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A novel fast MPPT strategy with high efficiency for fast changing irradiance in PV systems

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ABSTRACT

This paper discusses about the photovoltaic (PV) system novel non-iterative maximum power point tracking algorithm with faster converging speed under varying solar irradiation level. PV system is a scattered renewable energy resource and a safe environmental energy source. However, the PV power oscillates around MPP value due to the fluctuations of temperature and insolation effects, leading to nonlinear maximum power tracking issues. For each change in atmospheric condition, output of the PV system changes necessitating the need to search for new maximum power conditions. An efficient maximum power point tracking (MPPT) device that improves the power transmitting efficiency along with a suitable high frequency direct current (DC) to DC power converter device are required for efficient operation. Finally, a comparison is made between existing MPPT algorithms and proposed novel non-iterative MPPT algorithm. The proposed MPPT system show that the overall tracking speed of the proposed MPPT is 5.6 times, 3.8 times faster than perturb and observe (P&O) method and INC method respectively. During the variation of irradiance, the power loss is reduced by 18.84% and 11.29% in comparison with P&O and INC method. The proposed method also minimizes the steady state oscillations.

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1. INTRODUCTION

In recent years, the increasing global demand for renewable energy sources has propelled the widespread adoption of photovoltaic (PV) systems as a clean and sustainable alternative for power generation. PV systems harness solar energy and convert it into electrical power through photovoltaic cells. Maximum power point tracking (MPPT) algorithms play a pivotal role in optimizing the performance of PV systems by continuously adjusting the operating point of the solar array to extract maximum power under varying environmental conditions [1].

One critical challenge faced by PV systems is the rapid fluctuation in solar irradiance levels due to factors such as cloud cover, weather changes, and time of day [2]-[5]. Conventional MPPT algorithms often struggle to swiftly adapt to these fast-changing irradiance conditions, resulting in suboptimal energy extraction and reduced overall system efficiency [6]. Hence, the need for innovative MPPT strategies that can effectively address the dynamic nature of solar irradiance has become increasingly evident [7]-[10].

This research paper introduces a cutting-edge MPPT strategy designed to tackle the challenges posed by fast-changing irradiance in PV systems. The proposed strategy combines novel control algorithms with advanced sensing technologies to achieve rapid and accurate tracking of the maximum power point under dynamic irradiance conditions [11]. By enhancing the speed and efficiency of MPPT, the novel strategy aims to optimize energy harvesting and improve the overall performance of PV systems, especially in environments characterized by unpredictable and rapidly changing sunlight [12].

To substantiate the effectiveness of the proposed MPPT strategy, this research draws on a comprehensive review of existing literature on MPPT algorithms, solar irradiance dynamics, and PV system optimization [13]. Additionally, experimental results from real-world testing scenarios are presented to validate the performance and efficiency gains achieved by the novel MPPT strategy [14]. This study contributes to the ongoing efforts in the field of renewable energy research by providing a practical and efficient solution to enhance the adaptability of PV systems in the face of fast-changing irradiance. As the demand for clean energy continues to grow, the findings of this research have the potential to contribute significantly to the advancement and widespread adoption of solar power technologies.

2. MAXIMUM POWER POINT TRACKING METHODS

Maximum power point tracking (MPPT) is a technique used to achieve maximum power from photovoltaic devices. MPPT works based on various algorithms [15]. The ability of this algorithm to detect the maximum power output is the most important factor to be considered in choosing proper MPPT technique [16]. At different points on the solar panels irradiance levels may vary [17]. Due to this variation in one system, there may be multiple local maximum power points [18]. There are several publications that deals with MPPT, but each technique has its own limitations [19].

It is always desirable to extract maximum possible power from the solar panel. An MPPT controller enables extraction of maximum power from the PV array even at varying load and weather conditions [20]. The MPPT controller is a semiconductor device which is connected between the PV array and the battery or inverter [21]. Its working is based on an algorithm developed to extract maximum power. This controller consists of two important devices (PV system & DC-DC converter) [22]. A regulated DC-DC buck-boost converter uses the MPPT techniqcue to extract the maximum power from the PV array thereby required power is supplied to the load as shown in Figure 1.

Multiple algorithms exist to find the optimal operating point. Algorithms can be classified into two general categories:

- Indirect control (quasi seeking): These methods rely on a database of the solar-PV unit's parameters. The extensiveness of the database varies and can include items such as the unit's power-voltage (P-V) curve or empirical data [23]. Thus a drawback to these techniques is longer time to program and update the database as the unit ages.
- Direct control (true seeking): These methods share the commonality of relying solely on voltage and current measurements and therefore require minimal time as specific unit parameters are not required [24].

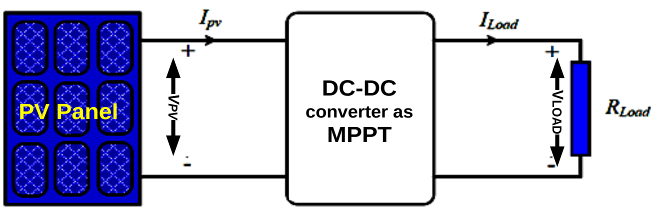

Figure 1. Figure regulated DC-DC converter as MPPT controller

2.1. Incremental conductance (IC) method (direct control)

The IC method seeks to reach the peak of the P-V curve by satisfying, as in (1).

$$\frac{dP}{dV} = \frac{d(V*I)}{dV} = I\frac{dV}{dV} + V\frac{dI}{dV} = 0 \quad (1)$$

Where P, V, and I are the measured DC power, voltage, and current, respectively. Multiplying (1) by1/V yields.

$$\frac{1}{V}\frac{dP}{dV} = \frac{I}{V} + \frac{dI}{dV} = G + dG \quad (2)$$

Where G is conductance and dG are incremental conductance.

In (2) establishes if the current operating point is above or below VMPP and the resulting voltage reference is determined from this. For example, if dP/dV> 0, then G + dG> 0 and the current operating point is on the left-hand-side of maximum power point (MPP) [25]. Alternatively, if dP/dV< 0, then G + dG< 0 and the current operating point is on the right-hand-side of MPP as shown in Figure 2.

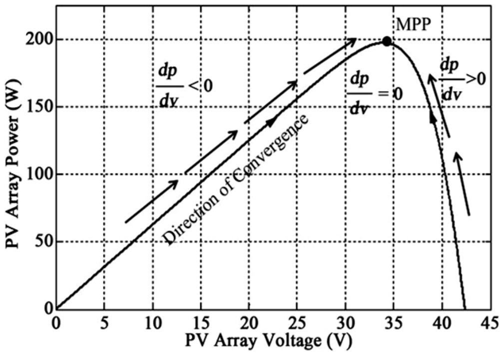

Figure 2. P-V curve for explanation of incremental conductance method

3. PROPOSED MODIFIED INCREMENTAL CONDUCTANCE MPPT

To extract the maximum power from solar PV systems MPPT technique is used. Between PV module and load a DC-DC converter is connected and duty cycle of the DC-DC converter always regulated to operate the PV system at maximum power point (MPP). Figure 3 shows the conventional INC method algorithm, which operates with high efficiency under steady irradiance. In this method the slope of the P-V curve is used to vary the duty cycle of converter to get the voltage corresponding to maximum power point, V_{mpp}. MPP is reached when $\frac{dP}{dV} = 0$, as in (3)-(6).

$$\frac{dI}{dV} = -\frac{I}{V} \tag{3}$$

$$\frac{dP}{dV} > 0, \text{ then } V_{pv} < V_{mpp} \tag{4}$$

$$\frac{dP}{dV} = 0, \text{ then } V_{pv} = V_{mpp} \tag{5}$$

$$\frac{dP}{dV} < 0, \text{ then } V_{pv} > V_{mpp} \tag{6}$$

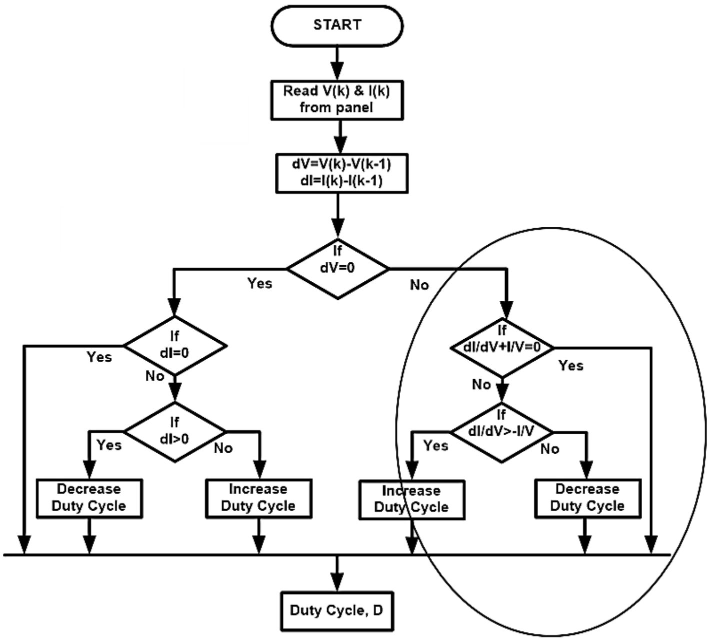

Figure 3. Incremental conductance MPPT algorithm

To determine the $V_{mpp,}$ knowledge of the relation between dI/dV and –*I/V*. If the slope $\frac{dP}{dV}$ is negative, then MPP must be moved to the left by decreasing the module voltage. If the slope is positive, the operating point must be moved to the right by increasing the module voltage. This process is repeated till the slope is zero. Finally, when the slope is null, the operating point is at the MPP and the algorithm stops the voltage adjustment.

For varying irradiance, the response of fixed step size is slow. So, the variable step size is proposed which decreases the step size, and convergence of MPP is slow when it reaches to near the peak of P-V curve. A modified INC algorithm is proposed to increase the converging speed with fast varying irradiance. The proposed block diagram is shown in Figure 4.

Figure 5 shows the *I-V* curve of the PV module under different levels of solar irradiance and also the MPPs which can be connected approximately by a straight line (MPP line). A load line is generated and it can be imposed on the I–V curve when the PV module supplies power to the load. The power generated by the PV module is the product of the voltage and current of PV module at the intersection point between the load line and the I–V curve. Therefore, the output power of PV module varies according to the solar irradiation (I–V curve) and the resistance of the load (load line).

The relation between the input-output voltage and currents for a DC-DC converter is represented by (7).

$$V_{input} = \frac{1-D}{D} V_{output} \tag{7}$$

$$I_{input} = \frac{D}{1-D} I_{output} \tag{8}$$

Divide in (7) with (8) we get (9).

$$R_{input} = \frac{(1-D)^2}{D^2} R_{output} \tag{9}$$

Where D is the duty cycle or duty ratio, V_{input} is the input voltage of the converter or the voltage of the PV module V_{pv}, I_{input} is the input current of the converter or the current of the PV module I_{pv}, R_{input} is the input resistance of the converter or the resistance seen by the PV module, and R_{output} is the output resistance of the converter or load resistance R_{load}.

From (9) it is noticed that duty cycle can be regulated to force the input resistance of the converter to be varied until the load line cuts the *I-V* curve at MPP. (9) can be written as (10). Load resistance can be calculated at any operating MPP by substituting the duty cycle, PV voltage, and PV current in (10).

$$\frac{D^2}{(1-D)^2} = \frac{R_{output}}{R_{input}} \tag{10}$$

$$D = \frac{\sqrt{\frac{I_{input}}{V_{input}} R_{load}}}{1+\sqrt{\frac{I_{input}}{V_{input}} R_{load}}} \tag{11}$$

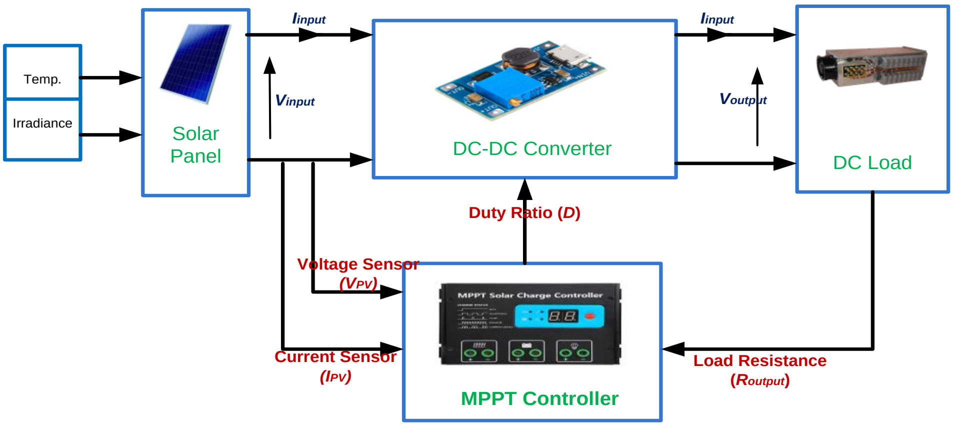

Figure 4. Block diagram of proposed DC/DC converter with modified INC algorithm

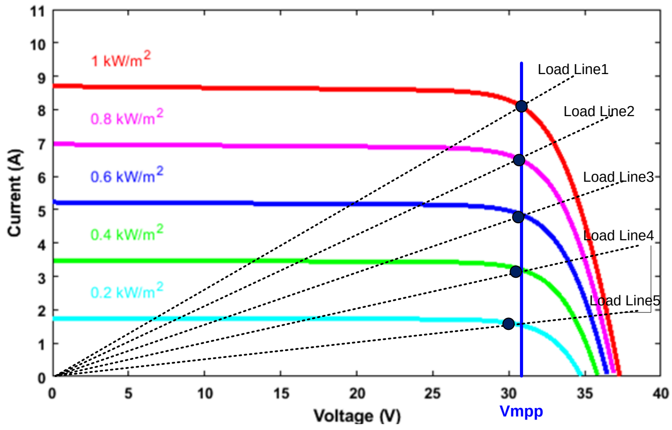

Figure 5. I-V Curves at different irradiances with load line and MPP line

In incremental conductance method the slope of power vs voltage ($\frac{dP}{dV}$) of solar panel is zero at the MPP. Getting zero slope in practical systems requires several iterations. It is reasonably accurate to allow an acceptable error while finding the MPP. An attempt has been made in this thesis to modify this condition of zero slope to find MPP, with a small permitted error. In proposed method, permitted error of 0.06 as shown in (12) is used to eliminate the steady-state oscillation in the system after the MPP is reached. The permitted error is chosen to be more than MPPT step size of 0.05.

$$\frac{dI}{dV} + \frac{I}{V} < 0.06 \qquad (12)$$

Figure 6 shows the flow chart for the proposed algorithm.

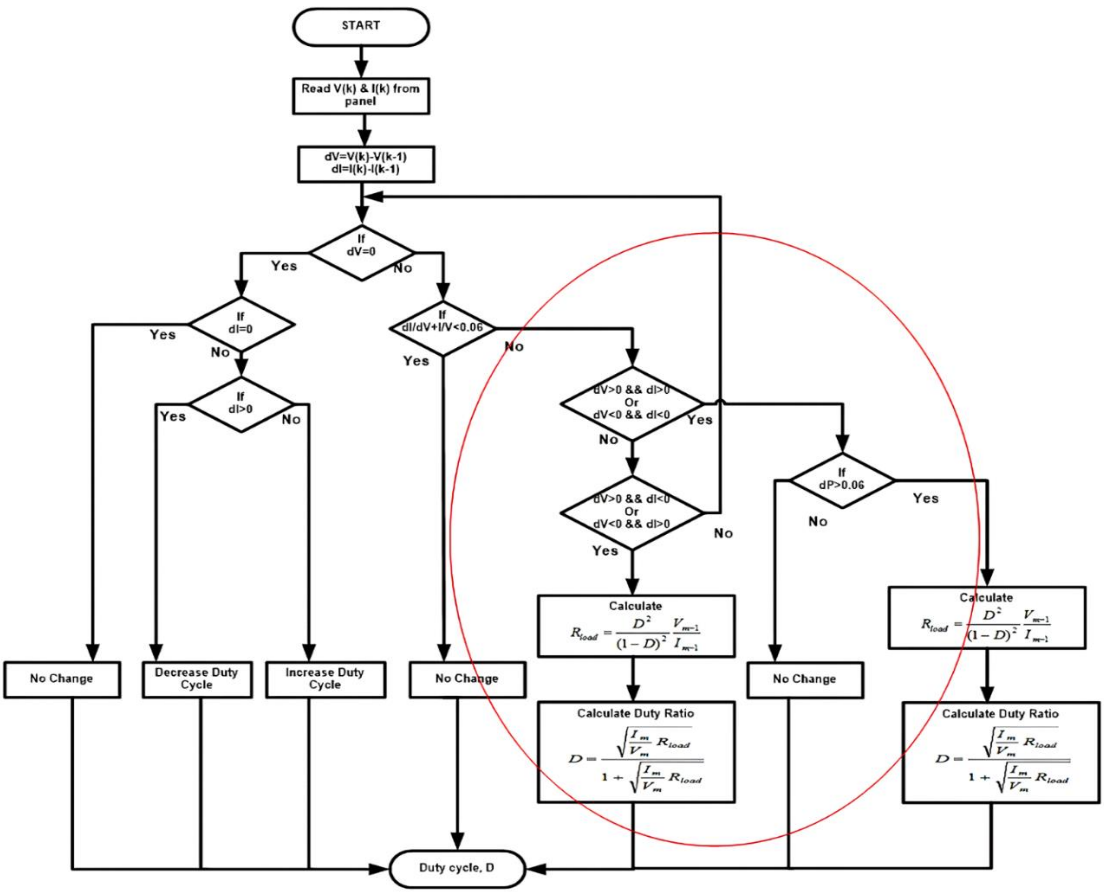

Figure 6. Proposed modified INC MPPT method under fast varying irradiance

3.1. Working procedure for decrease in solar irradiance level

Figure 7 shows the load lines on the *I-V* curves for solar irradiance level at 0.4 and 1.0 kW/m^2. When the PV module is operating at 1000 W/m^2, the MPP operates at the point A (V_{MPP1}, I_{MPP1}) of the load line 1 as shown in Figure 7. Then, if the solar irradiance is decreased from 1000 W/m^2 to 400 W/m^2, then the MPP immediately comes to point B (V_B, I_B) along the load line 1, which is far away from the MPP of 400 W/m^2, point C, because the duty cycle of the DC-DC converter remains unaltered. In order to track the new V_{MPP} and I_{MPP} of the PV module equation (11) is used. But these two values are unknown and their approximated values are submitted in (11) to track the new MPP. As shown in Figure 7, the current at point B, I_B is very close to the short circuit current of 400 W/m^2 and the I_{MPP} is approximately equals to 0.8 times of the short circuit current (0.8*I_{SC}). Then 0.8*I_{SC} is approximated as new I_{MPP}. The V_{MPP} at all the solar irradiance levels is almost equal hence the previous V_{MPP} is approximated as a new $V_{MPP.}$ So, substituting $I_{MPP} \approx I_B$ and $I_B = I_{PV,}$ $V_B = V_{MPP} = V_{PV}$ in (11) to track the new MPP to the load line 2, point C which is very near to new MPP.

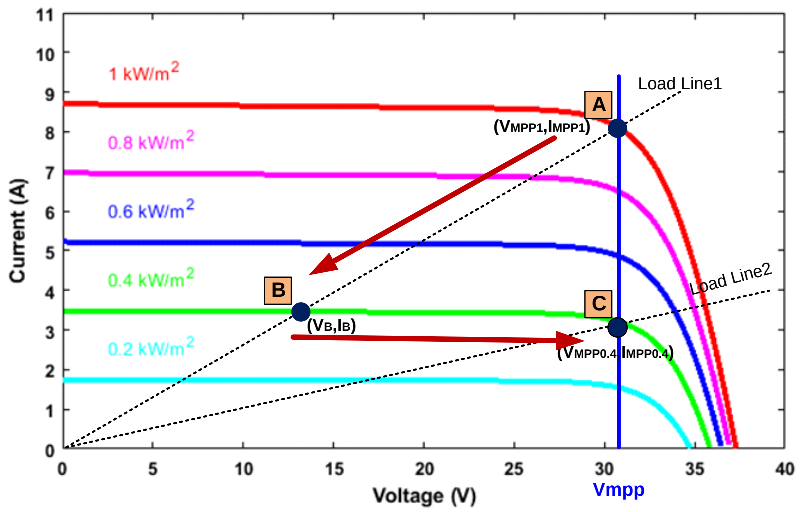

Figure 7. MPP on *I –V* curves for decrease of solar irradiation level from 1.0 to 0.4 kW/m^2

4. SIMULATION RESULTS

In the present work STH-250WH panel is considered and, as shown in Table 1, the specifications of photovoltaic panels offer only a few parameters. Consequently, several mandatory parameters for the modeling of the photovoltaic panel are omitted in the manufacturer's specifications, namely the diode saturation current, the current generated by the light, the ideality factor of the diode, and the series and shunt resistors.

Simulation for conventional incremental conductance algorithm and proposed algorithm are carried out for constant, variable irradiance and the results are compared. The sampling time for the MPPT controller is 0.05 s. Simulation is carried out for 1 sec for constant irradiance and time is 4 sec for solar irradiation level which varies from low (0.4 kW/m^2) to high (1.0 kW/m^2) and then reduced to low again in order to investigate the performance of the system under fast-varying solar irradiation level.

4.1. Simulation results with variable solar irradiance

In this test condition, solar irradiance is varied from 500 W/m^2 to 1000 W/m^2 at time period of 1 sec and then it is decreased from 1000 W/m^2 to 800 W/m^2 a 2 sec time period. Again, it decreased from 800 W/m^2 to 600 W/m^2 at 3 sec time period.

4.1.1. With the INC MPPT method

Over a four-second timescale, a solar photovoltaic (PV) system shows voltage and current changes under varying irradiance circumstances as shown in Figure 8. During the first and last intervals (0–1 sec and 3–4 sec) with irradiance levels of 500 W/m^2 and 600 W/m^2, the system shows variable voltage and current outputs (17-34 V and 2-4 A for the first interval, 20-32 V and 3-5 A for the last), never reaching a steady state. The system's responsiveness or other performance measures may explain the good dynamic performance during these swings and the failure to stabilize. At irradiance levels of 1000 W/m^2 and 800 W/m^2, the system provides more stable outputs of 30.7 V and 8.15 A, and 32 V with 6-7 A, respectively, throughout the 1–2 sec and 2–3 sec intervals. It reaches a steady state faster in these intervals, 0.02 seconds for the former and 0.05 seconds for the latter, again good performance. This shows that the PV system can handle greater irradiance levels well, establishing stability quickly, but at lower or more fluctuating levels, it struggles to reach a steady state despite a strong performance rating.

Simulation analyses for INC method, it fail to track MPP for sudden variation at different irradiance levels at low intensity and track better MPP at high intensity. Steady-state analysis and dynamic performance are shown in Table 2. The system reaches a steady state condition in 20 ms at maximum irradiance and dynamic performance is also good.

Table 1. Specifications of Soltech 1STH-250 WH PV panel at standard testing conditions (STC) of 1000 W/m^2 and 25 °C

Characteristics	Value
Maximum power	250 W
Voltage at Pmax, Vmp	30.7 V
Current at Pmax, Imp	8.15 A
Short-circuit current, Isc	8.66 A
Open-circuit voltage, Vco	37.3 V
Temperature coefficient of open-circuit voltage Voc, kV	-369.0 mV/C
Temperature coefficient of short-circuit current Isc, Ki	86.9 mA/C
The number of cells	60

Table 2. Voltage and current values at different irradiance conditions with INC method

Time period (in sec)	Irradiance (in W/m^2)	V (volts)	I (amps)	Reaches to steady state (in sec)	Dynamic performance
0 – 1	500	17-34 V	2-4 A	Never reaches	Good
1 – 2	1000	30.7 V	8.15 A	0.02	Good
2 – 3	800	32 V	6-7 A	0.05	Good
3 – 4	600	20-32 V	3-5 A	Never reaches	Good

4.1.2. With the proposed MPPT method

In the proposed MPPT controller initially duty cycle is generated according to the characteristics of the I-V curve and DC-DC converter and regulates the duty cycle by using a small step size. This small step size can improve efficiency by ensuring that the operating point is on the MPP. Figure 9 shows the dynamic performance of a solar photovoltaic (PV) system over four seconds under different irradiation levels. Starting at 500 W/m^2, the system outputs 24 volts and 4 amps, reaching a steady state in 0.0055 seconds, demonstrating excellent dynamic performance. When irradiance reaches 1000 W/m^2, voltage and current increase to 30.7 volts and 8 amps, respectively. The system reaches a steady state in 0.03 seconds, maintaining excellent performance. When irradiance drops to 800 W/m^2, the system adapts to provide 32 volts and 6 amps, reaching a steady state in 0.03 seconds, exhibiting consistent performance. Ultimately, reducing irradiance to 600 W/m^2 yields 33 volts and 5 amps, reaching a steady state in 0.03 seconds with excellent dynamic behavior. The solar PV system responds well to irradiance variations and stabilizes rapidly, which is essential for reliable and efficient solar energy conversion.

The voltage, current values, and performance of the PV system with the proposed MPPT are shown in Table 3. From the simulation result analysis, it is observed proposed MPPT tracks MPP within milliseconds at low and high intensity. The system will also reach to steady state within 30 ms and the dynamic performance of the system is very good.

Table 4 compares the performance of three different methods for maximum power point tracking (MPPT) in solar PV (photovoltaic) systems. The proposed method for maximum power point tracking in solar systems beats the P&O, INC, and P&O methods across many parameters. The best efficiency at 94.25%, lowest tracking power loss at 5.76%, and fastest tracking time of 0.28 seconds indicate outstanding adaptiveness to changing solar circumstances. Its steady-state oscillations are relatively negligible, ensuring constant power output. P&O has the lowest efficiency (83.47%), biggest tracking power loss (24.60%), slowest tracking response (1.42 seconds), and largest steady-state oscillations, making it the least desirable option. INC has a middle ground efficiency of 91.51%, moderate tracking power loss (17.05%), faster tracking time (1.16 seconds), and small steady-state oscillations than P&O. The proposed technology improves solar PV system performance, making it a promising solar energy harvesting solution.

It is found that, under the variation of solar irradiance, the tracking speed of the proposed technique is 5.6 times and 3.8 times faster than the P&O and INC methods. The power loss during the tracking is also less when compared with other techniques. The steady-state oscillations of P&O and INC methods are large due to the oscillations in the duty cycle, whereas it is negligible for the proposed method.

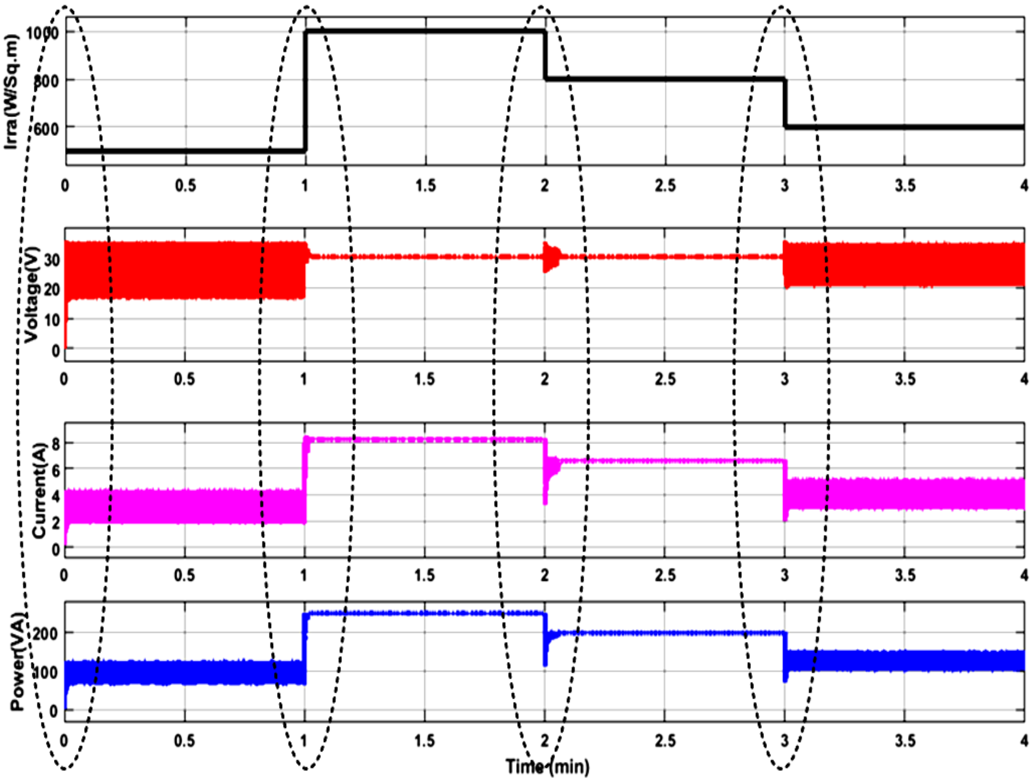

Figure 8. INC MPPT system simulation results with variable irradiance of 1000 W/m^2:
(i) irradiance, (ii) PV voltage, (iii) PV current, and (iv) PV power

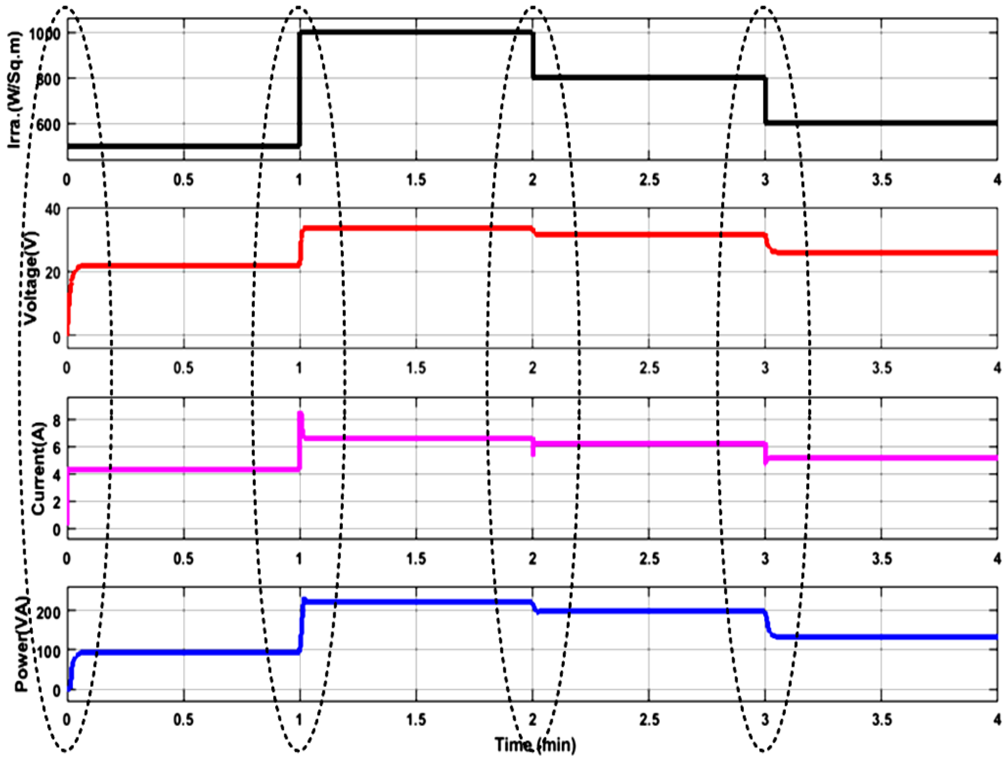

Figure 9. Proposed MPPT system simulation results with variable irradiance of 1000 W/m^2:
(i) irradiance, (ii) PV voltage, (iii) PV current, and (iv) PV power

Table 3. Voltage and current values at different irradiance conditions with proposed method

Time period (in sec)	Irradiance (in W/m^2)	V (volts)	I (amps)	Reaches to steady state (in sec)	Dynamic performance
0 – 1	500	24 V	4 A	0.0055	Very good
1 – 2	1000	30.7 V	8 A	0.03	Very good
2 – 3	800	32 V	6 A	0.03	Very good
3 – 4	600	33 V	5A	0.03	Very good

Table 4. Comparison of proposed MPPT with other techniques for variation in solar irradiance

Parameter	P&O method	INC method	Proposed method
Efficiency (%)	83.47	91.51	94.25
Tracking power loss (%)	24.60	17.05	5.76
Tracking time (s)	1.42	1.16	0.28
Steady state oscillations	Large	Small	Negligible

5. CONCLUSION

In the proposed work a novel and fast-acting MPPT for fast varying solar irradiance is implemented. Since the proposed MPPT is not an iterative method, directly it tracks the MPP when there is a sudden change in irradiance or in load. Simulation of the proposed MPPT method is implemented for various irradiance levels and compared with P&O, INC algorithms. In the conventional method by trial and error, the peak power point is reached. The time taken to track MPP is more. So, the power loss in those methods will be greater. These methods continuously track the voltage and/or current, without using empirical data. The main advantage of such methods is that they do not require prior knowledge of the PV array characteristics. The drawbacks of the conventional algorithms are slow tracking speed, and steady-state oscillation at the transient stages. To overcome this drawback a novel and fast-acting modified INC algorithm is proposed to increase the converging speed under fast varying irradiance. In the incremental conductance method, the slope of power vs voltage characteristic of solar panels is zero at the MPP. But it can never be met practically; so, a permitted error of 0.06 is acceptable to detect MPP. The proposed method directly calculates the required duty cycle to obtain the new MPP by considering the load line. This reduces the normal iterative process and reaches the required MPP point in a fast way. The results show that the overall tracking speed of the proposed MPPT is 5.6 times, 3.8 times faster than the P&O method and INC method respectively. During the variation of irradiance, the power loss is reduced by 18.84% and 11.29% in comparison with the P&O and INC methods. The proposed method also minimizes the steady-state oscillations.

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