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Review of maximum power point tracking algorithms of PV system

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Abstract

Purpose – Silicon photovoltaics technology has drawbacks of high cost and power conversion efficiency. In order to extract the maximum output power of the module, maximum power point (MPP) is used by implying the nonlinear behavior of I-V characteristics. Different techniques are used regarding maximum power point tracking (MPPT). The paper aims to review the techniques of MPPT used in PV systems and review the comparison between Perturb and Observe (P&O) method and incremental conductance (IC) method that are used to track the maximum power and gives a comparative review of all those techniques.

Design/methodology/approach – A study of MPPT techniques for photovoltaic (PV) systems is presented. Matlab Simulink is used to find the MPP using P&O simulation along with IC simulation at a steady temperature and irradiance.

Findings – MATLAB simulations are used to implement the P&O method and IC method, which includes a PV cell connected to an MPPT-controlled boost converter. The simulation results demonstrate the accuracy of the PV model as well as the functional value of the algorithms, which has improved tracking efficiency and dynamic characteristics. P&O solution gave 94% performance when configured. P&O controller has a better time response process. As compared to the P&O method of tracking, the incremental conductance response rate was significantly slower.

Originality/value – In PV systems, MPPT techniques are used to optimize the PV array output power by continuously tracking the MPP under a variety of operating conditions, including cell temperature and irradiation level.

Keywords Maximum power point tracking (MPPT), Photovoltaic (PV) system, Maximum power point (MPP), Perturb and observe (P&O), Incremental conductance (IC)

Paper type General review

1. Introduction

The maximum power point tracking (MPPT) is a control system-based method that enables PV module to generate all possible power they are capable of MPPT. Mechanical tracking device can be merged with to find MPPT but the control system adjusts the electrical operating point of PV modules to ensure optimal efficiency and, as a result, optimum output. Based on differences in irradiation and temperature, MPPT algorithms are used to derive the full power from the solar array. The highest power point of a PV module is the voltage at which it can output the most power (or peak power voltage). Ashok Kumar *et al.* (2015) mentioned that solar radiation, atmospheric temperature and solar cell temperature all influence maximum power.

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The charge controller used to accommodate for the fluctuating voltage current. Gergaud *et al.* (2002) showed that more power is extracted from the PV module as the charge controller behaves as it is changing the load continuously when it is not. The MPPT controls the solar panel's output voltage and current and calculates the optimum operating point for supplying the maximum amount of power to the load. If the MPPT version can precisely control the continuously changing operational point where the maximum power is available, the solar cell's efficiency will be raised. Beriber and Talha (2013) and Bollipo *et al.* (2021) proposed several algorithms, including P&O, IC and the fuzzy logic control (FLC) method. These algorithms differ in terms of their efficacy, complexity, convergence speed, needed sensors and cost.

A typical grid-connected PV system consists mainly of the boost converter, inverter and PV module was proposed by Gonzalez *et al.* (2012). Figure 1 shows the configuration of grid-connected PV system configuration, boost converter and a DC-AC inverter link the PV panel to the grid. The voltage and current from the solar panel are fed into the boost converter and MPPT controller in such a system; the first goal is to impose a desired voltage to the PV panel that ensures maximum power output, known as MPP voltage.

According to the electrical scheme the PV panel and DC–DC converter can be thought of as a single unit that must be controlled to reject disturbances like load and irradiance.

The power decreases over time, with maximum power available at lower temperatures was presented in (Beriber and Talha, 2013). Furthermore Younis *et al.* (2012) state that when a PV module is directly linked to a load, the load impedance determines the working state of the PV module, and only the optimum load, allows the PV module to collect the maximum power. A comparative Analysis between P&O method and IC method under steady and dynamic weather conditions was presented by Lodhi *et al.* (2017). Under the dynamic condition, IC algorithm shows the best proficiency among these two techniques. However, IC hardware design is more complex as compared to the P&O method. While P&O methods are simple and operating point oscillates from around MPP and some power will be lost. The MPPT applications was shown by Subudhi and Pradhan (2012) which includes solar water pumping systems, satellite power supply and off-grid and grid-tied power supply systems. The purpose of this paper is to review the various techniques of MPPT used in solar systems, as

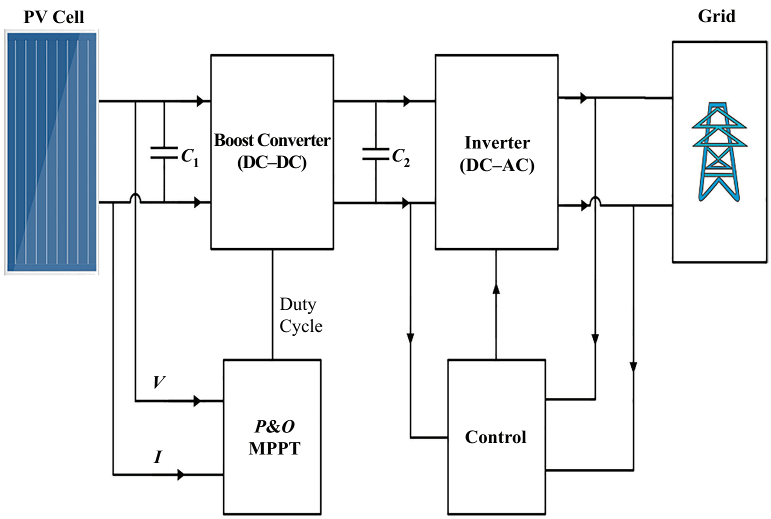

Figure 1.
Grid-connected PV power system

well as to compare and evaluate P&O and IC methods through theoretical analysis and MATLAB simulation under steady weather condition.

2. Different algorithms of MPPT

The challenging aspect in the field of solar energy is the dynamic nature of producing varying power and voltage depending on the environmental conditions. These parameters include conditions like shading and angle of solar radiation. As a result, at all electrical loads, full power generation is not assured. To derive the highest possible power from PV configurations, MPPT techniques are fitted with suitable controllers. Various MPPT algorithms have been researched for years (Beriber and Talha, 2013). To run PV modules at full power, a number of MPPT techniques are used. These techniques are classified as follows based on their monitoring existence under partial shading conditions (PSCs) (Bollipo *et al.*, 2021):

(1) Classical MPPT.

(2) Intelligent MPPT.

(3) Optimization MPPT.

(4) Hybrid MPPT.

2.1 Classical MPPT techniques

2.1.1 Perturb & observe (P&O) MPPT. The P&O algorithm enables the PV panel to achieve the MPP by varying the PV panel output voltage (Beriber and Talha, 2013). The module voltage is periodically perturbed in this method, and the output power is compared to the previous perturbing cycle (Atallah *et al.*, 2014). As seen in Figure 2, increasing (decreasing) the voltage increases (decreases) the power on the left side of the MPP while decreasing (increasing) the power on the right side of the MPP. As a result, if the power is increased, the perturbation must remain constant to obtain the MPP. If the power reduces the perturbation reverses (Esram and Chapman, 2007).

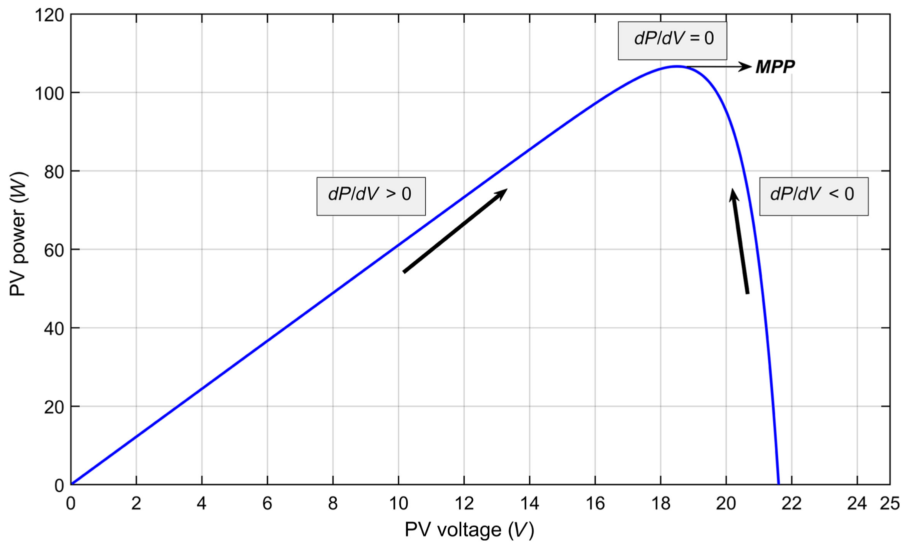

Figure 2.
Graph of power versus voltage for perturb and observe algorithm

This strategy essentially searches for a difference in PV cell power (dP) and then a change in PV cell voltage (dV). As a function of the obtained values, D is perturbed. The actual point appears to be in the left half of the MPP if the dP/dV is positive; if the dP/dV is negative, the actual point appears to be in the right half. Additionally, this step continues until (dP/dV) equals zero.

At the extreme point of any P-V curve, MPP is defined by (2), (3) and (4) are used to determined MPP's location (to the left or right).

$$\frac{dP_{PV}}{dV_{PV}} = 0 \text{ At } MPP \tag{1}$$

$$\frac{dP_{PV}}{dV_{PV}} > 0 \text{ Left side of } MPP \tag{2}$$

$$\frac{dP_{PV}}{dV_{PV}} < 0 \text{ Right side of } MPP \tag{3}$$

Figure 3 shows the A flowchart of P&O technique.

The merits of P&O are high tracking capability, simple and fast dynamic. The de-merits are oscillations around the MPP, unable to track exact MPP under PSCs and high power loss in stable conditions (Bollipo *et al.*, 2021).

2.1.2 Incremental conductance (IC). IC algorithm outperforms P&O in that it can decide when the MPPT has arrived at the MPP, as well as the location of the actual operating point in relation to the MPP and the distance at which P&O oscillates around the MPP. With IC technique claiming to enhance P&O by contrasting the PV array instantaneous I/V and incremental dI/dV conductance instead of the P&O's derivative of power versus voltage dP/dV (Sera *et al.*, 2013). Both data in this approach would be meant to use the slope of the system's P-V curve and track the MPP (Bollipo *et al.*, 2021; Jung *et al.*, 2005). The slope of P-V curve is zero at MPP, positive at left and negative at right of MPP (Beriber and Talha, 2013; Esram and Chapman, 2007) as given by:

$$\begin{cases} \dfrac{dP}{dV} = 0, & \text{At } MPP \\ \dfrac{dP}{dV} > 0, & \text{Left of } MPP \\ \dfrac{dP}{dV} < 0, & \text{Right of } MPP \end{cases} \tag{4}$$

Since
$$\frac{dP}{dV} = \frac{d(IV)}{dV} = I + V\frac{dI}{dV} \tag{5}$$

Can be rewritten as

$$\begin{cases} \dfrac{dI}{dV} = -\dfrac{I}{V}, & \text{At } MPP \\ \dfrac{dI}{dV} > -\dfrac{I}{V}, & \text{Left of } MPP \\ \dfrac{dI}{dV} < -\dfrac{I}{V}, & \text{Right of } MPP \end{cases} \tag{6}$$

The flowchart is shown in Figure 4.

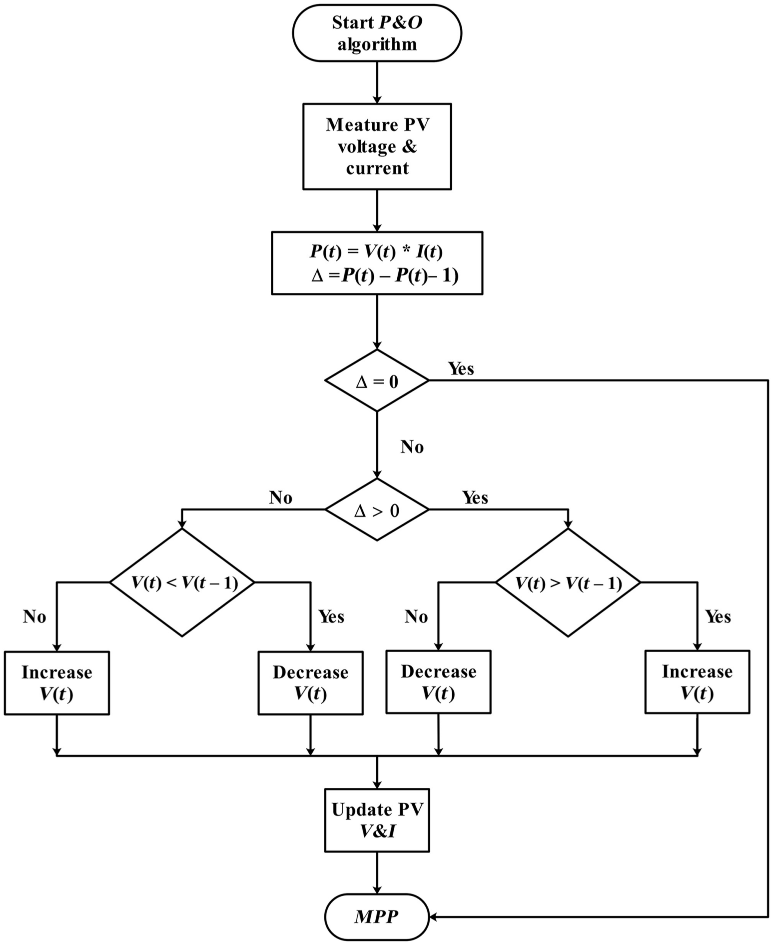

Figure 3.
Flowchart of P&O algorithm

The merit of IC technique is low oscillations around the MPP. The de-merits are different steps require complex and expensive controls (Bollipo *et al.*, 2021).

2.1.3 Constant voltage (CV). It is called voltage ratio method. The control technique requires contrasting the PV voltage with a defined reference voltage equal to V_{MPP}.

Nevertheless, the V_{OC}/V_{MPP} ratio is influenced by the solar cell temperature. Any minor variation of the V_{OC} after the sample will cause a significant shift in the follow-up time of the MPP.

The merit of CV is best implying where temperature varies very little. The de-merits are oscillations around the MPP and slow tracking (Atallah *et al.*, 2014; Bollipo *et al.*, 2021).

2.1.4 Open circuit voltage (OCV). V_{MPP} can be estimated using the analytical relationship as shown here:

$$V_{MPP} = K_v * V_{oc} \tag{7}$$

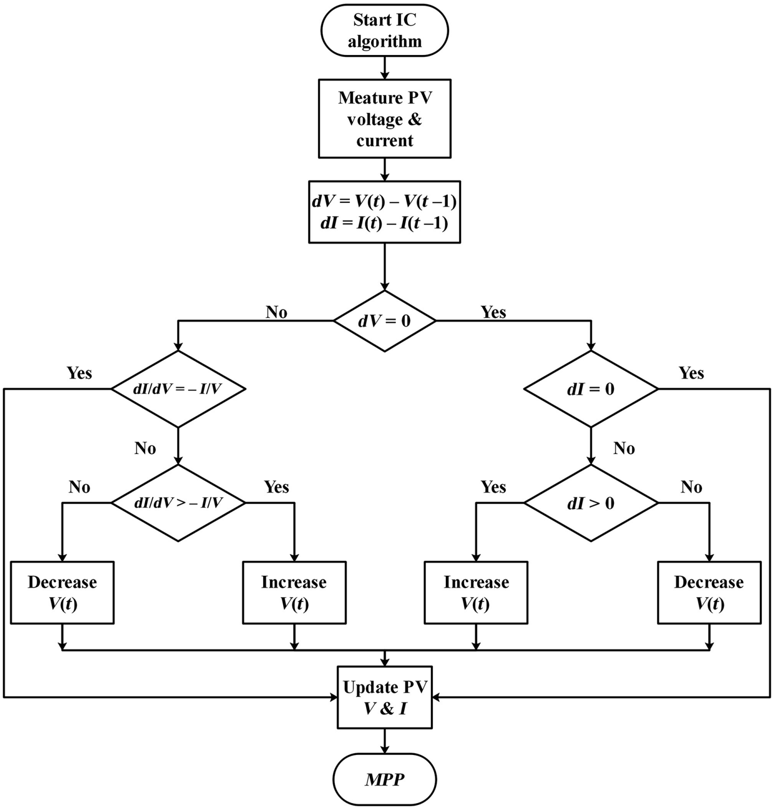

Figure 4.
Flowchart of incremental conductance (IC) algorithm

The constant K_v is between 0.78 and 0.92. At the load end, the PV unit is opened for a fraction of a second, and V_{oc} is determined, after which V_{MPP} is estimated. V_{oc} is sampled every few seconds during this process, and the value of V_{MPP} is changed (Subudhi and Pradhan, 2012).

The merits of OCV are that requires less no of sensors and complexity of the circuit is less. The de–merit is higher power loss under PSCs. (Bollipo *et al.*, 2021).

2.1.5 Short circuit current (SCC). It uses the PV module's current. In usual circumstances, current at MPP I_{MPP} occurs close short circuit current I_{sc} under some random environmental conditions (Bollipo *et al.*, 2021; Kota and Bhukya, 2017). Based on these V-I characteristics, a mathematical relationship between I_{MPP} and I_{sc} is

$$I_{MPP} = K_i * I_{sc} \tag{8}$$

The constant K_i is between 0.78 and 0.92 (Subudhi and Pradhan, 2012; Esram and Chapman, 2007).

The merit of SCC is simple and precise with less hardware computation. The de-merits are short circuit current must be calculated on a regular basis, and high power loss at dynamic weather conditions (Bollipo *et al.*, 2021).

2.1.6 Ripple correlation control (RCC). The switching process of the converter produces voltage and current ripple on the PV array if a PV array is connected to a converter. The PV system uses this ripple to execute MPPT in the RCC technique. (Subudhi and Pradhan, 2012; Esram *et al.*, 2006).

The merit of RCC is that there is no need for artificial perturbation. The de-merit is that accurate mathematical calculations are required.

Table 1 shows the comparison of MPPT techniques based on classical algorithms (Esram and Chapman, 2007; Subudhi and Pradhan, 2012; Bollipo *et al.*, 2021).

2.2 Intelligent MPPT techniques

2.2.1 Fuzzy Logic Controller (FLC). FLC consists of fuzzy rule, fuzzification and defuzzification (Reisi *et al.*, 2013). The controller achieves high efficiency regardless of whether the information is correct or not (Bollipo *et al.*, 2021; Esram and Chapman, 2007).

The flowchart of this method is appeared in Figure 5.

The merit of FLC is that no need of mathematical model and knowledge of the PV system. The de-merit is the tuning complexity of the membership function, scaling factor, and control rules that is presented by FLC. (Mohapatra *et al.*, 2017; Bollipo *et al.*, 2021).

2.2.2 Artificial neural network (ANN). Require no detailed information about the system. The ANN MPPT can be denoted by a directed graph, with the nodes and edges representing neurons and synapses, accordingly.

The merits of ANN are once trained with input sets, can able to track any PSC and, it is fast tracking and handle more complex problems. The demerits are the requirement of PV system information for training, storage of enormous data makes the technique a bit costly, and parameter tuning. (Bahgat *et al.*, 2005; Bollipo *et al.*, 2021; Mohapatra *et al.*, 2017).

2.2.3 Sliding mode controller (SMC). A highly sophisticated intelligence-based SMC is designed for quickly tracking the MPP without compromising in its efficiency. Two modes of operation: approaching mode and sliding mode. The methodology's basic concept is to use the current of the DC link capacitor to control the DC–DC converter.

The merits of SMC are very precise in tracking and well applicable for non-linear systems. The de-merit is the sliding surface choices have a strong impact on the efficiency of the SMC (Bollipo *et al.*, 2021; Mohapatra *et al.*, 2017).

2.2.4 Gauss Newton approach based MPPT. It will locate the MPP with the help of the centered differentiation which is newer of its type. It's most widely used to solve nonlinear problems involving the least square approximation.

Technique	P&O	IC	CV	OCV	SCC	RCC
Sensed parameters	V&I	V&I	V	V	I	V&I
Tracking speed	Slow	Slow	Slow	Slow	Slow	Fast
Tracking accuracy	Medium	Medium	Low	Low	Medium	High
Control strategy	Direct control (sampling method)	Direct control (sampling method)	Indirect control	Indirect control	Indirect control	Indirect control
Complexity level	Simple	Complex	Simple	Simple	Simple	Complex
Stability	No	Yes	No	No	No	Very stable
Parameter tuning	No	No	Yes	Yes	Yes	Yes
Ability to track under PSCs	No	No	No	No	No	Yes
Efficiency	97.8 %	98.5%	72.8%	92.4%	93.4%	96.4%
Cost	Affordable	Expansive	INEX	INEX	INEX	Expansive

Table 1. Comparison of MPPT techniques based on classical algorithm

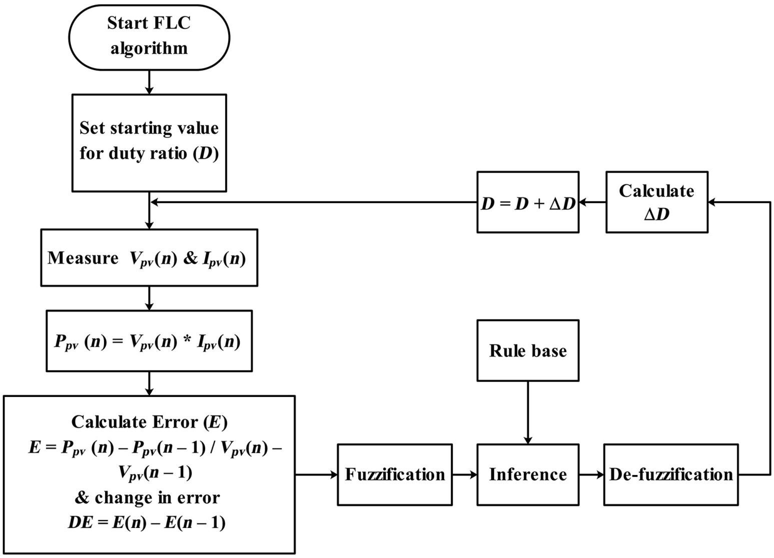

Figure 5.
Flowchart of fuzzy logic controller (FLC)

The merits of this method are the tracking is accurate with less time and no need for PV system knowledge. The de-merit is complex calculation (Mohapatra *et al.*, 2017; Subudhi and Pradhan, 2012; Bollipo *et al.*, 2021).

Table 2 shows the comparison of MPPT techniques based on intelligent algorithms (Reisi *et al.*, 2013; Bollipo *et al.*, 2021; Yu, 2018).

2.3 Optimization-based MPPT

2.3.1 Cuckoo search (CS). Cuckoo's nature is used as a metaphor for the representation of choosing the best solution during the process of MPP tracking.

The merits of CS are high convergence speed along with higher efficiency, bulk randomization and more robust in performance with lesser variables. The de-merit is composite mathematical modelling (Mohapatra *et al.*, 2017; Bollipo *et al.*, 2021).

Technique	FLC	ANN	SMC	Gauss Newton
Sensed parameters	V&I	G&T	V&I	V&I
Tracking speed	Fast	Medium	Very fast	Fast
Tracking accuracy	High	High	Medium	Medium
Control strategy	Fuzzy interface system	Back propagation	Current sensing	Reduction in mean square error
Complexity level	Less	Medium	More	More
Stability	Very stable	Very stable	Very stable	stable
Parameter tuning	Yes	Yes	No	No
Ability to track under PSCs	Yes	Yes	Yes	No
Efficiency	97.87%	98%	–	–
Cost	Affordable	Expansive	Expansive	Affordable

Table 2.
Comparison of MPPT techniques based on intelligent algorithms

2.3.2 Particle swarm optimization (PSO) technique. This PSO also a bio-inspired algorithm is taken from the analogy of bird flocking. It takes a few assumptions for the process of obtaining the best solution.

The merits of PSO are the bio-inspired nature of tracking is helpful for accurate tracking of global maximum power point (GMPP) and fast-tracking in variable conditions. The de-merit is that the objective function is a little complicated since it is dependent on the particle's velocity. (Bollipo *et al.*, 2021).

2.3.3 Grey wolf optimization (GWO). The merits of GWO are the decrement in both transient and steady-state oscillations, robust with better tracking efficiency and along with fewer variables. The de-merit is higher cost and computational time due to the large search space (Mohapatra *et al.*, 2017; Bollipo *et al.*, 2021).

2.3.4 Ant colony optimization (ACO). The merits of ACO are convergence is independent of initial sample position, simple control strategy, low cost and can handle the various PSCs due to robustness. The de-merits are simultaneous optimization of four variables is to be at a time which is a tough task for the controller and complex estimations (Dorigo *et al.*, 1996; Mohapatra *et al.*, 2017).

2.3.5 Artificial bee colony (ABC). This food-finding method is well-used in PV systems to find the optimum point by employing the correct activation function. Its efficiency is almost 99.99%. When the shading patterns changes instantaneously, efficiencies decrease.

The merit of ABC is that it uses fewer control parameters. The de-merits are slow tracking, complex and local maximum point tracking (LMPP) may be affected by less control parameters (Bollipo *et al.*, 2021; Mohapatra *et al.*, 2017).

Table 3 shows the comparison of MPPT techniques based on optimization algorithms (Mohanty *et al.*, 2017).

2.4 Hybrid MPPT

2.4.1 Fuzzy particle swarm optimization (FPSO). The merit of FPSO is the switching losses are decreased. PSO avoids the conventional usage of PI controller by tuning the membership functions and control rules by itself. The de-merit is that a portion of approximation and trial and error have to be included while designing the fuzzy rules and rule base on human intelligence (Bollipo *et al.*, 2021).

2.4.2 GWO-P&O. The merits of GWO-P&O are faster convergence speed, no oscillations, high efficiency and neglects the process of tuning and its process complexity. The de-merit is a high level of mathematical computations (Bollipo *et al.*, 2021).

Technique	Cuckoo search	PSO	GWO	ACO	ABC
Sensed parameters	V&I	V&I	V	V&I	V&I
Tracking speed	High	High	Medium	High	High
Tracking accuracy	High	Medium	High	Medium	Medium
Control strategy	Bio-inspired	Particle tracking	Bio-inspired	Bio-inspired	Bio-inspired
Complexity level	Simple	Medium	Simple	Simple	Medium
Stability	Very stable	stable	stable	stable	stable
Parameter tuning	No	Yes	Yes	Yes	Yes
Ability to track under PSCs	High	High	High	High	High
Efficiency	99.89%	99.91%	–	99.97%	99.78%
Cost	Very expansive	Affordable	Affordable	Affordable	Expansive

Table 3.
MPPT techniques compared using optimization algorithms

2.4.3 PSO-P&O. The merits of PSO-P&O are much simpler in algorithm modelling and their hardware implementation and it achieves better transient performance than the conventional method. The de-merit is oscillations around the MPP.

Table 4 shows the comparison of MPPT techniques based on hybrid algorithms (Wan *et al.*, 2019; Bollipo *et al.*, 2021).

3. Comparative analysis between perturb & observe (P&O) method and incremental conductance (IC) method

IC and P&O MPPT methods are best among other options, these two techniques are commonly used around the global for tracking of MPP. However, both of these techniques are beneficial in their own terms and features. Partial shading is common phenomena in daily life, and it effects the performance output. In (Díaz-Barnabé and Morales-Acevedo, 2019; Nkambule *et al.*, 2019) after implementing the MPPT techniques, IC has better performance than P&O techniques under partial shading and converges quicker towards the maximum power point. It was also stated in partial shading that P&O has a faster settling time around MPP. Moreover, in (Lodhi *et al.*, 2017) the performance of IC and P&O was simulated in steady and dynamic weather conditions. Under the steady condition the IC has less response time and power oscillations around MPP are minor. P&O method requires high response time and it has large power oscillations at MPP. Under the dynamic condition IC algorithm has better response speed and easily controlled through high accuracy. However, incremental conductance hardware design is more complex as compared to the P&O method. While P&O methods are simple and operating point is moving around the MPP therefore, some power will be lost and it will not be accurate track under dynamic conditions. Compared to P&O, the IC algorithm is excellent (Banu *et al.*, 2013; Khadidja *et al.*, 2017).

4. Results and simulation

4.1 P&O simulation results

MATLAB Simulink software is used to model and simulate the system to verify the control technique and measure system output (photovoltaic generator, boost converter, and MPPT Tracking algorithm P&O).

The simulation results of the output power of the PV panel using the P&O process controller at steady temperature ($T = 25$ °C) and irradiance ($E = 1{,}000$ w/m^2) indicate that the P&O solution provides 94% performance. As the irradiation switches quickly, however, the P&O controller has a better time response process.

After implementing the algorithm in Simulink, voltage level, current level was improved. Figure 6 shows the output voltage, current and power of PV panel. Initial surge was observed

Technique	FPSO	GWO-P&O	PSO-P&O
Sensed parameters	V&I	V	V&I
Tracking speed	High	Medium	High
Tracking accuracy	High	High	Medium
Control strategy	FIS and Bio-inspired	Bio-inspired	Fine-tuning of D
Complexity level	Simple	Medium	Medium to complex
Stability	Very stable	stable	stable
Parameter tuning	No	Yes	Yes
Ability to track under PSCs	High	High	High
Efficiency	–	99.77%	100%
Cost	Very expansive	Affordable	Affordable

Table 4. Comparison of MPPT techniques based on hybrid algorithms

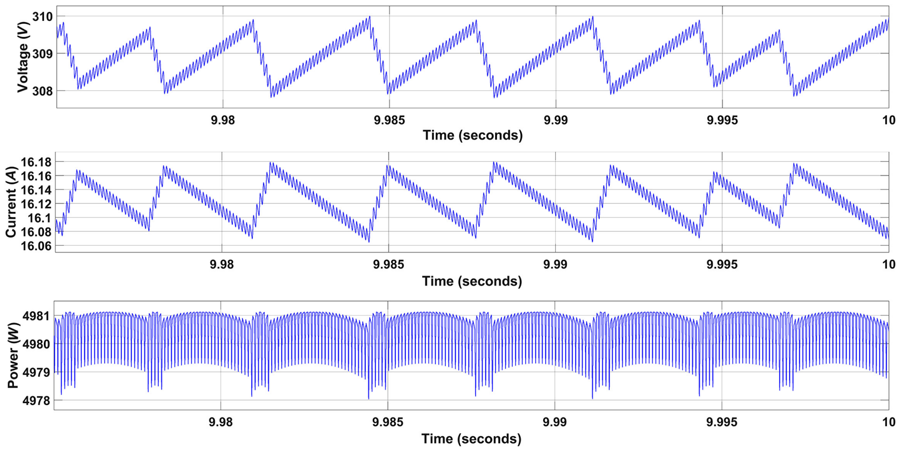

Figure 6.
Output voltage, current and power of PV panel using P&O MPPT

in millisecond which was balanced by the P&O converter to obtain the constant voltage over the course of time.

4.2 Incremental conductance (IC) simulation result

The simulated model shows a steady ($T = 25$ °C) temperature and irradiance ($E = 1{,}000$ w/m^2). IC algorithm was successfully implemented in MATLAB Simulink, the output voltage was improved but response time was slower as compared to P&O algorithm. In Figure 7, the overall, performance can be observed through graph of voltage, current and the output power.

5. Conclusion

The paper reviewed the different techniques of MPPT and comparatively reviewed P&O and IC techniques used to track the MPP. Both techniques were implemented on Simulink

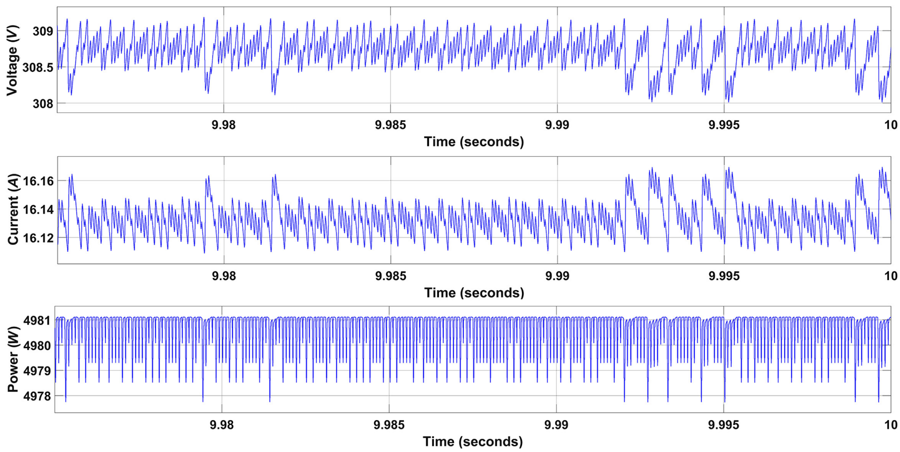

Figure 7.
Output voltage, current and power of PV panel using IC MPPT

MATLAB and results were compared. Simulink model of both MPPT techniques consist of solar panel, algorithm block and load. The P&O technique is relatively easy to implement but gets difficult to collect data during oscillation. Under conditions of steady temperature ($T = 25$) and irradiance ($E = 1{,}000$ w/m^2) the P&O solution provides 94% performance. From the data it has been demonstrated that P&O controller has a better time response process than the IC controller. Voltage, Current and Power output graph of Solar Panels were obtained and concluded that P&O method has better performance than IC and response time is quicker.

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