A COMPARATIVE STUDY ON MAXIMUM POWER POINT TRACKING TECHNIQUES FOR PHOTOVOLTAIC POWER SYSTEMS

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(PSO)-based MPPT, etc., have been reported since then. Hence, it is necessary to prepare a review that includes all the efficient

and effective MPPT techniques proposed before 2007 and after that until 2012. In this review, an attempt has also been made to compare the MPPT techniques on the basis of their advantages, disadvantages, control variables involved, types of circuitry, complexity of algorithm, complexity level on hardware imple- mentation, and types of scientific and commercial application. This paper attempts to provide a comparative review on most of the reported MPPT techniques excluding any unintentionally omitted papers because of space limitations.

The paper is organized as follows. In Section II, MPPT techniques extracted from a vast literature survey on MPPT appeared until 2012 are discussed. These have been compared in Section III. MPPT efficiency analysis has been made in Section IV with the concluding remarks are presented in Section V.

I. REVIEW ON MPPT TECHNIQUES

The following techniques are some of the widely used MPPT techniques applied on various PV applications such as space satellite, solar vehicles, and solar water pumping, etc.

A. *Curve-Fitting Technique*

MPP is the extreme value of the – characteristic of a PV panel, hence at first the P – V characteristic of a PV panel is pre- dicted in this technique. To predict, this P – V characteristic, PV panel can be modeled offline based on mathematical equations or numerical approximations [4], [5]. To achieve an accurate P – V curve fitting, a third-order polynomial function is

$$P = aV^3 + bV^2 + cV + d \qquad (1)$$

where the coefficients a, b, c, and d are determined by sampling of PV voltage and power in intervals. Differentiation of (1) gives

$$\frac{dP}{dV} = 3aV^2 + 2bV + c \qquad (2)$$

$$\text{At MPP,} \quad \frac{dP}{dV} = 0. \qquad (3)$$

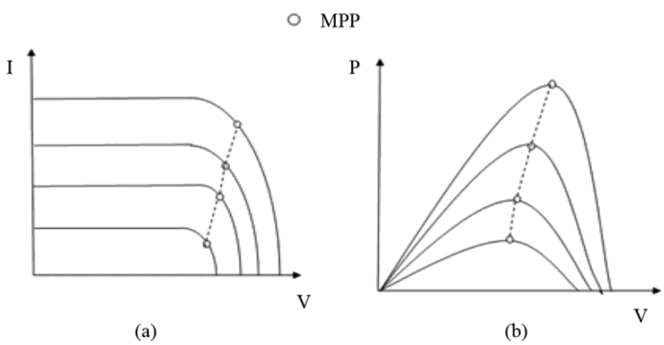
Thus, the voltage at MPP can be calculated as

$$V_{\text{mpp}} = \frac{-b \pm \sqrt{b^2 - 3ac}}{3a}. \qquad (4)$$

In this technique, a, b, c, and d are repeatedly sampled in a span of few milliseconds using mathematical equations defined in [5] and then V_{mpp} is calculated.

B. Fractional Short-Circuit Current (FSCI) Technique

There exists a single operating point called MPP at which the power of the panel $P(V_{mpp}, I_{mpp})$ is maximum (P_{mpp}) at a given environmental condition (Fig. 1). If by some means, anyone of I_{mpp} or V_{mpp} are tracked then the corresponding P_{mpp}



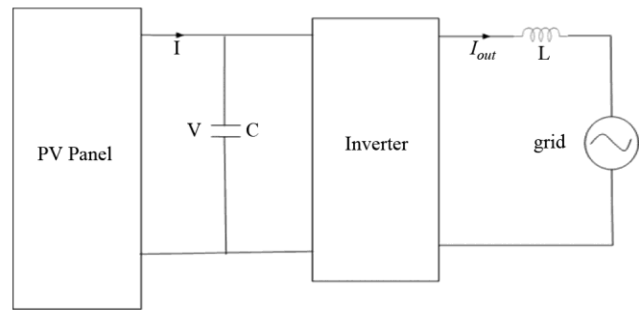


Fig. 1. (a) $I-V$ and (b) $P-V$ characteristics of PV panel at different environ- mental conditions.

can be tracked. In the FSCI technique, the nonlinear $I-V$ char- acteristics of PV system is modeled using mathematical equa- tions or numerical approximations taking account of a wide range of environmental conditions and degradation level of PV panel. Based on those $I-V$ characteristics, a mathematical re- lation between I_{mpp} and I_{sc} is constructed as I_{mpp} is linearly dependent on I_{sc} by an empirical relation shown as follows:

$$I_{mpp} \approx K_{sc} I_{sc}. \qquad (5)$$

Equation (5) constructs the FSCI method. The value of K_{sc} gen- erally varies between 0.64 and 0.85 [6]. K_{sc} can be calculated by analyzing the PV system at wide range of solar radiations and temperatures.

C. Fractional Open-Circuit Voltage (FOCV) Technique

In this technique, V_{mpp} can be calculated from the empirical relationship shown as follows:

$$V_{mpp} \approx K_{oc} V_{oc}. \qquad (6)$$

It is found that the value of K_{oc} varies between 0.78 and 0.92 [6], [7]. K_{oc} can be calculated by analyzing the PV system at wide range of solar radiations and temperatures. In this method, the PV system is open-circuited at load end for a fraction of second and V_{oc} is measured, then V_{mpp} is calculated using (6). Repeating this process is sampled repeatedly in every few seconds and value of V_{oc} V_{mpp} is updated.

D. Look-up Table Technique

In this technique, MPP of a PV system is calculated before hand for each probable environmental condition and stored in the memory device of MPPT's control system. During the op- eration, the corresponding MPP for a particular condition is se- lected from that memory and implemented [8], [9].

E. One-Cycle Control (OCC) Technique

OCC is a nonlinear MPPT control technique. It involves the use of a single-stage inverter where the output current (I_{out}) of the inverter can be adjusted according to the voltage of the PV array (V) so as to extract the maximum power from it [10]–[12]. There is only one power conversion stage that realizes on both MPPT control and dc/ac inversion. The OCC system is shown in Fig. 2. The parameters (L, C) involved in this system should

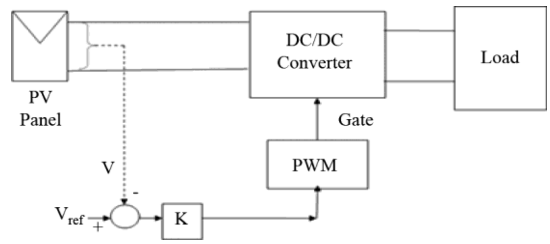


Fig. 2. Block diagram of OCC technique.

Fig. 3. Block diagram of voltage-feedback technique.

be properly tuned as their values greatly affect the accuracy of OCC technique.

F. Differentiation Technique

This technique determines MPP of a PV system on solving the following:

$$\frac{dP}{dt} = \frac{d(IV)}{dt} = I\frac{dV}{dt} + V\frac{dI}{dt} = 0. \quad (7)$$

But, this technique is very difficult because at least eight mea- surements and calculations such as measurements of V and I, calculations of corresponding dV and dI for a time span of dt, calculation of $I*dV/dt$, $V*dI/dt$, and then $I*dV/dt+V*dI/dt$ are required for this [13]. For faster MPP tracking operation, this technique needs a strong and expensive processor for solving the complex MPP equation.

G. Feedback Voltage or Current Technique

This technique is used in the system which has no battery. Without a battery, a simple controller is needed to fix the bus voltage at a constant level [2]. Hence, a simple MPPT controller can be applied as shown in Fig. 3. In this method, the feedback of panel voltage (or current) is taken and compared with a pre- calculated reference voltage (or current); the duty ratio of dc/dc converter is continuously adjusted so that it operates close to that of MPP [14].

H. Feedback of Power Variation With Voltage Technique

This technique [Fig. 4(a)] is similar to that of feedback voltage technique, but the only difference lies in the power variation with voltage (dP/dV) . Maximum power control is achieved by forcing the derivative (dP/dV) equal to zero under power feedback control. A general approach to power feedback control is to measure and maximize the power at the load terminals [15].

In this method, power to the load is maximized not the power from the solar array due to some unavoidable power-loss across

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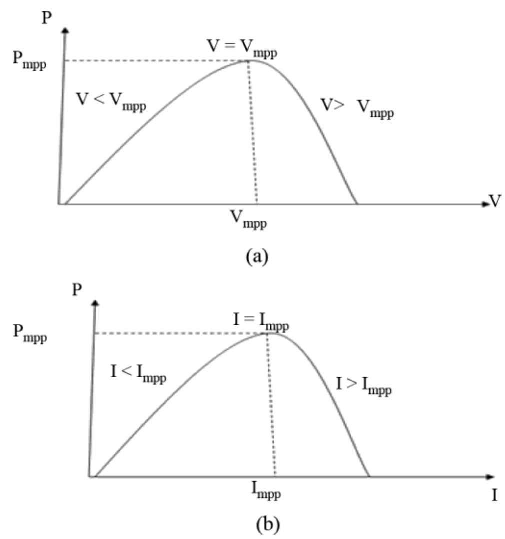


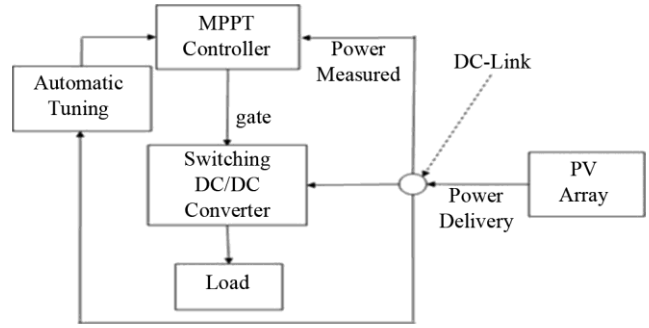


Fig. 4. (a) P–V curve explaining feedback variation of power with voltage.
(b) P – curve explaining feedback variation of power with current.

the converter. Therefore, the design of a high performance con-verter is an issue of concern in this technique [16].

I. Feedback of Power Variation With Current Technique

This technique [Fig. 4(b)] is similar to that of the dP/dV technique, except the difference in the feedback of power vari-ation with current (dP/dI) as its value is also zero at MPP. Hence, the duty cycle is adjusted till dP/dI becomes zero at MPP [17].

J. Perturbation and Observation (P&O) And/Hill-Climbing Technique

In this technique, first the PV voltage and current are mea- sured and hence the corresponding power is calculated. Con- sidering a small perturbation of voltage (ΔV) or perturbation of duty cycle (Δd) of the dc/dc converter in one direction corre- sponding power P_2 is calculated. P_2 is then compared with P_1. If P_2 is more than P_1, then the perturbation is in the correct di- rection; otherwise it should be reversed. In this way, the peak power point (P_{mpp}) is recognized and hence the corresponding voltage (V_{mpp}) can be calculated [18]–[20]. The major draw- backs of P&O/hill-climbing are occasional deviation from the maximum operating point in case of rapidly changing atmo- spheric conditions, such as broken clouds. Also, correct pertur- bation size is important in providing good performance in both dynamic and steady-state response [21]. To solve this problem, a modified adaptive hill climbing technique (Fig. 5) with a vari- able perturbation step size can be used [22], where an automatic tuning controller varies the perturbation step size to a large value when the power changes in a large range primarily due to en- vironmental variation, to satisfy the fast response requirement during the transient stage.

Further, the controller is formulated in such a manner that when the power change is less than or equal to the set lowest limit, the controller assumes that the system enters the steady- state and the value of perturbation becomes small. In similar

Fig. 5. Block diagram of adaptive Hill-climbing technique.

context, one Adaptive P&O technique [23] and another Predic- tive and Adaptive MPPT P&O ΔV

technique [24] have been intro- duced. In the Adaptive P&O method, instead of V_{mpp}, the main emphasis has been given on the voltage perturbation . In Predictive and Adaptive MPPT P&O method, a constant duty cycle perturbation (Δd) that linearly reduces with increase of power drawn from PV panel has been taken.

K. *Incremental Conductance (Inc-Cond) Technique*

For a PV system, the derivative of panel output power with its voltage is expressed as

$$\frac{dP}{dV} = \frac{d(IV)}{dV} = I + V\frac{dI}{dV} = I + V\frac{\Delta I}{\Delta V}. \quad (8)$$

Referring to (3), the solution of (8) is zero at MPP, positive on the left of the MPP and negative on the right of the MPP. So,
(8) can be rewritten as

$$\left.\begin{array}{ll} \frac{\Delta I}{\Delta V} = \frac{-I}{V} & \text{at MPP} \\ \frac{\Delta I}{\Delta V} > \frac{-I}{V} & \text{at left of MPP} \\ \frac{\Delta I}{\Delta V} < \frac{-I}{V} & \text{at right of MPP} \end{array}\right] \quad (9)$$

Thus, MPP can be tracked by comparing the instantaneous conductance (I/V) to the incremental conductance $(\Delta I/\Delta V)$ [25], [26]. It is the same efficient as P&O, good yield under rapidly changing atmospheric conditions. Here, also the same perturbation size problem as the P&O exists and an attempt has been made to solve by taking variable step size [27]. But, it requires complex and costly control circuits.

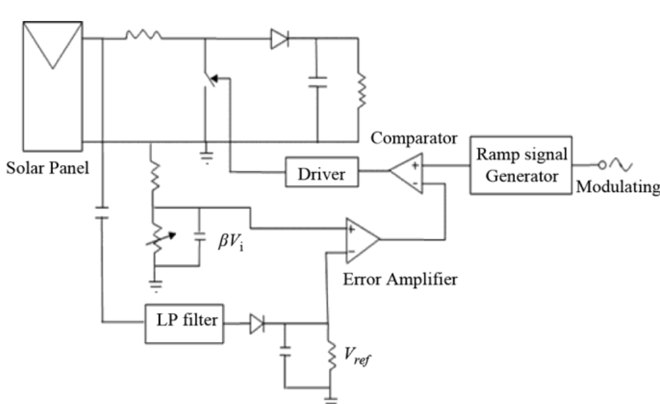
L. *Forced Oscillation Technique*

This technique is based on injecting a small-signal sinusoidal perturbation into the switching frequency and comparing the ac component and the average value of the panel terminal voltage as shown in Fig. 6. Here, the switching frequency is varied and V_i (input voltage) is sensed. Scaling down the value of β and comparing β_{Vi} with V_{ref}, the duty cycle of converter is set at MPP [28].

M. *Ripple Correlation Control (RCC) Technique*

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 [29], 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 with either

dp/dt



tic curve at the same interval. The function chosen
rtional to its derivative as

$$i(t) = k_1 \frac{di}{dt}. \quad (13)$$

$$i(t) = k_2 e^{t/k_1}.$$

Here, k_2 is taken as I_{MPP} at MPP. Again at MPP

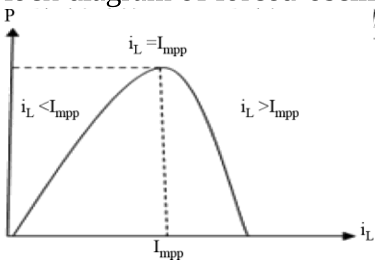
(14)

Fig. 6. Block diagram of forced-oscillation technique.

$\frac{dp}{dP_{mpp}}$ $\frac{di(t)}{dt} = 0.$

Using

(15)



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

(16)

Fig. 7. PV array power versus average inductor current.

di/dt or dv/dt and hence using (10.1) and (10.2) 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

$$\frac{dv}{dt} > 0 \text{ or } \frac{di}{dt} > 0 \text{ and } \frac{dp}{dt} > 0 \Rightarrow V < V_{\mathrm{mpp}} \text{ or } I < I_{\mathrm{mpp}} \tag{10.1}$$

$$\frac{dv}{dt} > 0 \text{ or } \frac{di}{dt} > 0 \text{ and } \frac{dp}{dt} < 0 \Rightarrow V > V_{\mathrm{mpp}} \text{ or } I < I_{\mathrm{mpp}}. \tag{10.2}$$

RCC applies to any switching power converter topology. This adjustment of can be done by using a boost converter. Here, the inductor current i_L is equal to the array current. At a given temperature and irradiance, i_L is adjusted together with vi_L. When there is any change in environmental condition, MPP is also shifted. Then referring to Fig. 7, (10.1)–(10.2) can be modified as follows:

$$\frac{di_L}{dt}\frac{dp}{dt} > 0 \Rightarrow i_L < I_{\mathrm{mpp}} \tag{11.1}$$

$$\frac{di_L}{dt} > \frac{dp}{dt} < 0 \Rightarrow i_L > I_{\mathrm{mpp}}. \tag{11.2}$$

Adjusting the duty ratio d, the value of i_L can be adjusted.
The value of d can calculated using the following:

$$d = k \int \frac{di_L}{dt}\frac{dp}{dt} dt \tag{12}$$

where k is a constant.

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N. Current Sweep Technique

The current sweep [30] 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

where $i(t)$ can be calculated using (14), followed by V_{MPP} using (16). Here, the reference point is frequently updated in a fixed time interval and hence the technique yields accurate results if proportionality coefficients k_1 and k_2 are properly chosen.

O. Estimated-Perturb-Perturb (EPP) Technique

The EPP technique is an extended P&O method. This tech- nique has one estimate mode between two perturb modes. The perturb process conducts the search over the highly nonlinear PV characteristic and the estimate process compensates for the perturb process for irradiance-changing conditions. The tech- nique is complex but its tracking speed is faster and more accu- rate than that of P&O method [31].

P. Parasitic Capacitance Technique

The parasitic capacitance technique [3], [32], [33] is similar to that of the Inc-Con technique, but the difference is in consid-eration of the effect of the PV cells' parasitic junction capaci- tance C_p, which is denoted by charge storage in the p-n junctions of the PV cells. This capacitance effect can be acknowledged by adding the current through the capacitance as $i(t) = C_p dV/dt$ in the PV panel model equation as follows:

$$I = I_{pv} - I_o\left[\exp\left(\frac{V+IR_s}{aV_t}\right) - 1\right] - \frac{V+IR_s}{R_{sh}} + C_p\frac{dv}{dt}. \quad (17)$$

Equation (17) can be rewritten as

$$I = f(v) + C_p\frac{dv}{dt} \quad (18)$$

where

$$f(v) = I_{pv} - I_o\left[\exp\left(\frac{V+IR_s}{aV_t}\right) - 1\right] - \frac{V+IR_s}{R_{sh}}. \quad (19)$$

Power output from the PV panel is represented by

$$P = V(f(v) + C_p\frac{dv}{dt}). \quad (20)$$

The MPP is located at the point where $dP/dV = 0$. That mens, (21

$$g_p = \frac{df(v)}{dv} + C_p\left(\frac{\dot{V}}{V} + \frac{\ddot{V}}{\dot{V}}\right) + \frac{f(v)}{dV} = 0$$

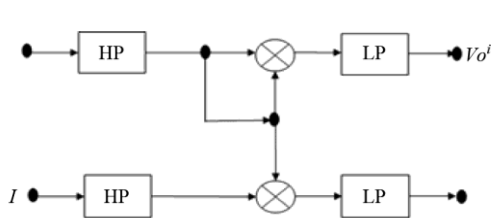

Fig. 8. PV Array connected to boost circuit in RCC technique.

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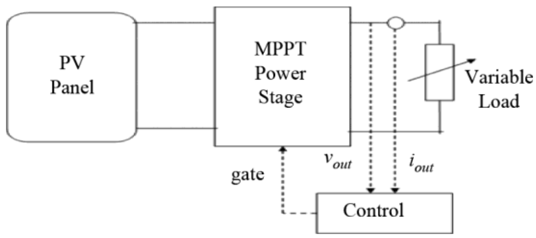

Fig. 9. Experimental set-up for load current/voltage maximization technique of PV panel.

where $df(v)/dv$, $C_p(\dot{V}/V + \ddot{V}/\dot{V})$ and $f(v)/dv$ represent the instantaneous conductance, the incremental conductance, and the induced ripple from the parasitic capacitance, respectively. The first and second derivatives of the array voltage are taken into account for the ac ripple components generated by the con-verter. The array conductance is the ratio of the instantaneous array current to the instantaneous array voltage and is calculated as follows [33]:

$$g_p = \frac{p_{gp}}{V_o^2} \qquad (22)$$

where P_{gp} is the average ripple power, V_o is the magnitude of the voltage ripple. Values of P_{gp} and $(V_o)^2$ may be obtained from a circuit configuration (Fig. 8).

The inputs to the circuit are the measured PV array current and voltage. The high-pass (HP) filters remove the dc compo- nent of V. The two multipliers generate the ac signals of V_O^2 and P_{gp}, which are then filtered by the low-pass filters (LP), leaving behind the dc components of V_O^2 and P_{gp}.

Q. Load Current/Load Voltage Maximization Technique

If directly connected to the load, operation of the PV array at the MPP cannot be ensured even for constant loads. Thus oper- ation at the MPP cannot be achieved using a tunable matching network that interfaces the load to the PV array. The main com- ponents of the MPPT circuit are its power stage and the con- troller (Fig. 9). As the power stage is realized by means of a switched mode power converter, the control input is the duty cycle [34].

R. DC Link Capacitor Droop Control Technique

DC-link capacitor droop control technique [2], [33] is de- signed to work with a PV system that is connected in parallel with an ac system line. The duty ratio (d) of an ideal boost con- verter is represented as

$$d = 1 - \frac{V}{V_{\text{link}}} \qquad (23)$$

where V is the voltage across the PV array and V_{li}
kept constant, the power coming out of the conver
going in the inverter. While the current is increasing, t

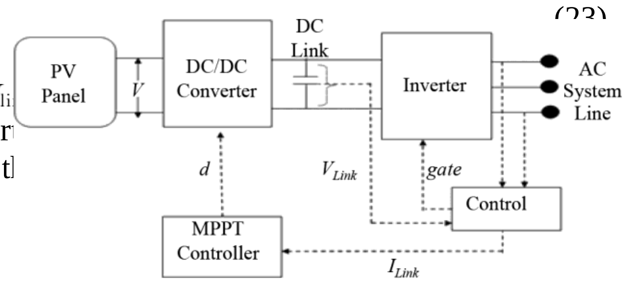

Fig. 10. Block diagram of dc-link capacitor droop technique.

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

d

PV array operates at the MPP. The ac system line current is fed back to dc-link to pre- vent V_{link} from drooping and is optimized to achieve MPPT as shown in Fig. 10. This technique is restricted to only to PV system that is connected in parallel with an ac system line.

S. Linearization-Based MPPT Technique

Both PV module and converter demonstrate nonlinear and time-variant characteristics, which make the MPPT design diffi- cult. In this method, successive linearization simplifies the non- linear problem back to the linear case. The MPP of a PV module is estimated using a set of linear equations [36], exploiting the relation existing between the values of module voltage and cur-rent at the MPP locus. The analytical study of the PV panel model shows that this relationship between voltage and current tends to be linear for the higher irradiation conditions due to the effect of the PV panel series resistance. Based on that relation- ship of voltage and current, a linear approximation of the MPP locus is derived, whose parameters are simply related to those of the electrical parameters of a PV cell [35], [36].

T. Intelligence MPPT Techniques

1) *Fuzzy Logic (FL)-Based MPPT Technique:* Introduction of intelligent MPPTs in PV systems is very promising. They achieved very good performances, fast responses with no over-shoot, and less fluctuations in the steady state for rapid temper- ature and irradiance variations. FL-based MPPT do not require the knowledge of the exact PV model [37], [38]. The FL-based MPPT in [37] has two inputs and one output. The two input vari- ables are error (e) and change in error (C_e) at the th sampled time are defined as follows: k

$$e(k) = \frac{dP}{dV}(k) - \frac{dP}{dV}(k-1) \quad (24)$$

$$C_e(k) = e(k) - e(k-1) \quad (25)$$

where $e(k)$ implies if the error of position of operating point of load at the th instant, while $C_e(k)$ expresses the moving direction of this point. The fuzzy k inference is carried out by using Mamdani’s method and the defuzzification uses the centre of gravity to compute the output (duty ratio,) of this fuzzy logic-based MPPT as shown in Fig. 11. d

2) *Artificial Neural Network (ANN)-Based MPPT Technique:* ANN control operates like a black box model, requiring no de-tail information about the PV system [39]. The link between the th and th nodes has weigh as shown in Fig. 12. i j ω_{ij}

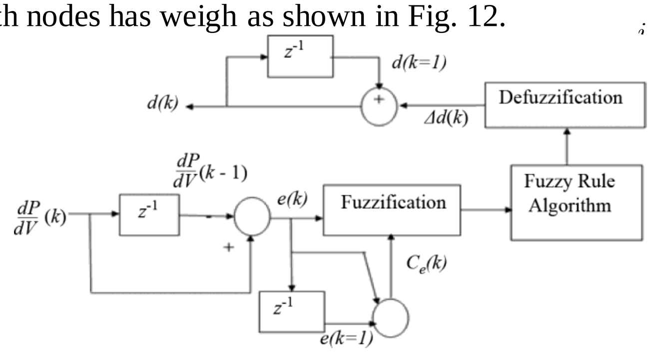

Fig. 11. Block diagram of fuzzy logic MPPT technique.

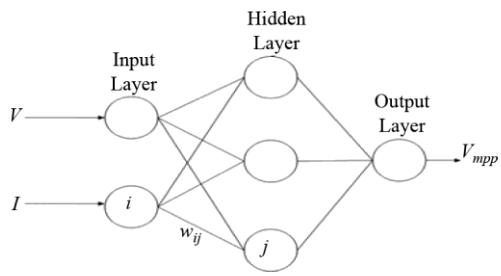

Fig. 12. ANN-based MPPT [40].

overcome to great extent by using discrete sliding mode con- troller [46] and PWM-based integral sliding mode controller [47]. Another problem in SMC-based MPPT is the measure- ment of V and I. Since I is dependent on inductor current, estimation of I needs a state observer [48].

V. *Gauss-Newton Technique*

The Gauss-Newton technique is the fastest algorithm [49], which uses a root-finding algorithm. In its algorithm, first and second derivatives of the change in power are used to estimate the direction and number of iterations of convergence while solving the following:

$$v(k+1) = v(k) \frac{\frac{dp}{dv}|_{v=v(k)}}{\frac{d^2p}{dv^2}|_{v=v(k)}}. \quad (27)$$

W. *Steepest-Descent Technique*

In this technique [50], the nearest local MPP can be tracked by computing the following function:

For MPPT, ANN input can be PV array parameters like PV voltages and currents, environmental data like irradiance and temperature, or any combination of these, whereas the output signal is the identified maximum power or the duty cycle signal used to drive the electronic converter to operate at the MPP. The NN input and output data are obtained from experimental measurement or model-based simulation results. After learning relation of V_{MPP} with temperature and irradiance, ANN can track the MPP online [39]–[41].

3) *Particle Swarm Optimization-Based MPPT (PSO-MPPT) Technique:* Multiple maxima found in P–V characteristics for partial shading conditions in multi-PV array structures. To handle this situation, an evolutionary computing approach called PSO has been employed for the multi-PV array structure in partial shading conditions because PSO works efficiently in multivariable problem with multiple maxima [42]–[44].

U. *Sliding-Mode-Based MPPT Technique*

In Inc-Cond technique, ratio of array current and voltage (I/V) term is compared with change in ratio of current and voltage $(\Delta I/\Delta V)$ term. Let h be a constant term and defined as $h = I/V + \Delta I/\Delta V$. At MPP, $h = 0$. This concept is used in sliding mode-based MPPT technique [45]. The dc/dc converter is designed such that its switching control signal (u) is generated as shown as

$$u = \begin{cases} 1, & h < 0 \\ 0, & h \geq 0 \end{cases} \quad (26)$$

where $u = 0$ implies the converter-switch is opened while it refers to closing of the switch when $u = 1$. In this way, the converter is forced to operate at MPP [45].

SMC-MPPT is compatible with a wide range of proces- sors such as DSP, microcontroller, FPGA, etc. Conventional SMC-MPPT has limitations like variable operating frequency and presence of nonzero steady state error. These problems are

$$v(k+1) = v(k)\frac{\frac{dp}{dv}|_{v=v(k)}}{K_\varepsilon} \quad (28)$$

where K_ε is the step-size corrector and dp/dv is the deviation in power. Here, dp/dv is calculated as follows:

$$\frac{dp}{dv} = f(v,p) \quad (29)$$

$$f(v(k),p(k)) = \frac{p(k+1) - p(k-1)}{2\Delta V} + O(\Delta V^3) \quad (30)$$

where $O(\Delta V)^3)$ is the local truncation error for the centered differentiation and is of second-order accuracy. The value K_ε decides how steep each step takes in the gradient direction.

X. *Analytic-Based MPPT Technique*

This technique is based on observations and experimental re- sults. From the experiments and observations, V_{oc} and I_{sc} are observed. Based on these observed values of V_{oc} and I_{sc}, a ball of small radius ε is selected for each panel such that MPP is in- side the ball. The analytic-based MPPT technique [51] is based on the mean value theorem, where, MPP is obtained from that ball by using mean value theorem. This technique is a simple heuristic strategy based on observations and experimental re- sults.

Y. *Hybrid MPPT (HMPPT) Techniques*

It is found that the P&O technique is the most extensively used in commercial MPPT systems because it is straight for- ward, accurate, and easy to implement. Its accuracy and tracking time depend on perturbation size. Hence, hybrid control tech- niques are essential. In a recent proposed hybrid MPPT tech- nique with both P&O and ANN, the perturbation step is contin- uously approximated by using ANN. Using this P&O-ANN hy- brid MPPT [52], on-line MPP tracking is possible. It is accurate and fast. Once tuned, it does not depend on environmental con- ditions. For strengthening search capability of the ANN-based MPPT technique, its weights should be properly tuned. Consid- ering this, the genetic algorithm (GA) concept is used for tuning

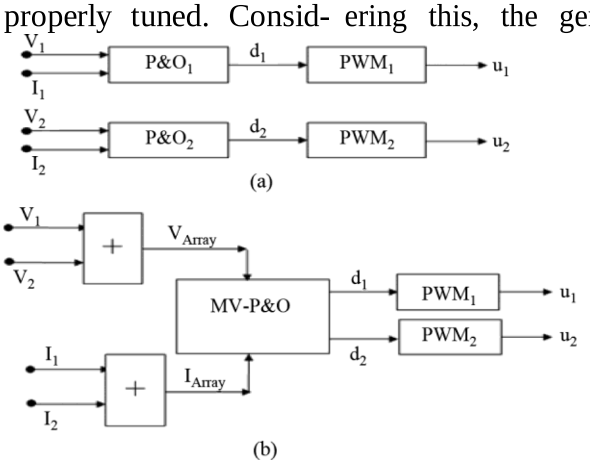

Fig. 13. Comparison between (a) traditional P&O and (b) multivariable P&O structures.

weights of ANN in [53]. Similarly, a GA optimized fuzzy-based MPPT is proposed by [54]. In this technique, membership func-tions and control rules are simultaneously optimized by GA. Further, poor stability and power fluctuation due to the highly nonlinear nature of the PV characteristics using simple P&O can be eliminated using the Adaptive Neuro-Fuzzy inference system (ANFIS) [55], [56]. Once properly trained, ANFIS can interpo-late and extrapolate the MPP with high accuracy.

Z. *MPPT Techniques for Mismatched Conditions*

Since a PV plant comprises of number of arrays, it may happen that there may be different orientations of PV modules belonging to the same PV field. Further, there could be shad- owing effects by clouds and bodies surrounding the plant. There could be manufacturing tolerances, nonuniformity of ambient temperature in proximity of each panel due to uneven solar irradiation and air circulation, dust and spot dirtiness (leaves, bird droppings). Mismatched conditions have strong impact on the shape of the – characteristics of the PV arrays and the energy productivity of mismatched strings can drop down to 20% of that of the not mismatched strings. In addition, in case of mismatch, the – characteristic of the PV field may have more than one peak. Hence, MPPT algorithms may fail causing a drastic drop in the overall system efficiency [57]. Distributed Maximum Power Point Tracking (DMPPT) [57]–[59] allevi- ates the above mismatched problems, because in the DMPPT technique, each module uses a single MPPT. Five different distinct DMPPT approaches are described in [57]. DMPPT ensures higher energy efficiency than other discussed MPPTs in presence of mismatching conditions. A recent MPPT technique is based on the Equalization of the Output operating points in correspondence of the forced Displacement of the Input oper- ating points of two identical PV systems is known as TEODI [58]. In TEODI-MPPT, each PV panel of a PV array has its own dc/dc converter but all the dc/dc converters are centralized controlled by a single control block. Further, a multivariable MPPT (MVMPPT), as shown in Fig. 13(b), is suggested in [59].

As shown in Fig. 13(a), the control unit of this MVMPPT takes the current and gives the signal for the controlled switches of the dc/dc boost converters. As shown in Fig. 13(a), in the P&O-based MPPT technique, the number of required P&O blocks is equal to the number of switching control variables

(d_1, d_2), whereas as shown in Fig. 13(b), one block of MV-P&O is sufficient to generate multiple control variables. In MV-P&O the number of control stages is reduced compared to that of P&O. Hence, power loss in the whole MPPT system is reduced considerably maximizing the PV power at the output of the converter.

II. COMPARISON OF MPPT TECHNIQUES

In this paper, classifications of the MPPT techniques have been attempted based on features, like the number of control variables involved, the types of control strategies, circuitry, and approximate making cost.

A. *According to Control Strategies*

Control strategies can be of three types: indirect control, direct control, and probabilistic control. Indirect control techniques are based on the use of a database that includes parameters and data such as characteristics curves of the PV panel for different irradiances and temperatures or on using some mathematical empirical formula to estimate MPP. Direct control strategies can seek MPP directly by taking into account the variations of the PV panel operating points without any ad- vanced knowledge of the PV panel characteristics. This is again of two types such as sampling methods [60] and modulation methods. In sampling methods, first a sample is made from PV panel voltage and current . The sample comprises of power (P), and . Gathering the past and present information of the sample, the location of the MPP is tracked. In modulation methods, MPP can be tracked by generating oscillations automatically by the feedback control.

B. According to Number of Control Variables

Two different control variables such as voltage, current or solar irradiance, temperature etc. are often chosen to achieve the MPPT applications. According to the variables which need to be sensed, MPPT techniques can be classified into two types, such as one-variable techniques and two-variable techniques. It is easier and cheap to implement voltage sensor whereas current sensor is bulky and expensive and hence implementation of cur- rent sensor is inconvenient in PV power systems.

C. According to Types of Circuitry

The circuitry involved in MPPT techniques are of two types such as analog circuit and digital circuit. Preference of MPPT techniques is also dependent upon the fact that some users are comfortable with analog techniques while others like the digital techniques. Hence, the MPPT techniques are classified based on type of used circuitry (analog or digital) used.

D. According to Cost

Some applications need accurate MPPT and cost is not an issue, such as, solar vehicles, industry, large-scale residential. But some systems like small residential applications, water pumping for irrigation, etc., need a simple and cheap MPPT technique. Expensive applications generally use advanced and complex circuitry because accuracy and fast response are main priorities there. Considering the above facts, the MPPT tech- niques are categorized taking into account the cost involved for designing the MPPT circuit. It is very difficult to provide exact

TABLE I

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COMPARISON OF DIFFERENT MPPT

MPPT Technique	Control Strategy	Control Variable	Circuitry (A/D)	parameter Tuning	Cost	Complexity Level	Applications	Converter used (DC/DC or DC/AC)	Commercial products
Tech-A	INC	V	D	yes	INEX	Simple	Stand-alone	DC/DC	Outback-Mx60 and FlexMx60 (Arlington, WA)
Tech-B and C	INC	V or I	Both	yes	INEX	Simple	Stand-alone	DC/DC	
Tech-D	INC	V, I	D	yes	INEX	Simple	Stand-alone	DC/DC	
Tech-E	SM	I	Both	yes	INEX	Simple	Grid	DC/AC	Model Enphase, Enphase Energy (Petaluma, CA)
Tech-F	SM	V or I	D	yes	EX	Complex	Stand-alone	DC/DC	Uni Lynx-PV inverter, Danfoss (Denmark)
Tech-G	SM	V or I	Both	no	INEX	Simple	Stand-alone	Both	Triple Lynx-PV inverter, Danfoss (Denmark)
Tech-H	SM	V, I	D	no	EX	Complex	Stand-alone	Both	
Tech-I	SM	V, I	D	no	EX	Medium	Stand-alone	Both	
Tech-J	SM	V, I	Both	no	EX	Complex	Stand-alone	DC/DC	
Tech-K	SM	V, I	D	no	EX	Complex	Stand-alone	DC/DC	
Tech-L	MM	V or I	A	yes	EX	Complex	Stand-alone	DC/DC	
Tech-M	MM	V or I	A	yes	EX	Complex	Stand-alone	DC/DC	
Tech-N	MM	I	D	yes	EX	Complex	Grid	DC/AC	
Tech-O	SM	V, I	Both	no	EX	Complex		DC/DC	
Tech-P	SM	V, I	D	yes	EX	Simple	Stand-alone	Both	
Tech-Q	MM	V	A	no	INEX	Medium	Stand-alone	DC/DC	AERL COOLMAX SR Maximizer™ of AERL Company (Australia)
Tech-R	MM	V	Both	yes	EX	Simple	Grid	Two-stages DC/DC+DC/AC	
Tech-S	SM	Irradiance	D	yes	INEX	Medium	Stand-alone	DC/DC	
Tech-T	INT	V or I	D	yes	EX	Medium	Both	Both	Morningstar-Trakstar MPPT charge controller, Solar Electric Supply (USA)
Tech-U	SM	V or I	D	no	EX	Complex	Both	Both	
Tech-V	SM	V or I	D	no	EX	Simple/medium	Stand-alone	DC/DC	
Tech-W	SM	V or I	D	no	EX	Medium	Stand-alone	DC/DC	
Tech-X	INC	V or I	Both	yes	EX	Medium/complex	Stand-alone	DC/DC	
Tech-Y	SM	V or I	D	yes	EX	Medium/complex	Both	Both	
Tech-Z	INT	V or I	D	yes	EX	Medium	Both	Both	Parallux, eIQ energy, (San Jose, California), Powerbox, solar-edge technologies, (UK), Solar Magic, National Semiconductor, (America), Maximizer-ES and Maximizer-EP, Tigo Energy and Sun Mizer, Xandex, (California)

Note: INC=Indirect control, SM=sampling method, MM=modulation method, INT=intelligent or probabilistic control, V=voltage, I=current, A=analog, D=digital, EX=expensive, INEX=inexpensive and Tech A-Z are MPPT techniques described in section II and subsections A-Z respectively.

TECHNIQUES ACCORDING TO THEIR CLASSIFIED TYPES

expenses in building each MPPT circuit due to unavailability of cost-data by the developer. Hence, in this paper, we have set a cost-line of US$1000 (in 2012); a cost below this line is termed as inexpensive while a cost equal to or above this is taken as an expensive MPPT technique. This categorization can be well described in Table I.

III. MPPT PRODUCTION, APPLICATIONS, AND EFFICIENCY CALCULATION

Solar technologies are tested and validated by the National Renewable Energy Laboratory, USA. MPPTs are primarily manufactured in Germany, Japan, mainland China, Taiwan, and the U.S. Some of the practical applications of MPPT techniques are in the solar water pumping system [36], solar vehicles (car, flights) [3], satellite power supply, off-grid [15] and grid-tied

[10] power supply systems [14], and small electronics applica-tions [2] (mobile charging), etc.

Getting maximum profit from a grid-connected PV system requires knowledge about efficiencies of the PV modules and inverters. Three different efficiencies such as conversion efficiency, European efficiency, static and dynamic MPPT efficien- cies are defined in [62] combined with their procedure of eval-uation. The MPPT efficiency is calculated as follows:

$$\eta_{\mathrm{MPPT}} = \frac{P_{\mathrm{PV}}}{P_{\mathrm{mpp}}} \times 100. \quad (31)$$

V. CONCLUSION

This review article provides a classification of available MPPT techniques based on the number of control variables involved, types of control strategies, circuitry, and cost of applications, which is possibly useful for selecting an MPPT technique for a particular application. It also gives an idea about grid-tied or standalone mode of operations and types of

preferable converters for each MPPT technique. This review has included many recent hybrid MPPT techniques along with their benefits. Further, the review has also included MPPT techniques meant for mismatched conditions such as partial shedding, nonuniformity of PV panel temperatures, dust ef- fects, damages of panel glass, etc. It has also given the idea of commercial products of MPPT techniques with the company names wherever possible. The review has discussed the effi- ciency calculation procedure of the developed MPPTs. This review is expected to be a useful tool for not only the MPPT users but also the designers and commercial manufacturers of PV systems.

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