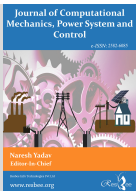
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Comparative Study of P&O and INC MPPT Algorithms for Photovoltaic Systems

Djaafar Toumi
Laboratory of Valorisation and Technology off Sahara Resources (VTRS), University of El Oued, El Oued, Algeria

Hettiri Messaoud
Department of Electrical Engineering, University of EL-Oued, Algeria

Ahmed Ibrahim
Department of Electrical Power & Machines, Faculty of Engineering, Zagazig University, Egypt

Abdelkarim Ahfouda
Department of Electrical Power & Machines, Faculty of Engineering, Zagazig University, Egypt

Salah Boughezala Mohammed
Department of Electrical Engineering, University of EL-Oued, Algeria

Abstract: The maximum power point tracking (MPPT) method is usually used in photovoltaic (PV) systems to increase the electric energy production in a photovoltaic generator (PVG) and reduce the PV array cost. The output of the photovoltaic (PV) system depends on the temperature, solar radiation, and impedance of the load. The value for the maximum power point (MPP) is not constant. The principle of this technique is to maximize the electric energy production of a photovoltaic generator (PVG). In this paper, we present à comparative simulation study of two important MPPT algorithms incremental conductance (INC) and perturb and observe (P&O). using the MATLAB/Simulink for performance evaluation by a 50W photovoltaic (PV) array. Some of the important parameters such as voltage, current, and output power of each method are traced for both algorithms. It is demonstrated that the incremental conductance-based MPPT tracking provides more accurate results in less time than the P&O algorithm-based MPPT.

Keywords: Photovoltaic (PV), MPP, Perturb and observe, Simulink, MPPT, fuzzy logic, controller

Nomenclature

Abbreviation	Expansion
ARO	Artificial Rabbit Optimization
INC	Incremental Conductance
MPP	Maximum Power Point
MVP	Most Valuable Player
P&O	Perturb and observe
ML	Machine Learning
TSML	Terminal Sliding Mode Control
PV	Photo Voltaic
PSC	Partial Shading Conditions
NFN	Neuro Fuzzy Network
STC	Standard Test Conditions
LRMRAC	Lyapunov-based Robust Model Reference Adaptive Controller
SA	Simulated Annealing
RES	Renewable Energy Sources

1. Introduction

Energy is defined as the ability to work. Energy become the basic indispensable commodity for human life. The increase in population, changes in people's lifestyles, and technological developments led to a tremendous increase in energy needs. There are two types of energy. They are renewable and non-renewable energy. Non-renewable resources are on the verge of existence. So, there is a growing interest in RES. Some of the renewable sources of energy are solar energy, wind energy, tidal energy, geothermal energy, artificial photosynthesis, etc.,[6] Due to the growing electricity demand of the world fossil fuel exhaustion and the tremendous risk of climate change associated with the use it is [1]. Among all RES, solar power systems can be considered the most promising, it is clean, inexhaustible, and free, also widely available [2][3]. It is considered a better choice based on its low maintenance operational cost. Once it is setup it works for decades. Solar energy is produced by converting the photon energy from the sun that falls directly on the PV cells [4].

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The main drawback of PV systems is that the energy conversion efficiency is relatively low due to varying solar irradiation and the temperature and V–I and P–I characteristics are nonlinear [5][7]. However, solar power was not continuously available throughout the day. It also required large space for the solar energy system. Solar power has no maintenance or operational cost but it is fragile. The initial cost for solar panels, inverter, batteries, wiring, and installation is costly. The solar technologies are constantly developing and the prices and processes will go down in the future. Consequently, the PV panel doesn't coincide with the MPP [33]. To execute the process, we need a DC-DC converter to extract the maximum power from the PV generator. To implement this process at least nineteen different algorithm was used to improve the performance [34]. The best-known methods are P&O and INC. The system consists of a PV panel from which the electricity is passed to the DC-DC converter and it also contains a load to balance the flow of electricity. Finally, the MPPT control system controls the overall flow of current and output voltage. The main contribution of the paper is

- To identify the maximum efficiency of the solar panel to optimize the design part of the PV system under different sunlight radiation and temperature.
- Compare the reliability of MPPT algorithms through a comparison between P&O and INC techniques.

In this paper, we proposed the MPPT technique [8], In this study, we execute this technique with the use of the P&O algorithm and INC, Simulations are carried out in MATLAB / Simulink. Then we perform a comparison between the MPPT techniques of P&O and INC.

The organization of this paper is in this order: Section 2 presents the literature review, and Section 3 explains the mathematical modeling of the PV module. The modeling of the boost converter is explained in section 4. Section 5 covers the MPPT algorithms (P&O, INC). Section 6 explains the simulated result and discussion, Section 7 explains the comparison between MPPT Algorithms for P&O and INC, Section 8 explains the advantages and disadvantages, and Section 9 concludes the paper.

2. Literature Review

In 2023, Ravi *et al.* [25] have compared the performance of ARO.INC, MPPT, MVP, and P&O algorithm under PSC. INC detects the slope of the P-V curve and tracks the MPP by searching the peak of the P-V curve using the instantaneous conductance. The maximum power point identifier factor is defined as $\frac{dP}{dV}$, and the INC approach has accurately monitored a PV array's MPP by leveraging this component.

In 2023, Ahmad *et al.* [26] have used ML and TSMC to optimize large-scale PV systems operating under PSC. It involves two stages. In the first stage, an NFN was used to improve the accuracy of the reference voltage. In the second stage, a TSMC was used to track the MPP voltage using a non-inverting DC-DC buck-boost converter. It is then validated through numerical simulations and experiments. Further, the superiority among MPPT algorithms, PID, and P&O was identified for higher power and less control time.

In 2023, Khodair *et al.* [27] have implemented MPPT, P&O, and INC and their modified version through a boot converter for two types of solar panels. They used MATLAB to simulate the efficiency of the solar module under various environmental conditions and STC, solar irradiance, and temperature. The results improved the algorithms and demonstrated an enhanced PV module performance over conventional algorithms in many factors including steady-state conditions, tracking time, and converter efficiency.

In 2023, Manna *et al.* [28] have executed LRMRAC for MPPT in a solar PV system. The MPPT control block was responsible for generating the reference voltage for the PV system, while the LRMRAC block was responsible for tracking the reference voltage and achieving the MPP of the PV system. The LRMRAC block was designed based on the Lyapunov stability theorem for a second-order PV MPPT system to achieve rapid convergence, higher efficiency, ripple-free, less oscillation in the steady-state, negligible overshoot, and undershoot. The controller accurately achieves MPP under slow, abrupt, and rapid changes in radiation, temperature, and load profile.

In 2023, Abo-Khalil *et al.* [29] have applied P&O and SA algorithms in the solar PV system. The system was initialized and initial values of the parameters were assigned. Then the output voltage and current were measured and calculated. Using the P&O algorithm, the MPP of the system was estimated. Modify the P&O algorithm using the SA algorithm to improve its performance under partial shading conditions. By Adjusting the duty cycle of the DC-DC converter the exert match of MPP was estimated.

In 2023, Haro-Larrode *et al.* [30] have demonstrated through P&O, INC, and VDCIQ control structures. Each MPPT method with a different step size and considers the influence of the inverter control constants. The algorithm prioritized the improvement of different performance aspects over others using two coordination schemes. The impact of the algorithm was evaluated and compared with

the impact of conventional MPPT algorithms according to the trackability of power, the impact on DC voltage, and the AC grid side. The results were analyzed by simulations conducted in MATLAB-Simulink.

In 2023, PK, V.K. and Jijesh, J.J., [31] have developed Bio-inspired MPPT in the solar PV system. Initially, it set us the number of fireflies and evaluate the fitness of the fireflies. The objective of the fireflies was determined and the light intensity. Finally, they were ranked and the best solution was obtained.

In 2023, Harrison, A., *et al.* [32] have tried hybrid MPPT in the solar PV system. The INC algorithm was used to seek the maximum power voltage of the PV system. The output of the INC algorithm was fed into a nonlinear integral backstepping controller. The integral backstepping controller ensured the stability and robustness of the PV system against fast-changing operating conditions through Lyapunov theory.

2.1 Review

Table 1 portrays the methodology, advantages, and disadvantages of the existing method. We considered eight papers that used a different methodology for the various algorithms of photovoltaic systems. Each method has certain benefits and shortcomings, that were explained in detail.

Table 1: *Review Based on Existing Methods*

Author	Method	Advantage	Disadvantage
Ravi *et al.* [25]	ARO, INC, MPPT, MVP and P&O	• Provided a better solution under partial shading conditions • Improved the efficiency and tracking speed of the system.	• Performance may vary based on its condition.
Ahmad *et al.* [26]	ML and TSMC	• Higher power generation. • Performed well under real-world conditions and load variations.	• The experiment was conducted on a small-scale PV system. • Doesn't have robustness to different weather conditions and environmental factors. • Expensive method.
Khodair *et al.* [27]	MPPT, P&O, and INC	• Provided better performance in steady-state conditions, tracking time, and converter efficiency. • Effective in tracing the MPP under STC.	• Only a limited number of solar panels were used. • Expensive method.
Manna *et al.* [28]	LRMRAC	• Operated smoothly without any oscillations in the steady state. • PV system generates more power compared to other methods.	• May require more computational resources compared to other methods. • Limitated to some applications.
Abo-Khalil *et al.* [29]	P&O, SA algorithm	• Reduced the transient periods. • Increased the generated energy • Reduced the convergence time under all operating conditions. • Simplified Implementation. • Used with low-complexity photovoltaic systems, which makes it suitable for a wide range of applications. • Improved the energy efficiency of photovoltaic systems. • Reduced the environmental impact of energy production.	• Computation complexity. • Expensive method.
Haro-Larrode *et al.* [30]	P&O, INC, VDCIQ control structure	• Better results and improved performance compared to conventional MPPT algorithms. • A cost-effective and efficient evaluation of the algorithm's performance. • Used in many applications.	• Not performed in Real-time. • Evaluated for a specific type of PV system and control structure, and its applicability.
PK, V.K. and Jijesh, J.J., [31]	Bio-inspired MPPT	• Better performance • Helped researchers and practitioners to choose the most appropriate algorithm for their specific application.	• Didn't discuss the effect of the proposed overall system performance, such as the battery life, system stability, and reliability. • Expensive method
Harrison, A., [32]	Hybrid MPPT	• Four times faster than the INC in tracking the maximum power with better energy yield than the latter. • Ensured the stability and robustness of the PV system against fast-changing operating conditions.	• More complex hardware and software implementation compared to some conventional MPPT algorithms. • Requires more computational resources, which may increase the cost of the PV system.

2.2 Challenges

The challenges experienced by MPPT Algorithms for photovoltaic systems are given as follows,

- The ARO, INC, MPPT, MVP and P&O better performance compared with the existing method [25][27][29][30]. However, the performance may vary based on weather conditions and other external factors.
- In [26][27][29] [31[32], generate more power than other methods. Additionally, Performed well under real-world conditions. Moreover, this method is costly.
- When compared to current approaches, it produces good results in [27][28][30]. Nevertheless, evaluated a specific type of PV system and control structure, and its applicability.

3. Mathematical Modeling of Pv Module

In this paper, we modeled and implemented a 50 W PV array. The solar cell is the basic building block of PV arrays, which is effectively a p-n semiconductor junction, as illustrated in Fig 1.

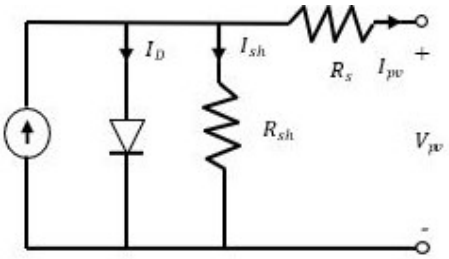


Fig.1.*Mathematical modeling of PV module*

The model of a PV panel defies the following equations:

$$I_{ph} = \frac{G}{G_{ref}}(I_{ph.ref} + \mu_{sc} * \Delta T) \quad (1)$$

Where, I_{ph} is the photocurrent, G represents Irradiance ($W/m2$), G_{ref} means Irradiance at STC= 1000 $W/m2$, $I_{ph.ref}$ is the photocurrent (A) at STC, μ_{sc} refers the coefficient temperature of short circuit current (A/K) and $\Delta T = T_c - T_{c,ref}(\text{Kelvin})$, where T_c represent the actual temperature.

The photoelectric plate model we have studied is defined by the following equations.

$$I_{pv} = I_{ph} - I_d - I_{sh} \quad (2)$$

Where I_{pv} represent the output current, I_d the diode current, and I_{sh} represent the shunt current. To calculate the diode current I_d, the expression is represented as

$$I_d = I_0[\exp(\frac{V_{pv} + I_{pv} * R_s}{q}) - 1] \quad (3)$$

Where I_0 represents the reverse saturated current, V_{pv} is the output terminal voltage, I_{pv} means output current, R_s represents the series resistance, and q is the electron charge. To calculate the shunt current I_{sh}.

$$I_{sh} = \frac{V_{pv} + I_{pv} * R_s}{R_{sh}} \quad (4)$$

Where R_{sh} represents the parallel resistance.

The MSX-50 PV module was chosen for the simulation setup in this article. Table 2 tabulates the electrical parameters and Figures 2 to 5 show the characteristic curves. The P-V and I-V characteristics of the MSX-50 module under varying irradiances is shown in Fig 2 and 3 and the P-V and I-V characteristic under varying temperature conditions is shown in Fig 4 and 5.

Table 2: *Electrical Characteristics of MSX-50 PV panel*

Parameters	Value
VoltageatmaximumpowerVmpp	17.98V
CurrentatmaximumpowerImpp	2.78A
MaximumpowerPmax	50W
Short-circuitcurrentIsc	3.04A
Open-circuitvoltageVoc	21.87V

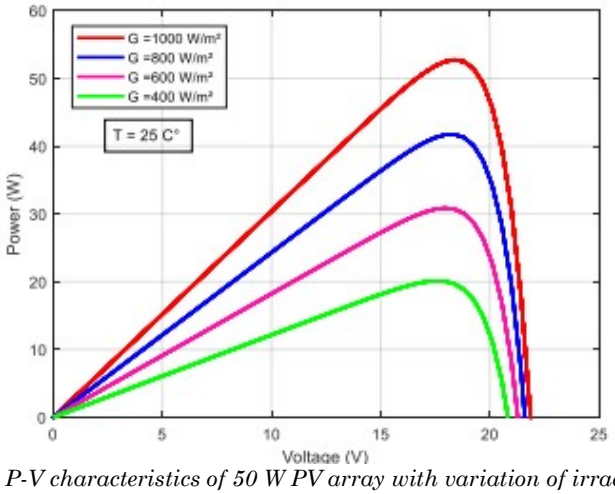


Fig.2. *P-V characteristics of 50 W PV array with variation of irradiance*

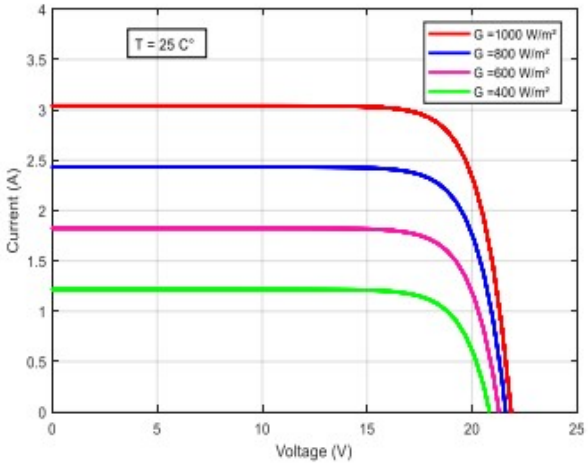


Fig.3. *I-V characteristics of 50 W PV array with a variation of irradiance*

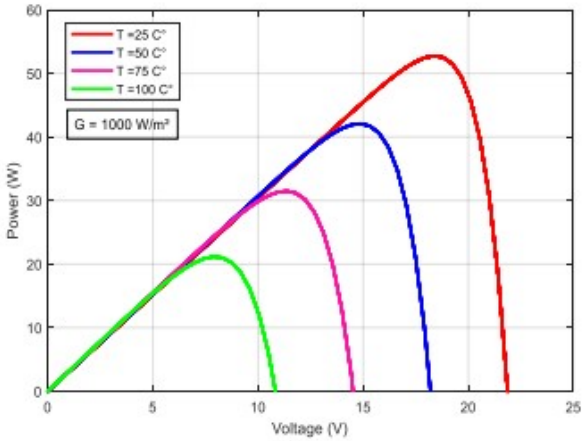


Fig.4. *P-V characteristics of 50 W PV array with variation of temperature*

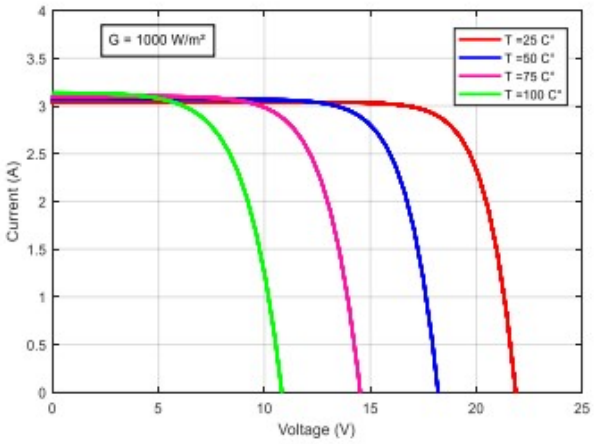


Fig. 5. *I-V characteristics of 50 W PV array with a variation of temperature*

4. Modeling of Boost Converter

We would suggest modeling the boost converter between the GPV and the DC load before beginning our research on the modeling of MPPT controls.

The Boost kind is the converter used in our work. This causes the output voltage of Vs to be increased compared to the input voltage of V_{pv} [11] [12]. The circuit diagram modeling the converter is shown in Fig 6, whereas Table 3 summarizes the values of the elements used to make this converter[11].

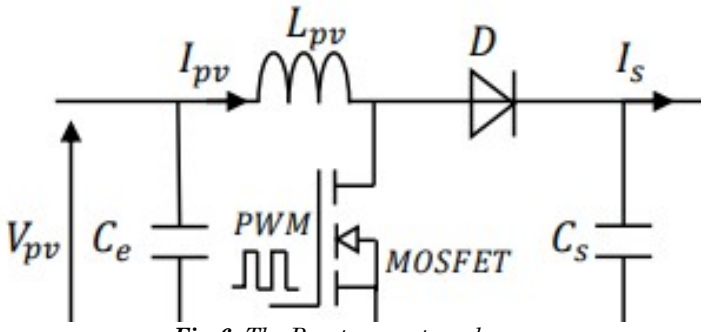


Fig.6. *The Boost converter scheme*

Table 3: *Values of Boost converter elements*

Parameters	Value
Bobbin L_{pv}	18mH
Input capacitor C_e	2200µF
Output capacitor C_s	2200µF
Switching frequency of the MOSFT f	1KHz
Load R	22Ohm

Our converter is represented by the following equations from the Fig 5 scheme and the analysis of the different sequences of the functioning of the boost converter [10] [13]. To identify the output terminal voltage V_{pv}.

$$V_{pv} = L_{pv}\frac{di_{L_{pv}}}{dt} + (1 - a_{pv})V_s \tag{5}$$

$$C_s\frac{dV_s}{dt} + \frac{V_s}{R} = (1 - a_{pv})i_{L_{pv}} \tag{6}$$

Where a_{pv} is the duty cycle of the PWM signal. Its value is between 0 and 1.

5. MPPT Algorithm

5.1 P&O Algorithm

Due to its simple structure and ease of implementation, the Perturb and Observe algorithm is considered the most widely used MPPT algorithm of all techniques. It is based on the idea that $\frac{dP}{dV}$ the top of the curve goes to zero on the power curve as illustrated in Fig 7 [17]. The P&O operates by periodically disturbing the PV array terminal voltage or current (increasing or decreasing) and comparing the corresponding output power of the PV array $P(n+1)$ with that of the previous disturbance $P(n)$. If the terminal voltage disruption leads to a power increase $\frac{dP}{dV} > 0$ [14][16], The disturbance should be held in the same direction, otherwise, the disturbance will be moved in the opposite direction. The perturbation cycle is repeated until at the $\frac{dP}{dV} = 0$ point the maximum power is reached.

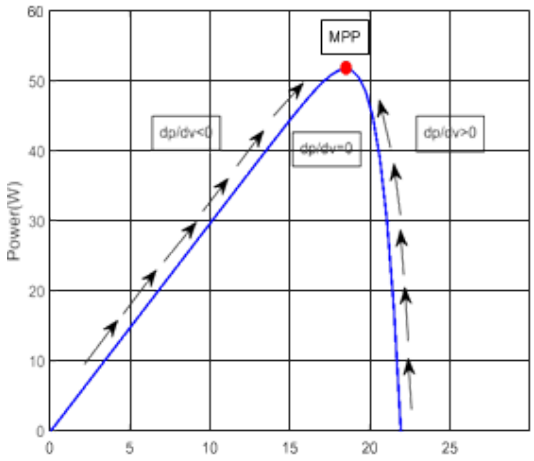


Fig.7.*P&O-based MPPT technique*

The P&O method helps to track the maximum power point. The minor perturbation can cause power variation in the PV module. However, The PV output power is periodically measured and compared with the previous power [24]. If the output power (I_{PV}) increases then perturbation is reversed. When voltage is increased then power will be increased which leads to the operating point of the PV module on the left of the MPP. Further perturbation helps to reach MPP. The flow chart of the adopted P&O algorithm for the charge controller is given in Fig 8 [15].

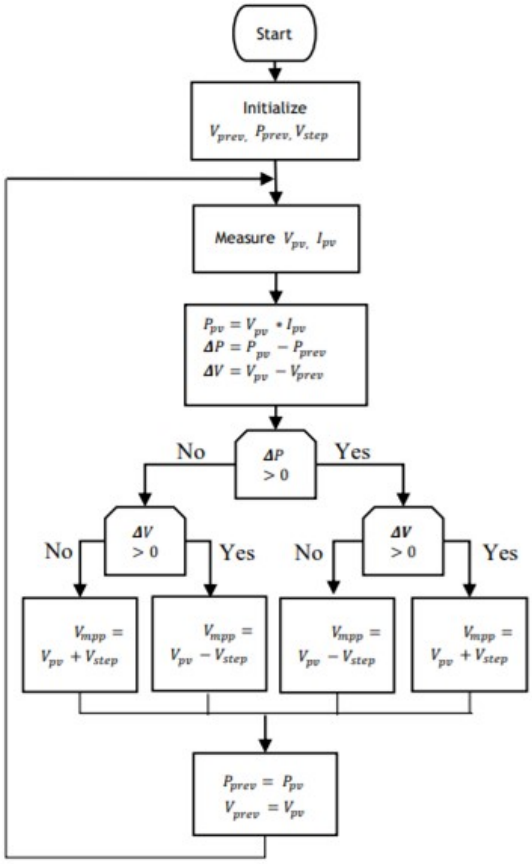


Fig.8. *P&O MPPT Algorithm*

5.2 INC Algorithm

The INC method overcomes the drawback of interference and observes the method for monitoring peak power under increasingly varying atmospheric conditions. This approach can be used to assess if the MPPT has hit the MPP and also avoids disturbing the operating stage [18] [19]. If this condition is not met, the direction in which the MPPT operating point must be disturbed can be calculated using the relationship between $\frac{dI}{dV}$ and $-\frac{I}{V}$ [20] [21].

This relationship is extracted from the fact that when the MPPT is to the right of the MPP, $\frac{dP}{dV}$ is negative, and positive when it is to the left of the MPP. As P&O oscillates around the MPP, this algorithm decides when the MPPT has hit the MPP. Over P&O, this is an advantage. Also, the INC can follow increasing and decreasing irradiance conditions easily with greater precision than disturbance and method observation. The downside to this algorithm is that, as opposed to P&O, it is more complex. The following flow chart, shown in Fig 9, can be easily understood by the algorithm [22] [23].

$$\frac{dI}{dV} + \frac{I}{V}$$

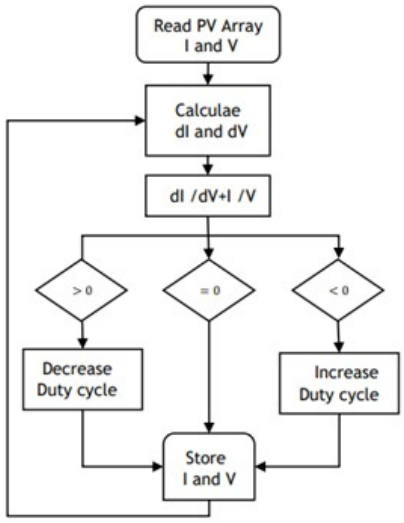


Fig. 9. *INC MPPT Algorithm*

6. Simulation and Results

Fig 10 shows a simulated PV array model with a DC-DC boost converter the P&O algorithms and the INC. under the same conditions. as Fig from 11to 13. shows the Different output results of the photovoltaic generator simulated using the P&O algorithm and the INC and compares them with each other at standard conditions (E=1000W/m² and T=25°C)

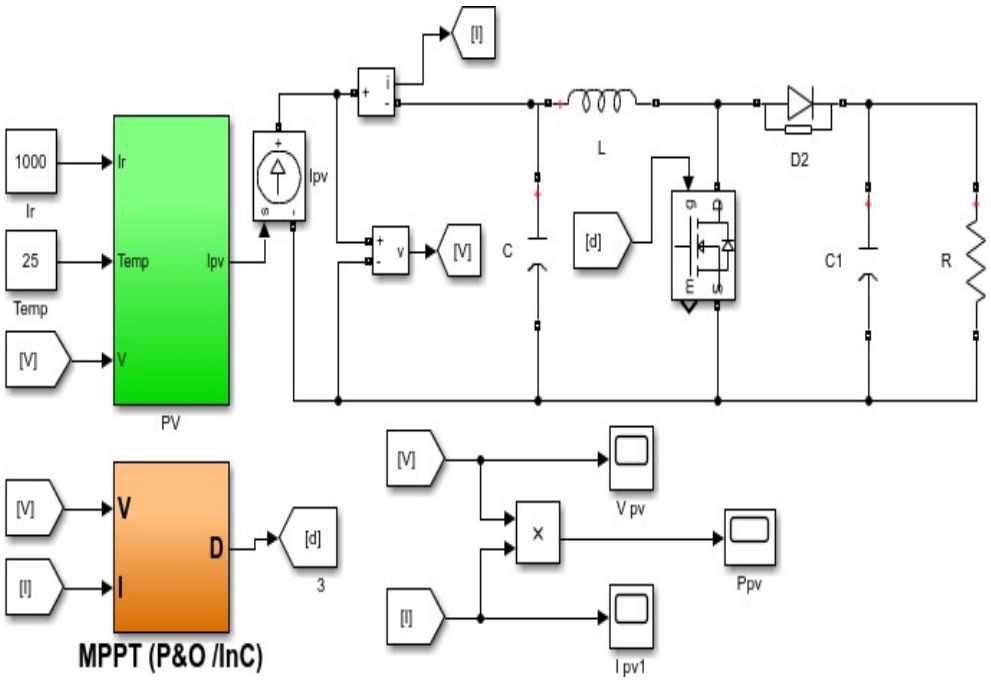


Fig.10. *Simulink Model of INC and P&O MPPT with dc-dc boost converter*

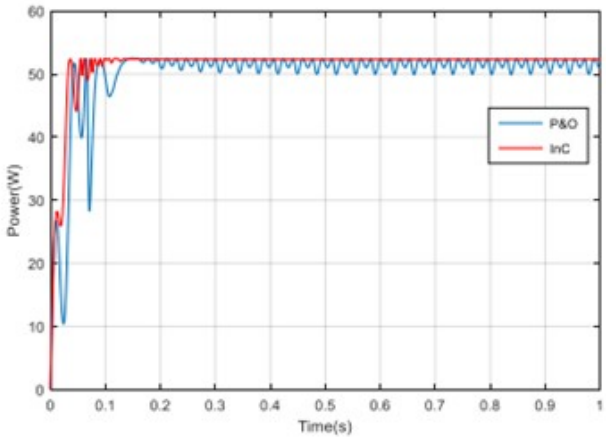


Fig.11. *Output power at standard condition with INC and conventional P&O controller*

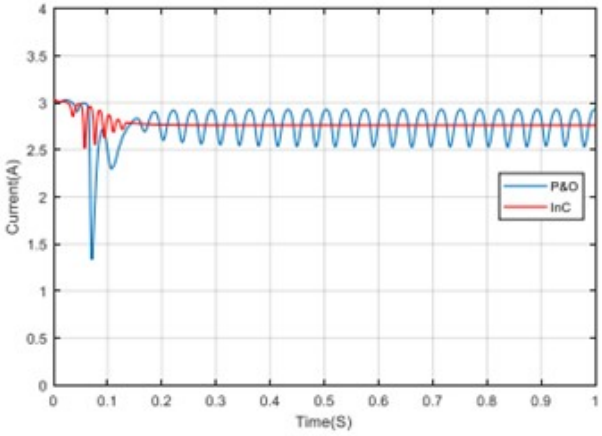


Fig.12. *Output current at standard condition with INC and conventional P&O controller*

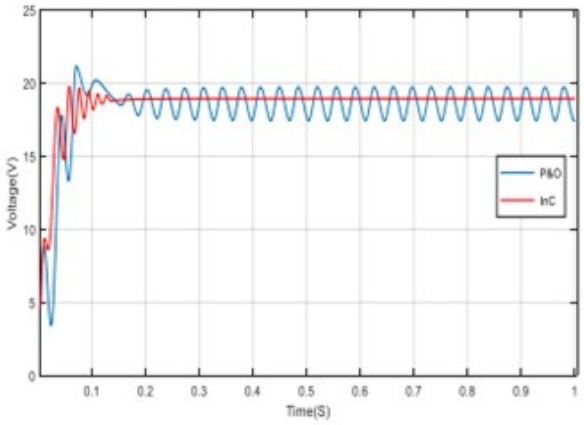


Fig.13. *Output voltage at the standard condition with INC and conventional P&O controller*

The following simulations were presented for several solar irradiance values (1000W/m², 900W/m², and 800W/m²) at a fixed temperature of 25°C, To highlight the best performance of the system proposed.

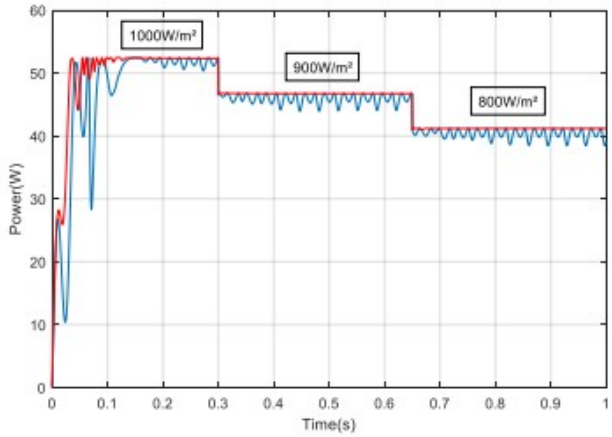


Fig.14. *Output power at different environmental conditions with INC and conventional P&O controller*

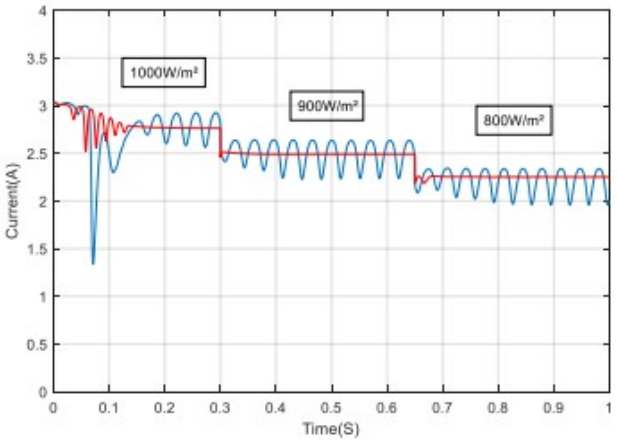


Fig.15. *Output current at different environmental conditions with INC and conventional P&O*

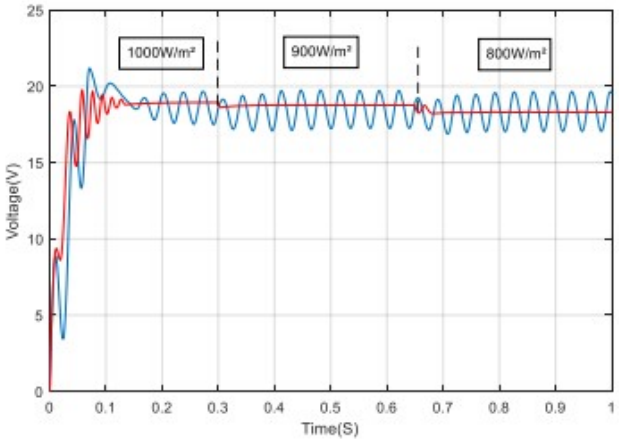


Fig.16. *Output voltage at different environmental conditions with INC and conventional P&O controller*

7. Comparison between MPPT Algorithms for P&O and INC

The MPPT algorithms of P &O and INC are simulated and compared using the same conditions. The P&O MPPT oscillates similarly to MPP when atmospheric conditions are stable or change slowly, but INC still finds the MPP reliably when atmospheric conditions change. In Table 3, comparisons are given between the two algorithms for different parameters at standard conditions (E=1000W/m² and T=25°C).

Table 4:*Comparison between MPPT Algorithms for P&O and INC*

	P&OMPPT	INCMPPT
Output Power	50.41-52.39W	52.31W
Output Current	2.54-2.93A	2.76A
Output Voltage	17.63-19.66V	18.94V
Time Response	0.042sec	0.035sec
Accuracy	Less	Accurate

8. Advantages and Disadvantages

Advantage

- This method provided accurate results in less time than P&O.
- This method showed INC is reliable even when atmospheric condition changes.
- INC follows increasing and decreasing irradiance conditions easily with greater precision than P&O.

Disadvantage

- The INC is more complex than P&O.

9. Conclusions

A mathematical model of a 50W photovoltaic panel using MATLAB Simulink was built in this paper. This model is used for the algorithms of full power point monitoring. For the highest power point tracking algorithms, this model is used. The MPPT algorithms for P&O and INC are discussed and their results for simulation are presented. It has been shown that the approach of INC has better efficiency than the P&O algorithm in terms of tracking speed, accuracy, and efficiency. These algorithms enhance the photovoltaic system's dynamics and stable state performance, as well as increase the efficiency of the DC-DC converter system.

Compliance with Ethical Standards

Conflicts of interest: Authors declared that they have no conflict of interest.

Human participants: The conducted research follows the ethical standards and the authors ensured that they have not conducted any studies with human participants or animals.

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