control is one of the MPPT techniques which is exclusively designed for the PV system that is connected in cascade with an ac inverter. Usually the boost converter is connected between the inverter and PV output for better results. Here the MPPT technique is controlled by the voltage drop across dc link capacitor. The relation between the output voltage and the duty cycle of boost converter is given by

$$= 1 - \frac{in}{V_{out}} \qquad (23)$$

Initially, assume that the dc link capacitor voltage is constant, the increase in inverter current leads to increase in output power of boost converter and consequently the output from the PV module. The dc link capacitor voltage is maintained constant until the maximum power is obtained from PV module. Once the PV Module exceeds its maximum power, then the dc link capacitor voltage starts decreasing. To prevent the sag in voltage, drop across dc link capacitor, the ac line current is given as feedback and duty cycle is optimized for maximum output.

7) Array Reconfiguration Method

Array reconfiguration is an MPPT technique in which PV arrays are arranged in series and parallel combination to fulfill the load requirement. Due to time constraints, the array reconfiguration method is not preferred in real time [28]. In array reconfiguration method; the solar array is divided into primary and secondary module. The primary module is a basic one and the secondary consists of sub modules. The PV modules can be arranged in following ways,

1. Series
2. Parallel
3. Series-Parallel Combo

8) MPPT with Variable Inductor

In MPPT with variable inductor technique a buck converter is interfaced with PV system and the load. We know that the buck converter consists of an LC filter with the switching component connected in series. The inductor with minimum value plays a vital role in this technique [28-31]. The minimum value of inductor which ensures a continuous conduction mode is related with PV current using mathematical model to obtain MPPT. The minimum value of inductance is given by;

$$L_m = \frac{(1-D)}{2f} \qquad (24)$$

Where X_L is the load impedance, D is the duty cycle of PWM input of converter and f is the switching frequency.

Table: 7: Summary of MPPT based on Measurement and Comparison

Tracking methods	**Cost**	**A/D**	**Sensors**	**Complexity**	**Accuracy**	**Speed**
PV output senseless control	Less	D	Current	less	Less	Slow
Perturb &Observe	Expensive	A/D	V&I	less	Less	Medium
Incremental Conductance	Expensive	D	V&I	Medium	Medium	Medium
Three-point weight comparison	Less	D	V&I	High	Less	Fast
On line MPP search algorithm	Less	D	V	High	High	Fast
Dc link capacitor droop control	Expensive	D	V&I	Less	Medium	Medium
Array reconfiguration method	Less	D	V&I	High	Less	slow
MPPT with variable inductor	Expensive	D	V&I	Medium	Less	Medium

Table 7.1: Summary of MPPT based on Measurement and Comparison

Tracking methods	***Application***	***Merits***	***Demerits***
PV output senseless control	*Grid connected*	*More flexible higher rate of convergence.*	*Slow transient Response.*
Perturb &Observe	*Stand-alone*	*High efficiency, Simple and Robust. Widely used MPP for both standalone and Grid connected systems.*	*Not able to track under rapidly changing environment,*
Incremental Conductance	*Stand-alone*	*Attains MPP accurately. It can track even under rapidly changing environment.*	*Costlier than P&O. Instability due to the use of derivative algorithm.*
Three-point weight comparison	*Both*	*Reduced Oscillations Robust and Faster convergence.*	*Decrease in operating speed and Increased complexity.*
On line MPP search algorithm	*Stand-alone*	*Simple design and cheap hardware required. Fast convergence rate.*	*It is failed when the array required power is less than the array reference power.*
DC link capacitor droop control	*Grid Connected*	*Can be easily implemented with analog operational amplifiers and decision*	*Its response superior than*
Array reconfiguration method	*Both*	*Costlier than P &O.*	*Complexity to control.*
MPPT with variable inductor	*Stand-alone*	*Additions of variable inductor to the circuits increase range of continuous conduction mode.*	*Requires periodic tuning.*

III. ANALYSIS AND DISCUSSIONS

In this work different conventional MPP techniques have been discussed under three categories by considering the factors like tracking precision, the tracking speed, the compound cost, and the implementation complexity. In this review, we have presented each method by mentioning the limitations and the drawbacks of a complete tracking system, including speed, Cost, Precision, Complexity etc,. Based on tracking methods the entire conventional tracking techniques are classified into Four groups [Table 1]. Since P &O algorithm give a suitable solution for manufactures and end user, a detailed literature review was conducted on P & O method as it is the mostly used MPPT. The INC algorithms are equally important as compared to the P & O method since the INC shows a better performance towards oscillation around the MPP. A concise tabulation has been given in [Table 2, 2.1, 3, 3.1, 4, 4.1,7 and 7.1] highlighting various aspects such as cost, Complexity, efficiency, applications, merits and demerits etc,. The choice of choosing the MPPT depends on whether the solar energy harvesting system is to be used as a grid integrated system or stand alone application based on grid connected mode or stand-alone mode.

IV. CONCLUSIONS

Almost all renewable energy systems in general, and particularly the Solar PV systems exhibit non-linear characteristics by nature; hence an MPPT controller is essential to ensure the system operating at the optimum condition and to make best use of the expensive technology. Different research activities are going on with the objective to find simple low cost and highly efficient MPPT algorithms. This paper is intended to provide an insight into the various MPPT algorithms along with their advantages and disadvantages. This review is intended to be useful for academics, researchers and industrial designers engineers and manufacturers.

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