Maximum Power Point Tracking Algorithm Based on Particle Swarm Optimization to Capture Maximum Power from PV Strings

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Abstract. A fast-growing population, rising number of smart cities, and exponential usage of electronic gadgets have all contributed to a growing demand for electricity, possibly causing menacingly high levels of carbon emissions and atmospheric pollution in India. These energy sources do not release any greenhouse gases into the atmosphere. India as a sunshine country is an ideal place for harnessing solar energy which will help us to overcome pollution problems. Nowadays photovoltaic systems are popular due to their various advantages like sustainability, less maintenance, no complex part, possesses longer life, and many more. Solar photovoltaic systems have become the most ideal option for conventional energy sources that can develop energy sustainably. The power-voltage characteristics of a PV panel are non-linear and depend on the irradiance of sunlight and the atmosphere's temperature. The performance of a PV power plant mainly depends on various factors: the conversion efficiency of the PV system, the efficiency of the power electronics converter, and the maximum power extraction algorithm. Various tracking methods have been proposed in the literature to obtain maximum power from PV systems. Conventional methods like perturb and observe (P&O), incremental conductance method and improved perturb and observe method, etc. have advantages and disadvantages in terms of precision, speed, and power loss under changing weather conditions. In this regard, the utilization of optimization algorithms to track the MPP of PV panels under changing environmental conditions. This has motivated the present study to use the search-based Particle swarm optimization (PSO) technique for solar photovoltaic systems to extract maximum output under non-uniform weather conditions.

Keywords: Solar PV Panel · Incremental Conductance · PSO · MPPT

1 Introduction

Recently, researchers and scientists have started to investigate renewable energy sources for power generation because of the increase in energy demand, limited fossil fuels, and natural contamination. Among these solar, wind, sea tide, and so on is the various

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renewable energy sources for power generation. Focal points of the photovoltaic power generation are low operational cost and maintenance-free in which photovoltaic power generation is uncontaminated. Due to different variations in sun temperature and radiance, the PV array's power-voltage characteristics are non-linear. Because the irradiance of sunlight varies throughout the day, the power output of a PV panel varies as well. In addition, the MPP moves in response to changes in light from the sun and atmospheric temperature. Maintaining the performing point of a PV panel at MPP at any irradiance and temperature is called maximum power point tracking (MPPT). Another key issue with solar power generating is how to deal with non-uniform irradiation conditions. In a PV power generation system, For a given power rating, a large number of solar panels are connected in series as well as parallel. Under the condition of non-uniform irradiations, the PV panels are subjected to non-uniform irradiance and in this situation the power-voltage characteristics exhibit multiple peaks.

Batarseh et al. [1], reported the main disadvantage of the Perturb and Observe MPPT technique is that it wastes due to fluctuations in the operation point near and around the MPP, energy is maintained at a constant state. Several authors have proposed numerous changes to the Perturb and Observe technique to decrease these oscillations. These alternatives, on the other hand, slow down the algorithm's response time and diminish its efficiency, especially on overcast days. Femia et al. [2], examined Photovoltaic (PV) systems which were subjected to the Optimization of (P&O) methodology for tracking of maximum power. Researchers demonstrated that the P&O optimization method for MPPT was very efficient for low-cost application. The results of the tests demonstrated that effective MPPT regulators can be designed, and the flexibility of the Perturb and Observe approach may be explored by tweaking it concerning the system's dynamic features. The researchers also proposed that the test results and conclusions obtained from the current study be expanded to other converter topologies. Fernando et al. [3], Surveyed MPPT techniques such as CV, P&O, and IC, etc. The CV method needs only single sensor which is simple to build; the P&O method requires two sensors and has the benefit of operating point oscillations on and about MPP; and the INC technique employs a random step method to achieve a. low error. Kumar and Mishra [4], develop a changing perturbation size adaptive P&O MPP extraction approach. They improved dynamic performance under rapid operational limit violations, reduced oscillations around MPP, and used those methodologies to verify the modelling and experimental setup. Dileep et al. [5], designed an enhanced P&O approach for combining MPPT with PV systems originating from several schemes in each approach's tracking accuracy, circuit design, required parameters, cost, and switching circuit type were all described by the authors. According to the authors, Swarm intelligence approaches are better for monitoring MPP under shade conditions. Gonal and Sheshadri [6], have developed The maximum conductance approach is a new methodology for MPP tracking. A novel Matlab-Simulink model was created for analyzing the power output of a photovoltaic panel in various geographic locations When the suggested algorithm was compared against P&O, they discovered that the maximum conductance model outperformed P&O by 40%. Li et al. [7], developed a novel GMPP technique based on power increments and studied the behavior of algorithm and rate of convergence under various shading patterns. Haque et al. [8], had created the new approach by making alterations to improve sun radiation and point oscillations, use the Perturb & Observe approach. The writers concentrated on the benefits of the suggested technique. To demonstrate the viability of the unique approach, a prototype comprising a buck converter was displayed. Udaykumar et al. [9], defined PV balancer as a new idea of modulated integrated converters (MIC) that tracks the MPP of a PV system. In comparison to other commercial MICs, they discovered that PV balancers provided superior efficiency, minimal DC bus loss, and good regulation. Antonio et al. [10], examined the methods to improve the efficiency of PV systems, researchers looked at various MPPT approaches. Perturb and Observe, Neural networks, Ripple Correlation Control and Fuzzy Logic Control were among the strategies investigated by the authors. They also gave a comparison of several MPPT approaches. Tofoli et al. [11], For photovoltaic systems, a comparative examination of maximum power point tracking approaches was conducted. P&O technique is one of the numerous MPPT procedures that has pushed the operating point near to the MPP. Ram et al. [12] applied a modified P&O technique under uniform irradiance and partial shadowing conditions and verified the results by taking pump load. Nafesh et al. [13], The current and irradiation levels of photovoltaic modules were measured in various shading conditions, and for the solar PV system, a novel peak power extraction approach was devised and implemented. Swarm intelligence algorithms are stimulated through the conduct of social beings inclusive of chicken flocking, ants foraging, and animal herding. With assist and interaction, all entity movements collectively withinside the path of the promising regions withinside the search space. Particle swarm optimization (PSO) and Shuffled Frog Leaping are two well-known swarm intelligence-based methods (SFL). Ishaque et al. [14], The PSO strategy was investigated, PI control loop is eliminated that is employed in the direct duty cycle control method. The test was conducted if the proposed optimization technique can overcome the limitations of traditional MPPT tracking systems. The approach was used to construct an experimental prototype of a PV array model employing a buck-boost converter. They used data from a tropical country (Malaysia) to test the system under 10 irradiances, including partial shadowing situations, and the experimental findings showed that the suggested strategy overcomes the shortcomings of existing methods. Rehman et al. [15], advised the use of an optimization strategy to detect optimal setup to minimize cost and provide efficient solutions. Renaudineau et al. [16], applied the PSO approach for regulating to get more power out of a solar photovoltaic system, increase the switching pulse of the converter. Chen et al. [17], Focusing on the application of the enhanced PSO algorithm for PV MPPT, he reported that the PSO algorithm improved tracking efficiency. Nagadurga et al. [18] PSO technology was utilised to track the PV system's maximum power point at various irradiance levels, and the PSO approach produces more power under shade conditions than the conventional P&O method, according to simulation data.

2 Mathematical Model of PV System

The photovoltaic effect, in which light energy is transformed into electrical energy, is the primary operating principle of a solar cell. The solar cell's equivalent circuit might be a single diode or a two-diode model; The single diode model is more precise and simpler. Figure 1 shows the corresponding circuit diagram of a single diode solar cell. It consists

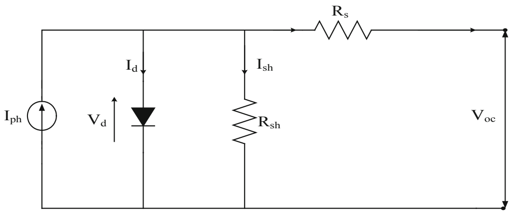

Fig. 1. Equivalent circuit of solar cell

of series resistance R_S, shunt resistance R_{sh}, diode current I_d, module photocurrent I_{ph} and current from the panel I_{pv}, and voltage from PV panel V_{pv}.

The equation for the solar panel output current is given by

$$I_{PV} = I_{SC} - I_d \tag{1}$$

where

$$I_d = \frac{I_{sr}}{\left[e^{\left(\frac{q*Voc}{KAT}\right)} - 1\right]} \tag{2}$$

The photocurrent is given by the expression

$$I_{Ph} = [I_{scr} + K_i(T - 298)] * \gamma/1000 \tag{3}$$

The reverse current of a PV module during saturation is given by

$$I_{rs} = I_{scr}/\left[e^{\left(\frac{q*Voc}{KAT}\right)} - 1\right] \tag{4}$$

The model output current

$$I_o = I_{rs}\left[\frac{T}{T_r}\right]^3 e^{\left[\frac{q*Ego}{Bk}\left\{\frac{1}{T_r} - \frac{1}{T}\right\}\right]} \tag{5}$$

The photo current generated by the solar PV cell is calculated in following way.

$$I = I_{Ph} - I_{sr}\left[\exp\left(\frac{q(V + R_s I)}{\eta KT}\right) - 1\right] - \frac{V + R_s I}{R_{Sh}} \tag{6}$$

The symbols used in this model are as follows:

I_{ph} Photoelectric current in A
I_{sat} Saturation current in Ma
T The temperature of the atmosphere in K
R_{sh} Shunt Resistance in Ω
R_s Resistance of lead in Ω
N_s Number of Series connected cells

N_p Number of parallel-connected cells
I_o Saturation current of PV panel in A
I_{ph} Developed current in the PV module in A

Solar PV operation depends on the type of load connected to the system and also environmental conditions. The solar irradiation strikes the PV panel continuously throughout the day (Fig. 2).

To get maximum benefits from solar PV MPPT tracking controller is accomplished to the system. The DC-DC boost converter acts as a charge controller (MPPT controller) to get maximum energy from the panel.

To match impedance of load with internal impedance of panel, which varies depending on conditions of climate, a DC-DC boost converter circuit is utilised. By regulating the duty cycle of the switching converter, the panel impedance on the exterior can be adjusted to match the impedance of load. The charge controller circuit comprises of PWM signal generator, DC-DC converter, PV array, and load as shown in Fig. 3.

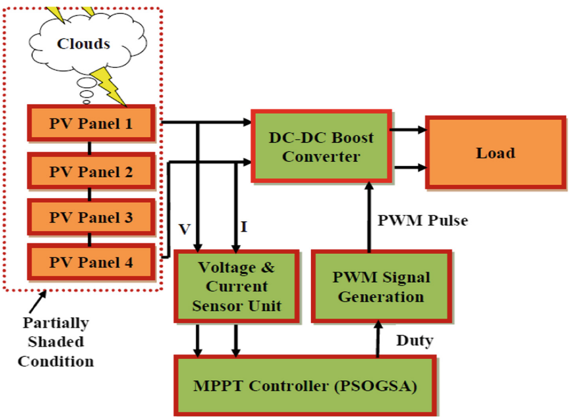

Fig. 2. Schematic structure of PV system with MPPT controller

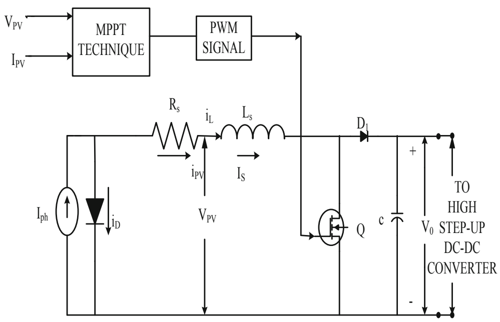

Fig. 3. Equivalent circuit model of solar PV module

2.1 DC-DC Boost Converter

PV array output voltage is very low, due to this it is insufficient to supply the required voltage to the load and to mitigate power quality-related issues and interruptions problems in the three-phase distribution system. MPPT tracking is used in connection with boost converter to improve the utilization of large arrays. A DC-DC converter is used between the source and the load to reduce power loss during transmission, adjust the load impedance to the panel impedance, and utilise the panel optimally. Figure 4 shows a schematic illustration of the boost converter.

2.1.1 Input-Output Voltage Relationship

For a single cycle, the average voltage across the inductor is zero. The voltage-second relationship is applied across the inductor in this case.

$$\mathrm{V_T(dT_s) + (V_T - V_0)(1 - d)T_s = 0} \tag{7}$$

$$V_0 = \frac{V_T}{1 - d} \tag{8}$$

At steady-state conditions average current through capacitor must be zero. For current via capacitors, the Ampere-Second balance is utilized.

$$(-i_o) * dTs + (i_T - i_0) * (1 - d)Ts = 0 \tag{9}$$

$$i_o = i_T(1 - d) \tag{10}$$

With the discussion from Eq. 10

$$R_o = \frac{R_T}{(1 - d)^2} \tag{11}$$

$R_T = \frac{V_T}{i_T}$ = impedance of the solar panel

$$\mathrm{R_T = R_o * (1 - d)^2} \tag{12}$$

where $\mathrm{R_0}$ = Impedance of the load.

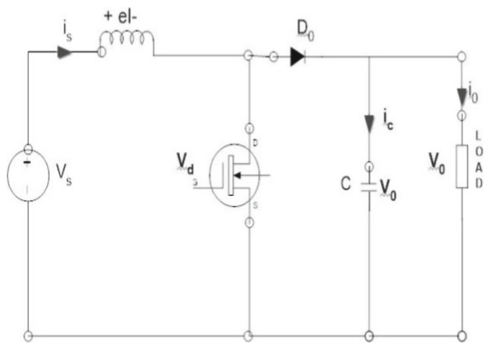

Fig. 4. DC-DC boost converter circuit

3 Conventional MPPT Methods

Perturb & Observe (P&O), Hill Climbing (HC) algorithm, Incremental Conductance (IC), Short Circuit Current (SCC), Open Circuit Voltage (OCV) and Ripple Correlation Control (RCC) approaches are some of the MPPT techniques that are suitable for uniform irradiance conditions. These procedures are basic and simple to execute but are not applicable for PV arrays operating under partial shading conditions.

3.1 Incremental Conductance Method

Solar weather conditions are changing relentlessly round the clock. Hence, the solar output voltage at the outside is changing; the operating point on the PV curve also changes accordingly. The incremental conductance method is one of the available tracking methods. This method controls the panel's output voltage perturbation in order to achieve the maximum functioning point. This can be attained by the measurement of output voltage and output current of the panel for a consequent interval of time. From this data, the instantaneous and incremental conductance is compared. At maximum power point the incremental and instantaneous conductance to be same.

Change in Incremental conductance

$$G_{\Delta d} = \frac{dI}{dV} \tag{13}$$

$$\text{Panel static conductance } G_s = -\frac{I}{V} \tag{14}$$

At maximum operating power point the change in slope of PV curve is zero (MPP) and is shown by below equation

$$\frac{dP}{dV} = 0 \tag{15}$$

The panel output power is the product of output current and voltage

$$\mathrm{P} = \mathrm{V} * \mathrm{I} \tag{16}$$

The equation for maximum power in the incremental conductance method is given by the following relation between power voltage and current

$$\frac{dP}{dV} = \frac{d(VI)}{dV} = I\frac{dV}{dV} + V\frac{dI}{dV} \tag{17}$$

At the maximum operating point $\frac{dP}{dV} = 0$ hence equating the above condition to zero can get the relationship between the incremental and instantaneous conductance as below.

$$\frac{dI}{dV} = -\frac{I}{V} \tag{18}$$

From the above equation, the maximum power is obtained when the incremental conductance (G_d) is equal to the static conductance (G_s) for the respective value of the MPP.

$$G_d = G_s \text{ at maximum power point (MPP)} \tag{19}$$

The panel output voltage and current are measured with the help of voltage and current sensors. If there is no voltage and current changes mean $\Delta V = 0$, $\Delta I = 0$ then the operating point reached the MPP. If the change in voltage is $\Delta V = 0$ but has a positive change in current indicates there is an increase in the isolation level hence, voltage is to be increased in the same direction to meet the MPP. In the next case if $\Delta V = 0$ but the change in current is negative then there is a decrease in the solar isolation level hence, voltage of the output is to be decreased to meet the MPP.

$$\frac{dI}{dV} = -\frac{I}{V} \tag{20}$$

The condition was satisfied then MPP is reached.

If $\frac{dI}{dV} > 0$ then the operating is on the left side of MPP of the PV curve, increase the voltage to reach MPP. If $\frac{dI}{dV} < 0$ the operating point is on the right side of MPP then decrease the output voltage to trace the maximum PowerPoint. The flowchart of the INC is as shown below in Fig. 5.

3.2 Particle Swarm Optimization Technique (PSO)

PSO has been successful as a probabilistic method based on bird movement. Concept of social analogy used to solve problems with PSO techniques. It was identified by

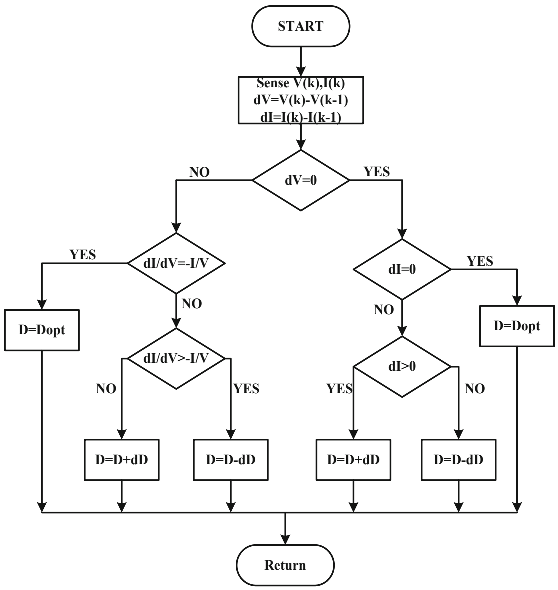

Fig. 5. Flowchart interpret the generalized INC method

James Kennedy in 1995. PSO creates a swarm of particles that moves around the search space to find the best solution globally. Each individual is depicted by a point in the n-dimensional exploratory space that modifies "flight" based on their own movement experience as well as that of the other birds in the flock.

Particle swarm optimization technique is attracting optimization problems and attempting to develop the candidate solution with the highest quality. Optimization of a problem with PSO based on the population size of the candidate size. Designate Particles and particle movements in search space based on particle position and velocity mathematical calculations. The local optimum position of each particle changes its position, and it moves to the ideal position of the N-dimensional search engine. It is, in this sense, a structured representation of particle movement within a swarm of fish (or) a colony.

PSO is a predictive optimization algorithm that solves optimization issues by scanning the base space of candidate solutions with fewer assumptions. PSO can address irregular and noisy optimization problems.

$$V_{nd}^{t+1} = w * V_{nd}^{t} + C_1\emptyset_1\left(P_{nd}^{t} - X_{nd}^{t}\right) + C_2\emptyset_2\left(P_{gd}^{t} - X_{nd}^{t}\right) \tag{21}$$

$$\mathrm{X}_{\mathrm{nd}}^{\mathrm{t+1}} = \mathrm{X}_{\mathrm{nd}}^{\mathrm{t}} + \mathrm{V}_{\mathrm{nd}}^{\mathrm{t+1}} \tag{22}$$

where

V_{nd}^{t}	n^{th} particle updated velocity at t^{th} iteration
V_{nd}^{t+1}	n^{th} particle updated velocity
X_{nd}^{t}	position of the n^{th}particle at t^{th} iteration
X_{nd}^{t+1}	Updated of n^{th} particle at t^{th} iteration
C_1, C_2	Cognitive and social learning factors
P_{nd}^{t}	Local optima position
$\emptyset_1, \emptyset_2$	Random values
w	Weight factor

The type of neighborhood particles used affects the calculation of Pg. The local best and global best neighborhoods are utilized in the PSO algorithm. To calculate Pg, all particles in the global space are taken into account. The neighborhood space considered by a particle on the complete space is known as the local search space. To ensure convergence, V_{ndt} is subjected to a limit (Vmax). Its value is normally retained with the interaction [−X ndmax, X ndmax], with X ndmax being the particle position's maximum value. The inertia weight W determines how much of the inertia search space is used, and how much of the inertia search space is used. The cognitive and social learning factors (C1, C2), as well as the inertia weight, are some of the tuning parameters for the PSO algorithm (w). The tuning factors have been studied in some empirical research.

This project covers PSOs for quasi optimization algorithms like maximum power point tracking, and the approach is outlined in Sect. 3.2. MPPT technology improves the power tired from the PV power system by regulating the duty ratio (determinant) of the boost converter. The PSO algorithm fine-tunes the duty cycle of each iteration to achieve peak power extraction from the PV string.

$$\mathrm{P_{PV}}\left(\mathrm{d_i^K}\right) > \mathrm{P_{PV}}\left(\mathrm{d_i^{k-1}}\right) \tag{23}$$

where

$P_{PV}\left(d_i^K\right)$ is the current power of i^{th} particle at k^{th} iteration
$P_{PV}\left(d_i^{k-1}\right)$ is the previous power of i^{th} particle at $(k-1)^{th}$ iteration.
$\left(d_i^K\right)$ is the kth iteration's duty cycle of the power converter

The duty cycle (d) of the boost converter is the constrained choice variable.

$$d_{min}^{0.05} < d_i^{K+1} < d_{max}^{0.95} \tag{24}$$

4 Results and Discussions

The conventional incremental conductance method is employed to determine boost converter duty cycle to get maximum power from PV panels using MPPT under various climatic conditions. The Simulink model of Fig. 6 consists of three strings with two series-connected PV modules, Resistive load and DC-DC boost converter. The PV module used in the simulation is shown in Table 1. Here, the controlling parameter is the duty cycle, and the upper and lower limit for PWM duty is set as 0.1 to 0.6, respectively (Tables 2, 3 and 4).

The power collected from the PV panels using the INC technique is 430.12 W for uniform irradiation condition, and the output power using the PSO method is 466.692 W, according to the simulation findings given in Fig. 7.

Table 1. PV Module Data

Parameter	Symbolic Representation	Value
Total number of cells	N_{cell}	60
Number of strings in parallel	Parallel strings	3
Number of strings in series	Series strings	2
Panel Voltage under open circuit	V_{OC}	21.6 V
Panel current under Short-Circuit	I_{SC}	6.2 A
Voltage at MPP	V_{mp}	15 V
I at current MPP	I_{mp}	5.5 A
Maximum Output Power	P_{MPP}	499.5 w

Table 2. Parameters for Particle Swarm Optimisation

Specification	Value
Coefficient of inertia (w)	0.8–1.12
decision variables (d)	1
Iterations count	10
Cognition learning Factor (C_1)	2
Social Learning Factor (C_2)	2

Table 3. Boost Converter Specifications

Parameter	Value
Inductor (L)	428.571 mH
Capacitance at input side (C_{in})	100 μF
Capacitance at output side (C_{out})	594 μF

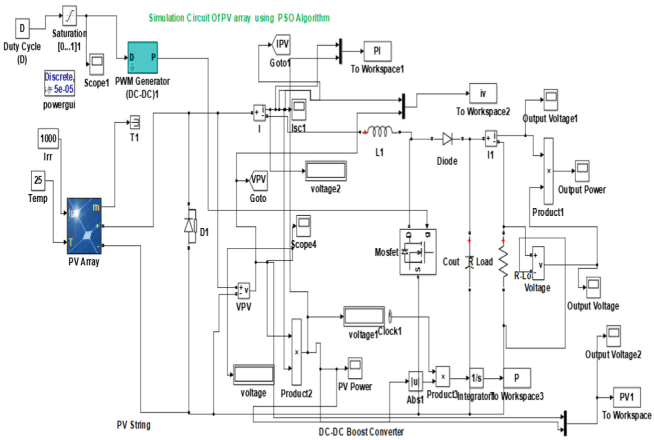

Fig. 6. Simulation circuit of PV system by implementing PSO Method

4.1 Experimental Validation

Figure 8 represents the hardware implementation of the development of MPPT algorithms using INC and PSO. To validate the proposed algorithm, the experimental test was conducted under uniform irradiation conditions.

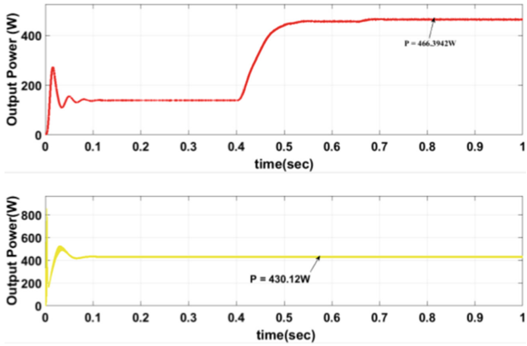

Fig. 7. Simulation results of Output power using PSO and INC algorithm

Table 4. Statistical Results of INC and PSO Optimization methods for Solar PV System MPP Extraction

Irradiance (W/m^2)	Temperature (°C)	Output of Solar Panel Using Incremental Conductance Method			Output values using PSO Algorithm			Output values using BAT (Roacha et al. [19]) Technique		
		Voltage (V)	Current (A)	Power (W)	Voltage (V)	Current (A)	Power (W)	Voltage (V)	Current (A)	Power (W)
1000	25	161.8	3.23	523.9	161.2	3.5	564.2	161.4	3.42	551.9
800	25	155.2	3.106	481.5	154.2	3.2	493.44	155.1	3.15	488.5
600	25	129.4	2.586	334.6	124	3.12	386.88	123.2	3.11	383.1
400	25	102.7	2.058	210.9	101.2	2.305	233.26	101.2	2.12	214.5

Fig. 8. Hardware implementation of the proposed PSO technique using FPGA controller

Figure 9(a) and 9(b) represent the output waveform and DC-DC boost converter's duty cycle of PV system. In comparison to the incremental conductance approach, the proposed PSO algorithm produced good results.

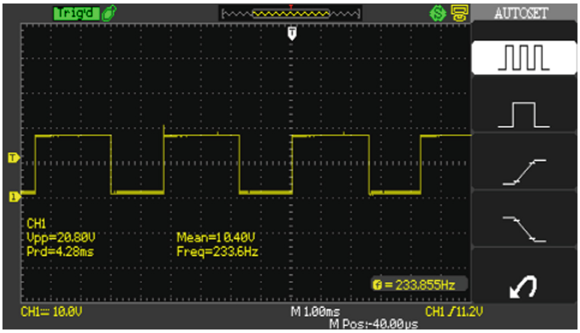

Fig. 9(a). Variation in duty cycle of boost converter.

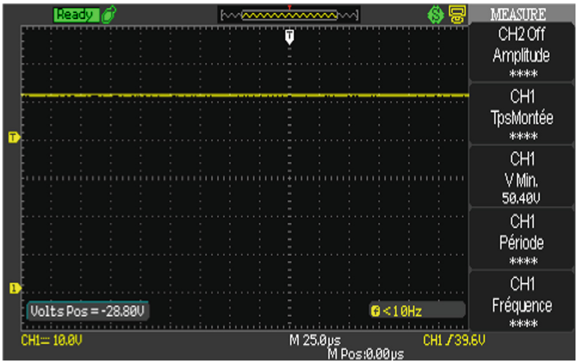

Fig. 9(b). Experimental output voltage of DC-DC Boost converter.

5 Conclusion

For a given solar PV array, the proposed research compares the PSO optimization approach to the standard INC algorithm based on MPPT. Under rapidly changing environmental conditions, the INC method fails to establish the exact MPP. Including partial shading. When the operating point comes close and around MPP in the Incremental conductance technique, it oscillates around MPP, resulting in power loss owing to oscillations. As a result, These methods cannot be used to track a PV system's maximum power point. The Incremental conductance method's efficacy and tracking speed are low, as evidenced by the findings and comments. Thus to track MPP, the variables are initialised using an efficient PSO approach, resulting in superior responsiveness. Despite this superior reaction, the suggested method ensures that there are no oscillations in the MPP's neighbourhood. Furthermore, in partial shade situations, the suggested The PSO technique locates global MPP and local MPP, thus the use of solar PV systems and efficiency are enhanced.

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Authors' Contributions. I. Divya Sathya Sree: Conceptualization, Methodology. P. Sobha Rani: Investigation, Validation. T. Nagadurga: Writing-Original draft, Software, Writing review and editing, Grammar correction.

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