Comparison between incremental conductance and perturb and observe algorithms in photovoltaic system under low temperature and irradiation levels

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ABSTRACT

This paper compares two mostly used maximum power point tracking (MPPT) methods, perturb and observe (P&O), and incremental conductance (INC), for a photovoltaic (PV) system integrated with a step-up converter and resistive load. The evaluation was conducted using MATLAB/Simulink under two specific environmental conditions: low irradiation and temperature levels. The results indicate that under irradiation levels below 200 W/m², the INC algorithm outperforms P&O by exhibiting minimal fluctuations and achieving higher efficiency. Conversely, under low temperature (below 25 °C) the P&O method reaches the highest efficiency, exceeding 99%. These findings highlight the importance of selecting the appropriate MPPT algorithm based on specific environmental conditions to optimize the energy output of PV systems.

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1. INTRODUCTION

The increasing awareness of the detrimental impact of traditional fossil fuel sources on air pollution and climate change [1] has intensified the search for alternative energy sources to minimize greenhouse gas emissions. Among the various natural energy sources, photovoltaic (PV) system is considered as the most promising option, it converts sunlight into electricity, providing a sustainable solution for energy generation during daylight hours [2].

Maximizing the performance of PV systems is crucial for them to be a suitable alternative to conventional energy sources. However, PV systems output characteristics are highly sensitive to environmental conditions, particularly temperature and irradiance [3]. To address these challenges maximum power point tracking (MPPT) systems are employed to ensure the operation of PV systems at their optimal power point. Many MPPT techniques have been suggested, which can be categorized into conventional and advanced approaches [4]–[7] such as perturb and observe (P&O) [8], [9], incremental conductance (INC) [10], [11] and artificial neural network (ANN) [12].

Several comparative studies on MPPT techniques have been conducted in [13], [14] Another comparison was presented in [15] where P&O, INC, and ANN were evaluated for their performance under dynamically changing conditions. The results show that both P&O and INC techniques are effective, especially under conditions of slowly changing irradiance, while ANN MPPT accurately tracks the MPP under both rapidly and slowly varying solar radiance**.** However, the results presented in [16] indicate that the P&O algorithm performs better close to the MPP under standard test conditions (STC) compared to variable conditions, On the other hand, the INC algorithm outperforms P&O in terms of speed and accuracy in reaching the MPP, particularly under fluctuating insolation and temperature conditions. However, the performance of these algorithms under low temperature and irradiation levels has not been previously studied.

The purpose of this paper is to assess the behavior of P&O and INC MPPT algorithms under specific conditions characterized by low irradiation levels (less than 200 W/m²) and low temperature levels (less than 25 °C). The aim is to evaluate the effectiveness of each algorithm under challenging environmental conditions that significantly impact PV system efficiency. By understanding how each algorithm performs under these specific conditions and to determine the optimal scenarios for their use. Furthermore, this study contributes to technological advancements by offering valuable data that can guide the development of more advanced and adaptive MPPT algorithms capable of switching between P&O and INC based on real time environmental conditions.

The organization of this paper is as follows: section 2 represents the mathematical modeling of the solar cell and the overall system configuration. The MPPT techniques are discussed in section 3, in section 4 a comparative analysis is conducted under two distinct scenarios in MATLAB/Simulink. Finally, the conclusion is presented in the last section.

2. METHOD AND SYSTEM DESCRIPTION

The standalone photovoltaic system proposed in this paper consists of four primary components, as shown in Figure 1. The first component is the energy source, which is the photovoltaic panel. The second component is a step-up converter. The third component represents the load, and the fourth component comprises the MPPT techniques.

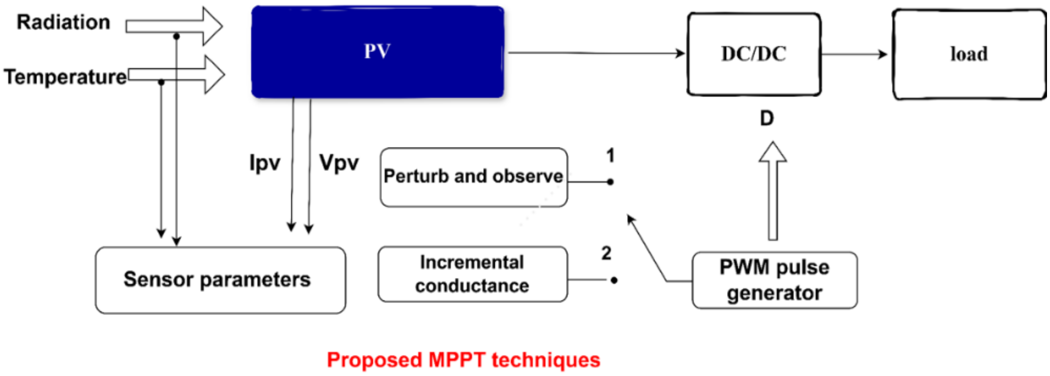

Figure 1. The PV system with the MPPT controller and DC load

2.1. Mathematical model of PV cell

The mathematical modeling of a PV cell is based on its operation as a p-n semiconductor junction. This model represents the PV cell using a current source I_{ph} in parallel with a diode, along with two resistors: one in series (Rs) and one in shunt (Rsh) [17], [18] as illustrated in Figure 2. I_{ph} simulates the photo-generated current, while the diode accounts for the p-n junction behavior. The series resistor represents internal losses due to current flow, and the shunt resistor represents leakage currents through the cell.

The characteristic equation of the PV cell is described as (1) [19]:

$$I_{pv} = I_{ph} - I_d - I_{shunt} \tag{1}$$

- The photocurrent I_{ph} is described as (2).

$$I_{ph} = \frac{G}{G_{STC}}(I_{S,STC} + K_T\,(T - T_{STC})) \tag{2}$$

where G the irradiance (W/m²), G_{STC} the irradiation reference (1,000 W/m²), K_T the temperature coefficient of cell, T_{STC} the temperature at standard test condition (K).

- The current through the diode is described as (3).

$$I_d = I_s\ [e^{\frac{q*(\mathrm{V_{pv}}+R_{series}*\mathrm{I_{pv}})}{N_S*\mathrm{K}*\mathrm{T}*\mathrm{a}}} - 1] \quad (3)$$

- The saturation current I_s is expressed as (4).

$$I_s = I_{RS} * \left(\frac{T}{T_{STC}}\right)^3 * \exp\left[\, \mathrm{q}E_G \frac{\left(\frac{1}{T_{STC}} - \frac{1}{T}\right)}{K*T*A}\right] \quad (4)$$

where E_G is semiconductor band gap energy (1.1 V).

- The reverse saturation current I_{RS} is expressed as (5).

$$I_{RS} = \frac{I_{SC}}{e^{[\frac{q*V_{OC}}{N_S*\mathrm{K}*\mathrm{T}*\mathrm{a}} - 1]}} \quad (5)$$

where I_{sc}, V_{oc} are the short circuit current (A) and the open circuit voltage (V) respectively.

- The current through the shunt resistance I_{shunt} is determined in function of the voltage V_{pv} and current I_{pv} of PV system as presented in (6).

$$I_{shunt} = \frac{\mathrm{V_{pv}}+R_{series}*\mathrm{I_{pv}}}{R_{shunt}} \quad (6)$$

- The current of the solar cell is represented using (7) [20].

$$I_{pv} = N_p I_{ph} - I_s N_p\ [e^{\frac{q*(\mathrm{V_{pv}}+R_{series}*\mathrm{I_{pv}})}{N_S*\mathrm{K}*\mathrm{T}*\mathrm{a}}} - 1] - \frac{\mathrm{V_{pv}}+R_{series}*\mathrm{I_{pv}}}{R_{shunt}} \quad (7)$$

The solar generator system studied in this paper is Sun Power SPR-305-WHT which has the specific parameters as mentioned in Table 1. A combination of sixty-six PV modules has been used. Figure 3 displays the characteristics curves (I-V) and (P-V) of the PV system.

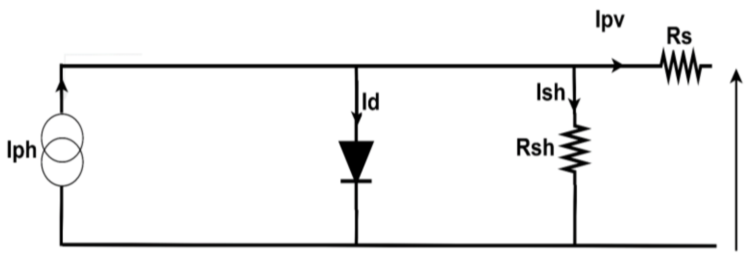

Figure 2. Electrical representation of a PV cell

Table 1. Inputs parameters of simulation of PV system

PV cell characteristic	Value
Maximum power (W)	305 W
Open circuit voltage V_{oc} (V)	64.2 V
Short circuit current I_{sc} (A)	5.96 A
Optimum voltage V_{MPP} (V)	54.7 V
Optimum current I_{MPP} (A)	5.58 A
Temperature coefficient of V_{oc}	-0.277
Temperature coefficient of I_{sc}	0.061745
Number of cells	96
PV system modules	66 modules connected in parallel, 5 modules in series in each

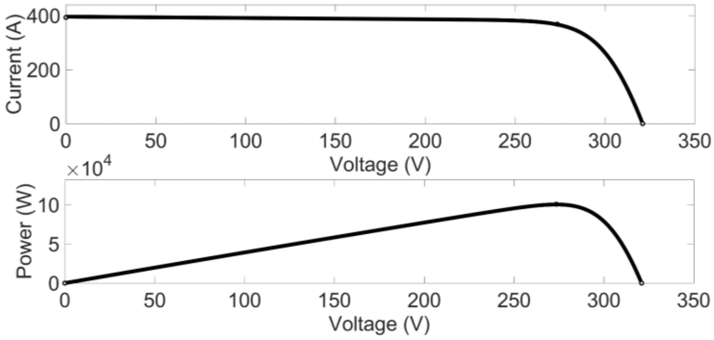

Figure 3. The characteristics of PV system under 1,000 W/m² and 25 °C

2.2. DC-DC step-up converter

A step-up converter's main objective is to raise the input voltage to a greater level at the output [21], it operates using components like an inductor, switch, diode, and capacitor as seen in Figure 4, the energy is produced in the inductor during the switch ON state and it is discharged at the OFF state of the switch. the input and the output voltage V_i, V_0 respectively depend on the duty ratio as expressed by (8) [22].

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

where d denotes the duty cycle. The step-up converter parameters are illustrated in Table 2.

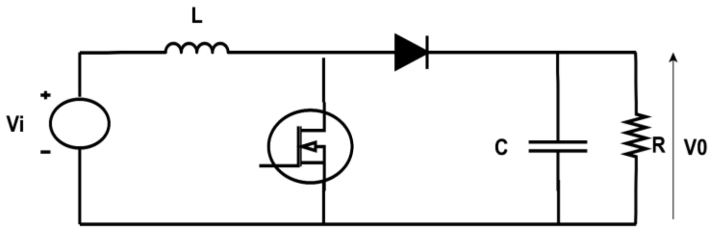

Figure 4. Boost converter model

Table 2. Inputs parameters of step-up converter

Parameters	Value
Inductor L (mH)	5
Switching frequency fs (Hz)	5,000
Output power P(KW)	100
Output capacity (μF)	12,000
Input capacitor (μF)	100

2.3. Maximum power point tracking

Maximum power point tracking (MPPT) is a vital technology in PV systems designed to optimize their efficiency and energy output. The primary function of MPPT methods is to continuously adjust the electrical operating point of the PV modules to ensure they generate the maximum power, under variable temperature and irradiance. by dynamically optimizing the voltage and current, MPPT systems can significantly enhance the overall performance of PV installations.

2.3.1. Perturb and observe

The perturb and observe (P&O) method is widely employed to maximize power output in solar energy systems, involving continuous adjustment of the operating voltage (V) of a solar panel while monitoring its impact on output power (P). This method starts by gradually increasing the voltage. If power increases, adjustments continue in that direction until reaching the maximum power point (MPP) [23].

Conversely, if power decreases, adjustments are reversed to steer the system towards its optimal operating point. Figure 5 depicts the algorithm's flowchart.

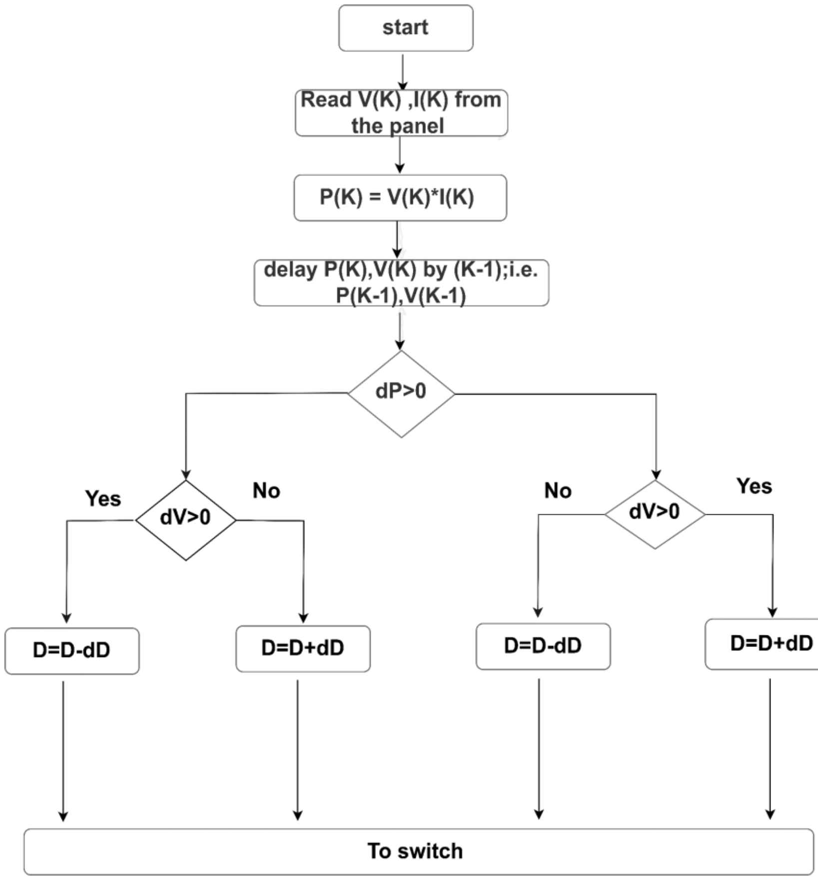

Figure 5. Flowchart of P&O algorithm

2.3.2. Incremental conductance

This algorithm identifies the MPP by analyzing the derivative of the power and voltage ($\frac{dP}{dV}$) of the photovoltaic generator. At the MPP, this derivative is zero, it is negative to the right of the MPP, and positive to the left of it [23] as illustrated in Figure 6. The technique evaluates the instantaneous conductance value ($\frac{I}{V}$) alongside the incremental conductance ($\frac{\Delta I}{\Delta V}$) to reach the maximum operating point. The inputs to the INC algorithm are V_{pv}, I_{pv} and the duty cycle D as the output. The flowchart of the INC algorithm is illustrated in Figure 7.

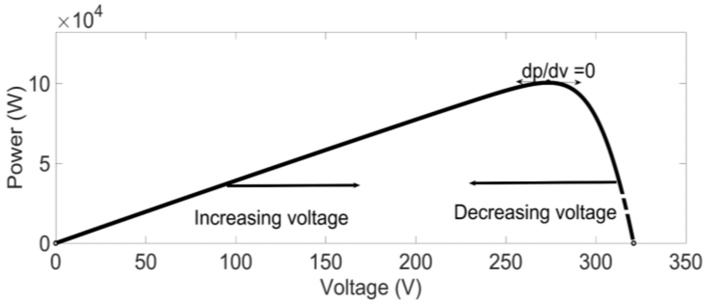

Figure 6. P-V characteristics of INC algorithm

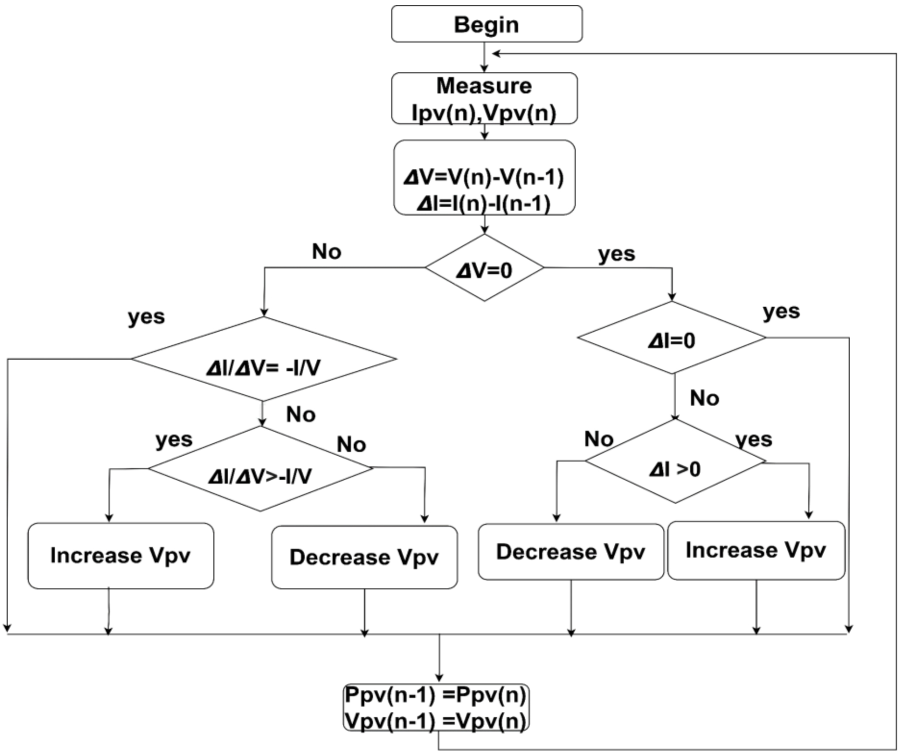

Figure 7. Flowchart of the INC algorithm

3. RESULTS AND DISCUSSION

The evaluation of the suggested MPPT techniques for a 100.65 kW photovoltaic system was conducted using the MATLAB/Simulink environment. The first strategy implemented is the P&O algorithm, with the simulated model as displays in Figure 8 while the second technique INC is presented in Figure 9. Two scenarios were applied for each model:

- The first scenario involves a fixed temperature of 25 °C and a dynamic decrease in low irradiation levels at 200, 180, 150, 120, and 100 W/m².
- The second scenario involves a fixed irradiation of 1,000 W/m² and a dynamic decrease in low temperature levels at 25 °C, 20 °C, 15 °C, 10 °C, and 5 °C.

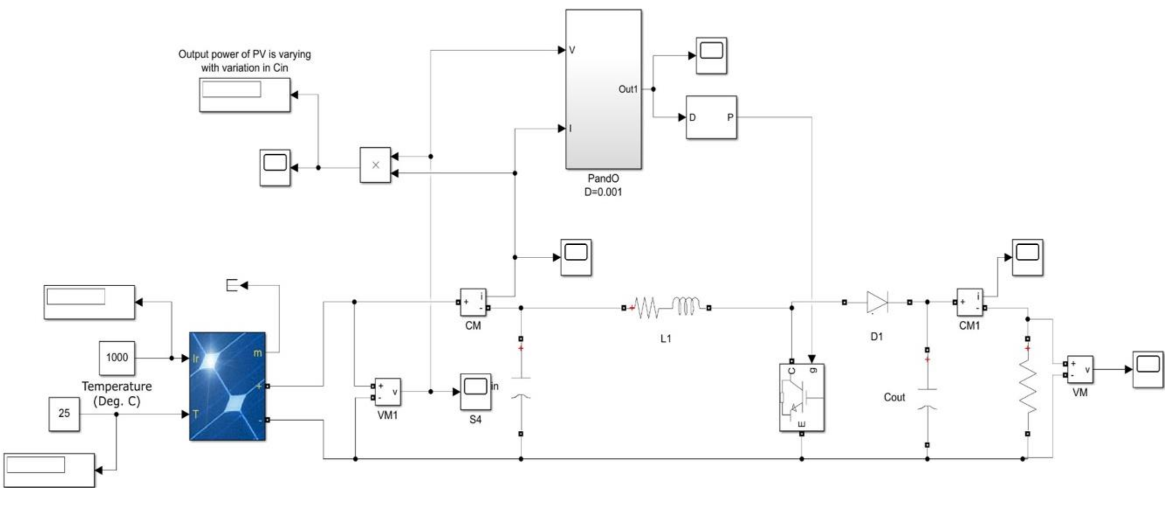

Figure 8. Simulation of a PV system integrated with the P&O algorithm in MATLAB/Simulink

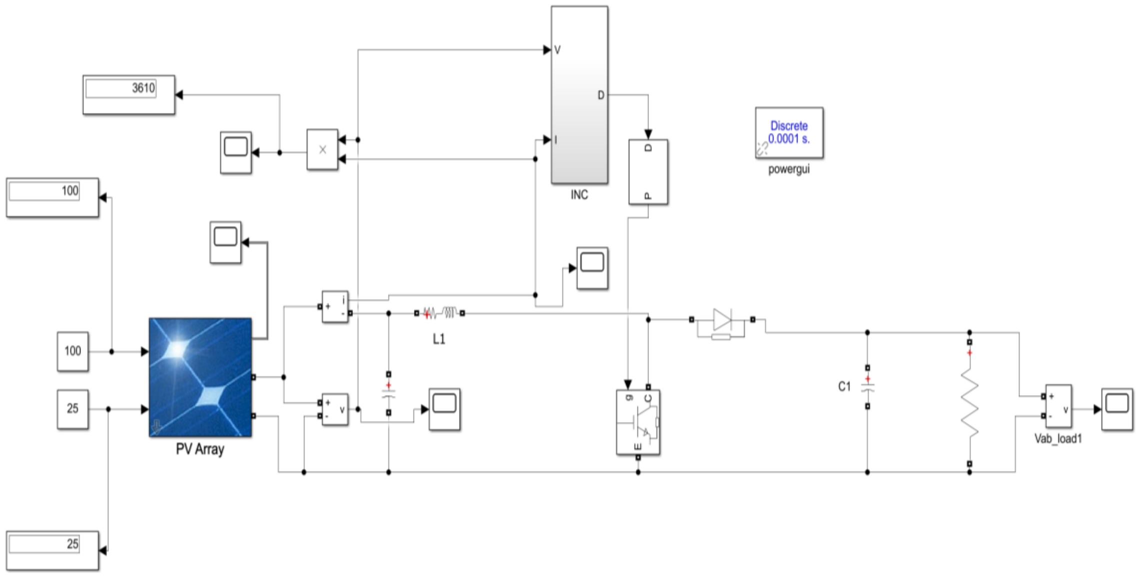

Figure 9. Model of PV system integrated with INC algorithm in MATLAB/Simulink

In this paper, the tracking efficiency (η_{MPPT}) is applied to assess the effectiveness of these MPPT techniques, which can be calculated as described in [24].

$$\eta_{MPPT} = \frac{\int_{t_1}^{t_2} P\,dt}{\int_{t_1}^{t_2} P_{max}\,dt} \tag{9}$$

where t_1, t_2 are the start and final instants of the simulation time. P is defined as the power extracted through MPPT algorithms. P_{max} represents the theoretical value of the PV system.

3.1. Scenario 1: Variation in low irradiation level at fixed temperature

Figure 10 illustrates the variations in irradiation levels from 200 to 100 W/m² throughout the simulation time, while maintaining a constant temperature (T=25 °C). These abrupt changes occur at specific times: 1, 2, 3, and 4 s. Figure 11 shows the power response of the MPPT algorithms to these sudden and rapid variations in irradiation levels.

The simulation results show that the INC was the first to reach the MPP at 200 W/m² and T= 25 °C with a response time of 0.15 s, with less oscillation at the steady state, this explain the benefits of this technique compared to the P&O which has a more significant oscillation [24] and it takes a longer tracking time than INC in contrast to [25], in addition the INC succeeded to extract more power better than P&O as depicted in Table 3 ,these findings agree with the results of the study mentioned in [26]. In term of efficiency, the INC reached a moderate average efficiency of 56.26% compared to P&O (45.7%).

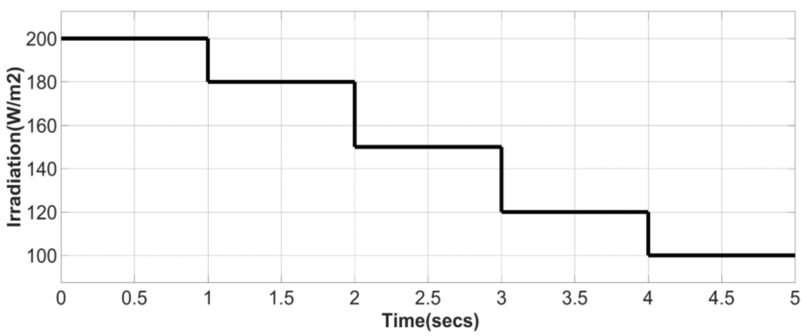

Figure 10. irradiation variation

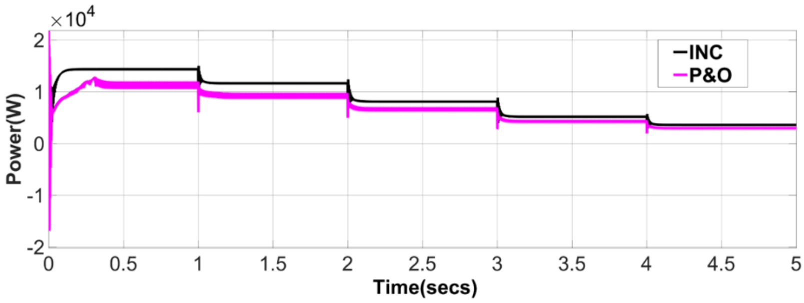

Figure 11. PV output power in according to scenario 1

3.2. Scenario 2: Variation in low temperature level at fixed irradiation

In this scenario, the temperature decreases from 25 °C to 5 °C at a fixed irradiation 1,000 W/m² as illustrated in Figure 12. It can be seen from Figure 13 that INC was the first to reach the MPP with a response of time (0.04 s) at the initial stage (1,000 W/m² and T=25 °C) the INC demonstrates superior power output compared to P&O. However when temperature decreases from 20 °C to 5 °C, P&O continues to move towards the desired MPP compared to INC which explains the higher efficiency reached by the P&O [27] as shown in Table 4. Furthermore, both algorithms exhibit negligible steady state oscillations. The results mentioned in Table 4 reveal that the P&O algorithm performs well in low temperature conditions, achieving an average efficiency exceeding 99%.

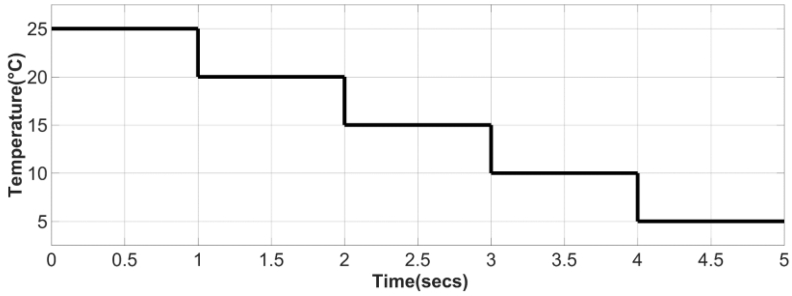

Figure 12. Temperature variation

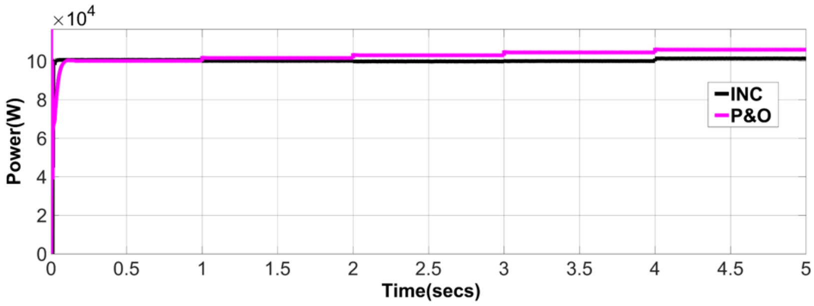

Figure 13. PV output power according to scenario 2

Table 3. Efficiency of MPPT algorithms under scenario 1

		Irradiation (W/m²)	200	180	150	120	100
MPPT techniques		Theoretical power (W)	19,352	17,352	14,364	11,394	9,427
	P&O	Power (W)	11,230	9,173	6,608	4,439	3,137
		Efficiency %	58.03%	52.8%	46%	38.9%	33.2%
	INC	Power (W)	14,360	11,650	8,101	5,192	3,610
		Efficiency %	74.2%	67.1%	56.3%	45.5%	38.2%

Table 4. Efficiency of MPPT algorithms under scenario 2

		Temperature °C	25	20	15	10	5
MPPT techniques		Theoretical power (W)	100,724	101,833	103,278	104,711	106,132
	P&O	Power (W)	99,870	101,400	102,800	104,600	105,700
		Efficiency %	99.15%	99.5%	99.5%	99.8%	99.5%
	INC	Power (W)	100,000	99,810	99,470	99,760	100,700
		Efficiency %	99.2%	98.01%	96.3%	95.2%	94.8%

4. CONCLUSION

This study compares the (P&O) and (INC) algorithms for a PV system application, focusing on tracking efficiency, oscillations, and response time. The simulation is conducted using MATLAB/Simulink software. The investigation highlights the impact of specific environmental conditions, such as low levels of irradiation (below 200 W/m²) and temperature (below 25 °C) on the output power performance of the PV system. The findings demonstrate that under low irradiation conditions, INC exhibits better performance than P&O with minimized oscillations and quicker tracking times. Conversely, P&O shows superior results in terms of high average efficiency only when temperatures levels are low.

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