Engineered Science
DOI: https://dx.doi.org/10.30919/es1485

Simulation Study of Photovoltaic Power Generation System based on MATLAB/Simulink

Zhiwen Xu[1] and Weiwei Zhao[1, 2,*]

Abstract

Photovoltaic (PV) power generation, as an important renewable energy source, has been widely applied in recent years. With continuous advancements in PV technology, improving the efficiency and stability of PV systems has become a research focus. Currently, the output power of PV systems is significantly affected by environmental factors. The Maximum Power Point Tracking (MPPT) algorithm plays a crucial role in PV systems. This paper compares three classical MPPT algorithms—Incremental Conductance (INC), Perturb and Observe (P&O), and Constant Voltage (CV). Through MATLAB/Simulink simulations, their tracking performance under different irradiance and temperature conditions is analyzed, including steady-state error, dynamic response speed, and power oscillation. The results show that the INC algorithm outperforms P&O and CV in both dynamic adjustment capability and steady-state accuracy, allowing faster and more stable tracking of the Maximum Power Point (MPP) while reducing power loss. This study provides a reference for selecting MPPT algorithms in photovoltaic applications.

Keywords: Photovoltaic power generation; MATLAB/Simulink; Maximum power point tracking (MPPT); INC algorithm.
Received: 09 March 2025; Revised: 07 April 2025; Accepted: 15 April 2025.
Article type: Research article.

1. Introduction

With the rapid development of renewable energy,[1] photovoltaic (PV) power generation technology is playing an increasingly significant role in the global energy mix. However, due to the influence of temperature and irradiance variations on the output characteristics of PV cells, the Maximum Power Point (MPP) also changes accordingly. Therefore, adopting an efficient Maximum Power Point Tracking (MPPT) algorithm is crucial for improving the energy conversion efficiency of PV systems.[2-4]

Currently, common MPPT algorithms include the Perturb and Observe (P&O) method,[5] the Constant Voltage (CV) method,[6] and the Incremental Conductance (INC) method.[7] The P&O algorithm is widely used due to its simplicity and low computational complexity, but it tends to cause power oscillations in steady-state conditions and may fail to track MPP under rapidly changing environments. The CV method approximates the MPP using a fixed voltage, but its accuracy is highly dependent on PV module parameters. The INC algorithm, based on the derivative information of the PV curve, can more accurately determine the MPP direction, making it more effective in dynamic environments.

This paper compares the performance of P&O, CV, and INC MPPT algorithms through MATLAB/Simulink simulations,[8] analyzing their dynamic response, steady-state error, and power loss under different irradiance and temperature conditions. The study results indicate that the INC algorithm exhibits superior tracking performance compared to P&O and CV, providing higher power output and stability under complex operating conditions. This research serves as a reference for selecting MPPT algorithms for PV systems.

Using the MATLAB/Simulink platform, this study establishes a complete PV system simulation model, including a PV module, a DC/DC converter, and an MPPT control unit. First, the mathematical model of the PV module is developed, considering environmental factors such as irradiance and temperature. The I-V and P-V characteristic curves are used to analyze the PV module's performance. Next, the Incremental Conductance method is applied to track the Maximum Power Point, and simulation analyses under different environmental conditions are conducted to enhance MPPT efficiency.

Simulation results show that the Incremental Conductance

[1] *School of Mechanical and Electronic Engineering, Wuhan University of Technology, Wuhan, 430070, China*
[2] *Birmingham Centre for Energy Storage (BCES) and School of Chemical Engineering, University of Birmingham, Birmingham, B15 2TT, United Kingdom*
**Email:* w.zhao@bham.ac.uk (W. Zhao)

algorithm can rapidly track the MPP under irradiance variations while maintaining high power output in steady-state conditions. Compared to the traditional P&O and CV algorithms, the INC algorithm more accurately determines power variation trends, reduces power oscillations, and improves system stability. Additionally, dynamic environmental variable inputs are used to further validate the effectiveness of the simulation model in enhancing MPPT response speed and steady-state accuracy.

In conclusion, this paper investigates MPPT control strategies for PV systems through MATLAB/Simulink simulations, focusing on the working principles, performance characteristics, and optimization strategies of the adaptive step-size Incremental Conductance algorithm to improve PV power tracking efficiency. Future research can integrate artificial intelligence-based optimization algorithms to enhance the global search capability and dynamic response performance of MPPT algorithms, ultimately improving the overall efficiency of PV systems and providing valuable insights into MPPT algorithm selection.

2. Structural characteristics and working principle of photovoltaic power generation systems

2.1 Current generation process

Solar photovoltaic cells are mainly composed of photovoltaic materials and electrical components. Their structure is divided into several layers, each with different functions. The most basic photovoltaic cell is composed of semiconductor materials (usually silicon), which generate electrons and holes through the photoelectric effect under light irradiation. When the two ends are connected to wires, an electric current is produced. Photovoltaic cells generate electricity using solar energy, which is clean, environmentally friendly, pollution-free, and renewable. They have low operating costs, simple maintenance, are not affected by fluctuations in the price of fossil fuels, and have strong adaptability, and can be applied in various scenarios such as residences, industries, and large-scale power stations.[9] Photovoltaic cells generate photovoltaic current through exposure to sunlight, and photovoltaic modules convert the generated direct current to industrial and household electricity and integrate it into the power grid system; the excess electricity is stored in batteries.

2.2 Mathematical model of photovoltaic module

The equivalent circuit of a photovoltaic cell usually consists of a current source,[10] a diode(D), series resistance (R_s), and parallel resistance (R_p). The equivalent circuit diagram of the photovoltaic cell is shown in Fig. 1.

The relationship between the output voltage and the output current of a photovoltaic module can be described by a nonlinear model.[11,12] The most common photovoltaic module model is the single-diode model,[13] whose output current is expressed by the following Eq. (1):

$$I = I_{pv} - I_D - I_p \tag{1}$$

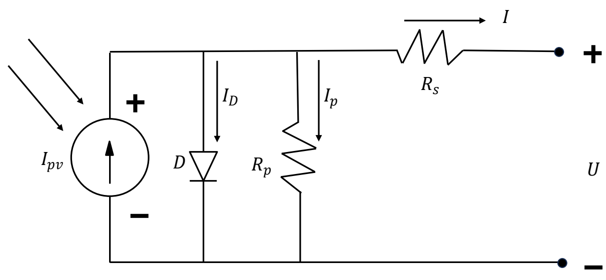

Fig. 1: Equivalent circuit diagram of photovoltaic cells.

From the diode characteristics can be known:

$$I_D = I_0 \left[\exp\left(\frac{V+IR_s}{R_p}\right) - 1\right] \tag{2}$$

According to Kirchhoff's law:

$$I_p = \frac{V+IR_s}{R_p} \tag{3}$$

Consult the photogenerated current formula of photovoltaic panels:

$$I_{pv} = (I_{sc} + K_t \triangle T)\frac{G}{1000} \tag{4}$$

where I_{pv} is the photovoltaic cell photogenerated current, I_0 is the reverse saturation current of the diode, I_p is the current flowing through the shunt resistor R_p , I_D is the current flowing through the diode, V is the output voltage, I photovoltaic cell is the output current, R_s is the series resistance which is generally very small, R_p is the shunt resistance which is generally thousands of Ω, n is the ideal factor of the diode, V_t is the thermal voltage constant, $V_t = kT/q$, where k is the Boltzmann constant with a value of 1.38×100^{-23} J/K, T is the absolute temperature (in Kelvin, K), q is the elementary charge of electrons with a value of 1.6×10^{-19} C, I_{sc} is the short-circuit current in the standard case (25 °C, 1000 W/m^2), K_t represents the temperature coefficient of the current, and G is the current PV cell receiving the light radiance, $\triangle T$ = T-298.15.

However, in practice, it is difficult to measure the ideal parameters according to the previous Eqs. (1)-(4). Combining the four parameters of V_m , I_m , V_{oc} , I_{sc} given by the manufacturer with the previous four equations can be obtained as follows:[14]

$$I = I_{sc}\left\{1 - C_1\left[exp\left(\frac{V}{C_2V_{oc}}\right) - 1\right]\right\} \tag{5}$$

In Eq. (5), V_{oc} is the breaking voltage under standard conditions, and C_1 and C_2 are constants, whose values are:

$$C_1 = \left(1 - \frac{I_m}{I_{sc}}\right) exp\left(-\frac{V_m}{C_2V_{oc}}\right) \tag{6}$$

$$C_2 = \left(\frac{V_m}{V_{oc}} - 1\right)\left[ln\left(1 - \frac{I_m}{I_{sc}}\right)\right]^{-1} \tag{7}$$

Combine Eqs. (4)-(7) and modify the parameters therein, and then build the simulation model.

3. Modeling and analysis of photovoltaic cell characteristics

Based on the above Eqs. (4)-(7) and parameter corrections, a stable parameter simulation model is established in sinmulink in matlab, and the parameters of the PV cell are shown in Table 1. The output characteristics (V-I and V-Pcurves) of the PV module change under different light intensity and temperature conditions.[15] The V-I curve describes the relationship between current and voltage, while the P-V curve describes the relationship between power and voltage, and is usually a nonlinear curve The maximum power point (MPP) usually occurs at the top of the V-P curve, which corresponds to the V-I curve is at the turn for maximum power. The voltage (V_m) and current (I_m) corresponding to the MPP are key parameters in the system design. This is also the target tracked by the MPPT algorithm. The parameters of this PV modeling are the result of a partial modification based on the parameters of a PV cell model that can be bought on the market: the TY-30M18V parameters.

Several basic parameters of the PV cell in the standard case are set: the breaking voltage U_{oc}, the short-circuit current I_{sc}, the current I_m corresponding to the maximum power point, and the voltage U_m, which provide the basis for the subsequent analysis of the characteristics of the PV cell. Based on Eqs. (5)-(7), the simulation model of the PV cell built in MATLAB/Simulink is constructed as shown in Fig. 2.

Table 1: Parameters of photovoltaic cells.

Parameters	Value
Short-circuit current（I_{sc}）	9.36A
Open-circuit voltage (V_{oc})	43.30V
Current at maximum power (I_m)	8.80A
Voltage at maximum power (V_m)	36.10V
Maximum output power（P_{max}）	317.68W

The model used to test the characteristics of PV cells after encapsulation is shown in Fig. 3. The input parameters are light intensity and temperature, and the output quantities are current and voltage.

In real life, many factors can affect both the local and overall output characteristics of PV cells. The following study will focus on simulating and analyzing the impact of irradiance intensity and temperature on the overall output characteristics of PV cells.

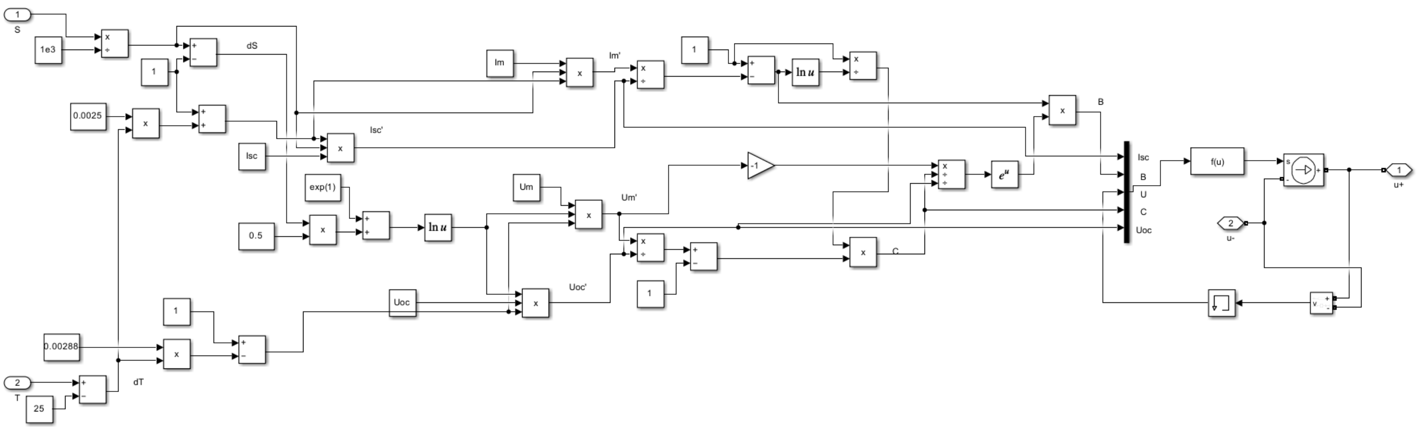

Fig. 2: Simulation model of photovoltaic cell.

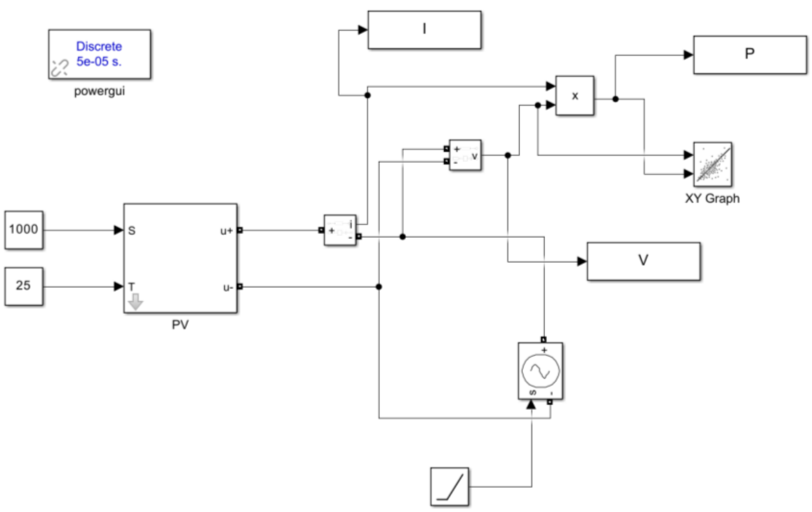

Fig. 3: PV cell output characteristics test package module.

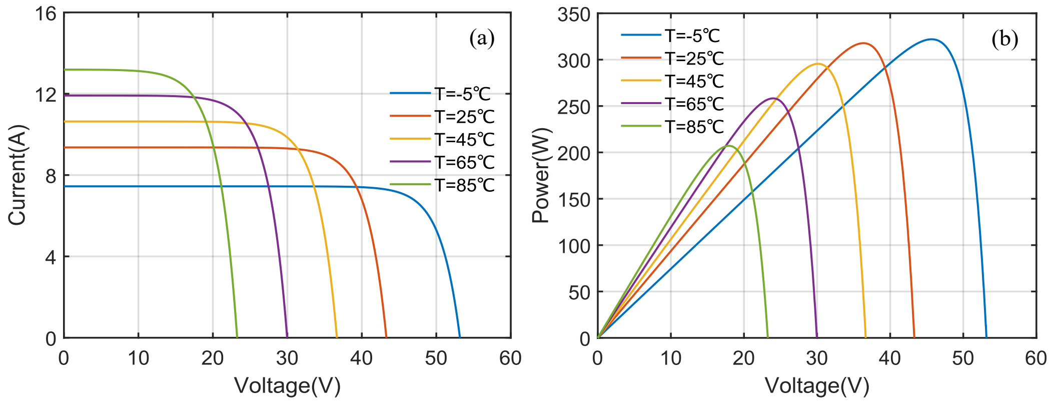

Fig. 4: Influence of different temperatures on output characteristics of photovoltaic cells (a) I-V curve and (b) P-V curve.

The standard solar irradiance is generally 1000 W/m², and the normal operating temperature for PV cells is 25 °C. The output power of PV cells is influenced by many factors in natural environments, with temperature and light intensity being the most significant. Using the method of controlling variables, the effects of light intensity and temperature on the output characteristics of PV cells are studied separately. Considering that the surface temperature of PV panels is lower than the air temperature in winter and higher in summer, the temperatures set here should take seasonal variations into account. Fig. 4 shows the output characteristics of the PV cell under light intensity of 1000 W/m² and temperatures of 85 °C, 65 °C, 45 °C, 25 °C, and -5 °C.

From Fig. 4, it can be clearly seen that when the voltage gradually increases, the current stays close to the high value of Isc until it enters the nonlinear region, and when the light intensity is certain, the maximum output power of the PV cell increases with the temperature but in the reverse direction. The reason for this is that an increase in temperature causes the open-circuit voltage (V_{oc}) of the PV cell to drop, which reduces the total power output of the cell, thus causing a leftward shift in the V-P curve. In general, for every 1 °C increase in temperature, V_{oc} decreases by about 2 mV (depending on the cell material and manufacturing process). The reason for this is that as the temperature increases, the carriers (electrons and holes) of the semiconductor material increase under thermal excitation, resulting in a weakening of the built-in electric field within the cell, which reduces the voltage output of the cell.

When the control temperature is constant at 25 °C, the light intensity is set to 1000 W/m^2, 900 W/m^2, 700 W/m^2, 500 W/m^2, and 300 W/m^2. The results are shown in Fig. 5. From Fig. 5, we can know that the photogenerated current increases with the increase of light intensity, and the output power of PV cell is proportional to the light intensity. This is because the photovoltaic cell generates current due to photon bombardment of electrons, and the greater the intensity of light, the more electrons are bombarded. This generates more current. Conversely, the lower the light intensity, the fewer electrons are bombarded, and thus the less current is generated. However, the effect on the open-circuit voltage is small, and the effect of light intensity on the output power of the PV cell is greater than the effect of temperature on the output power of the PV cell in comparison to Fig. 4. When increasing the light intensity, the peak of the P-V curve becomes higher and the power output increases significantly, but the Vmpp position changes less. When decreasing the light intensity, the peak of the P-V curve decreases, and the output power of the PV system decreases.

From Figs. 4 and 5, it is obvious that the effect of light intensity on PV cells is greater than the effect of temperature on PV cells. The main factor affecting the photovoltaic cell photogenerated current is the light intensity, which has little effect on the breaking voltage. The temperature mainly affects the

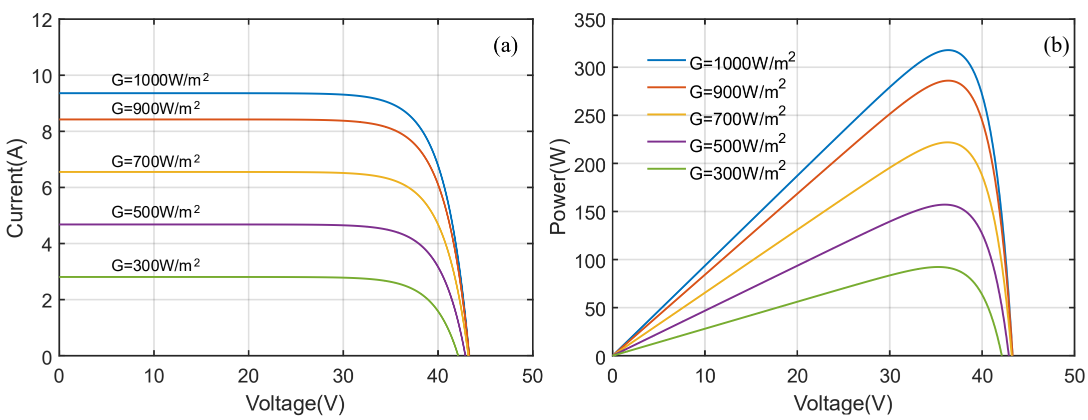

Fig. 5: Influence of different light intensities on output characteristics of photovoltaic cells (a) I-V curve and (b) P-V curve.

breaking voltage of the PV cell. By analyzing the maximum power point of the P-V curve, the control strategy is designed so that the PV system always works at the maximum power point to improve the power generation efficiency. The I-V test curve is used to detect if the component is aged or damaged, *e.g.*, a steep drop in the I-V curve may indicate a component failure. And increasing the series resistance R_s inside the module will reduce the output voltage and affect the power output.

4. Introduction to INC algorithm

The MPPT technique makes the operating point of the PV system always close to the maximum power point by adjusting the load resistance or changing the operating voltage to get the maximum power output. It is controlled based on the voltage and current variations of the PV modules in the system. In order to maximize the power output of the PV system, the maximum power point must be tracked in real time. In this paper, the INC method is used as an implementation of the MPPT algorithm. INC is a commonly used MPPT algorithm. The incremental conductance method is based on the mathematical characteristics of the PV cell power curve, and by comparing the negative value of the conductance increment with the instantaneous conductance, it determines whether the maximum power point has been reached or not, and dynamically adjusts the operating point so that it always operates near the maximum power point. The INC algorithm is highly accurate and responsive, and it is suitable for environments with large variations in light intensity and temperature.

The basic principle of the INC algorithm is that at the maximum power point,[16] the derivative of power to voltage is 0, that is, Eq. (8):

$$\frac{dP}{dV} = 0 \tag{8}$$

where, $P = V \times I$. Thus, we get Eq. (9):

$$\frac{dP}{dV} = I + V\frac{dP}{dV} = 0 \tag{9}$$

The results are as follows in Eq. (10):

$$\frac{dI}{dV} = -\frac{I}{V} \tag{10}$$

If $dI/dV = -I/V$, the system reaches the maximum power point. If $dI/dV > -I/V$, the system does not reach the maximum power, the need to continue to increase the voltage to improve the power; If $dI/dV < -I/V$, the system has not reached the maximum power point and needs to reduce the voltage to get closer to the maximum power point.

The realization steps are to collect the output voltage V and output current I of the PV module in real time, calculate the conductivity increment, and judge whether dV is 0. If it is 0, then see whether dI is 0: if it is greater than 0, then the voltage needs to be increased; if it is less than 0, then the voltage is reduced; if it is equal to 0, then it is just at the point of the maximum power. If dV is not 0, then compare the magnitude of conductivity increment with the size of the negative value of the conductivity in the transient, and then adjust the operating voltage of PV module by controlling the duty cycle of DC/DC converter, and then repeat the above steps. After the comparison result is obtained, the operating voltage of the PV module is adjusted by controlling the duty cycle of the DC/DC converter, and then the above steps are repeated continuously to track the MPP in real time. The flowchart is shown in Fig. 6.[17]

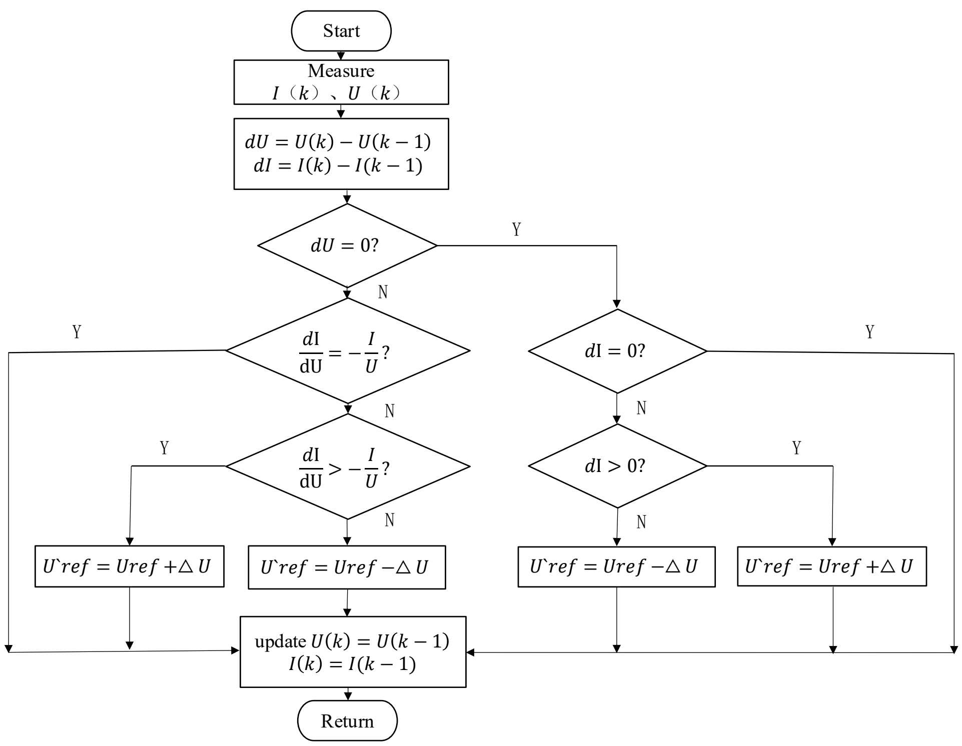

Fig. 6: Flowchart of INC algorithm.

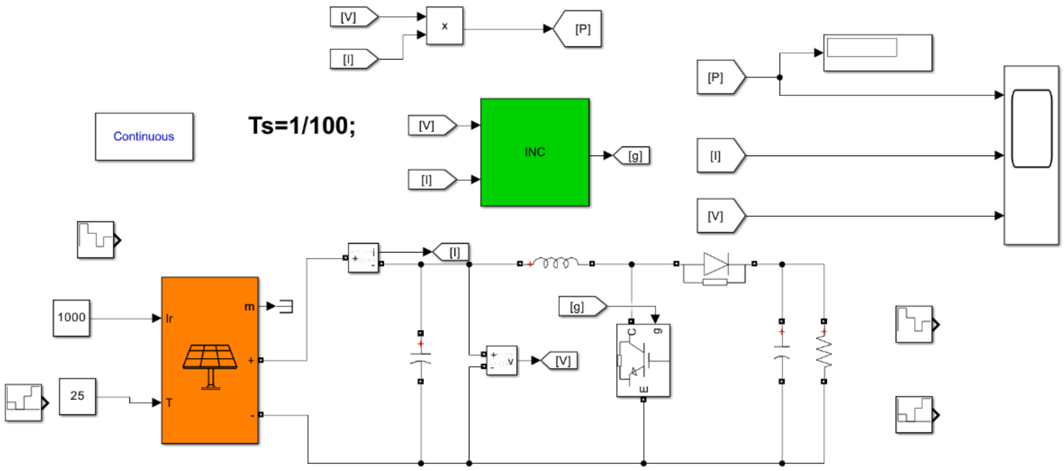

Fig. 7: Model of MPPT algorithm under stable input conditions.

5. Simulink modeling and simulation of MPPT algorithm

5.1 Simulink modeling

A new model different from the one described in Chapter 3 is used in this section. The simulation of the PV system in MATLAB/Simulink can be built using the self-contained Simscape Electrical toolbox. The model diagram is shown in Fig. 7.

The Simulink model in this paper contains the following main parts: (1) Photovoltaic Array Model: The "Photovoltaic Array" module in Simscape is used to configure the electrical parameters of the PV panel. The specific parameters of the PV module used in this study are shown in Table 2. (2) MPPT Controller: The MPPT controller implements the INC algorithm and compares it with the CV and P&O algorithms. It adjusts the voltage in real-time to track the MPP. (3) DC-DC Converter: A DC-DC converter is used to transform the DC output of the PV array into a voltage suitable for the load or the grid. In this simulation, a Boost converter is chosen as the regulation circuit. The schematic diagram of the Boost converter is shown in Fig. 8. (4) Load: The load simulates the connection between the PV system and the load or grid to analyze power output. The resistance of the load is set to 10 Ω.

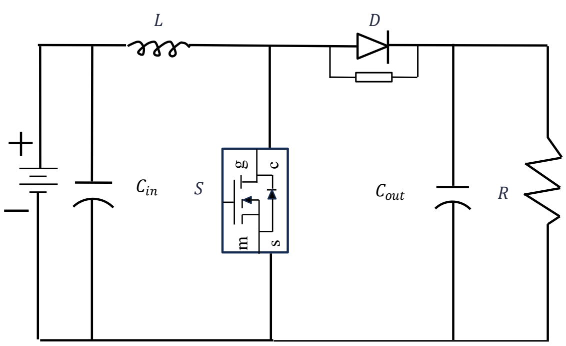

Fig. 8: Boost circuit schematic.

The input capacitor in the circuit is used for filtering at the input end.[18] Specifically, when there are changes in the input voltage or significant power supply noise, the input capacitor can prevent noise signals from entering the circuit,[19] thus preventing interference with the normal operation of the Boost circuit. The basic working principle of the Boost circuit is that when the switch is turned off, the inductor releases energy, and the current flows through the diode to the load and output capacitor, generating a Boost effect. Eq. (11) is the basic operating mode:

$$V_{out} = \frac{V_{in}}{1-D} \tag{11}$$

where, V_{out} is the output voltage, V_{in} is the output voltage of the PV cell, which is the input voltage of the Boost circuit, and D duty cycle, which is a key parameter for controlling the switching of the switching tube. The IGBT bipolar transistor is selected for this simulation. The PV cell can be made to operate at the maximum power when the previous load conditions are met by adjusting the size of D. The device simulation parameters of the Boost circuit are shown in Table 2.

Table 2: Simulated electrical parameters of the Boost circuit.

Parameters	Value
Inductance(L)	0.003H
Capacitance(in)	0.002F
Capacitance(out)	0.001 F
IGBT frequency	40 kHz
Load	10 Ω

The inductor in the Boost circuit functions as an energy storage component, converting electrical energy into a magnetic field for storage. The output capacitor also serves as a filter and provides voltage to the load when the switch is in the off state.

From the data in Table 3, we can determine that the maximum power of the photovoltaic array is 86.09 W. Next, we proceed with the MPPT simulation. The sampling frequency for this simulation is set to Ts = 0.01 s. First, we analyze the INC algorithm under steady-state conditions, and then we compare the three algorithms under dynamic input conditions.

Table 3: Specific parameters of photovoltaic modules.

Parameters	Value
Short-circuit current（I_{sc}）	5.17A
Open-circuit voltage (V_{oc})	22 V
Current at maximum power (I_m)	5.7 A
Voltage at maximum power (V_m)	18.36 V
Maximum output power（P_{max}）	86.29 W
Number of units per module	36
Number of modules in series per string	1
Temperature coefficient of open circuit voltage (%/deg.C)	-0.4385
Temperature coefficient of short-circuit current（%/℃）	0.0860

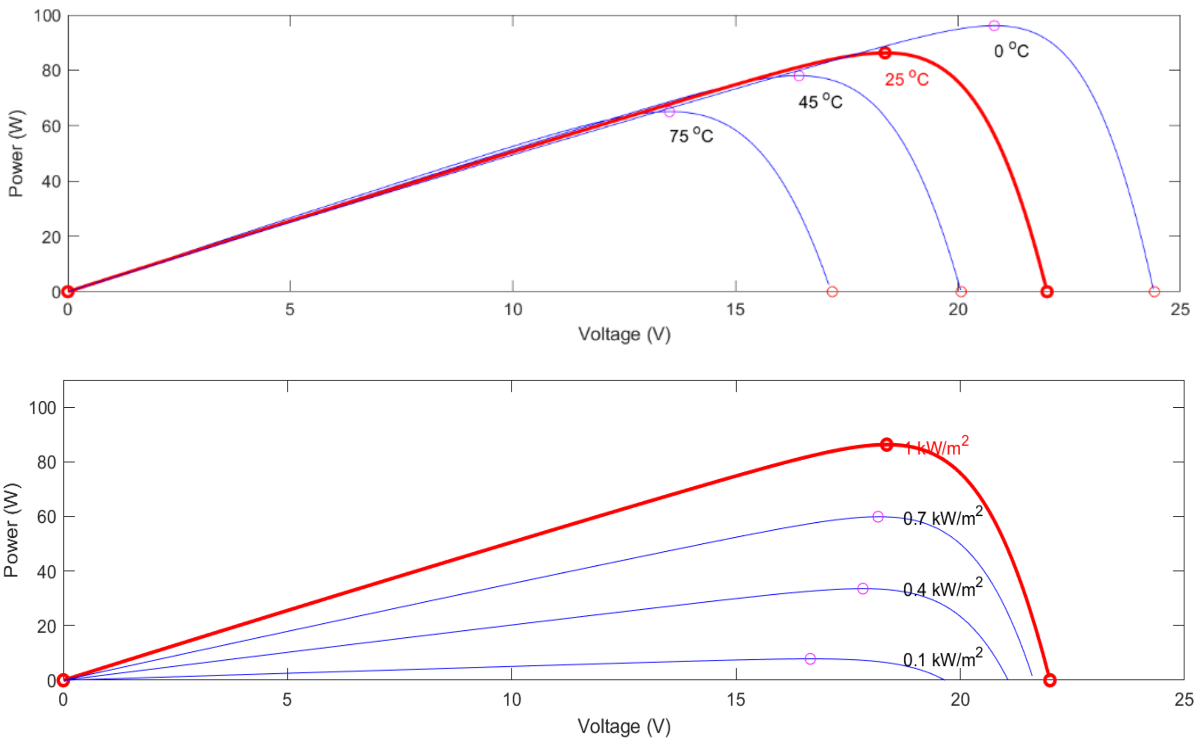

Fig. 9: V-P curves of photovoltaic cells under different conditions

The V-P graph of the photovoltaic cell used in this MPPT simulation under different conditions: At 25 ℃ with irradiance levels of 1000 W/m², 700 W/m², 400 W/m², and 100 W/m². At an irradiance of 1000 W/m² under temperatures of 0 ℃, 25 ℃, 45 ℃, and 75 ℃.The resulting power curves are shown in Fig. 9.

5.2 Analysis of simulation results

The simulation results indicate that the INC algorithm effectively enhances the output power of the photovoltaic system and ensures that the system remains near the maximum power point under varying environmental conditions. Compared to traditional fixed operating point methods, MPPT control significantly improves the overall system efficiency. Under an irradiance of 1000 W/m² and a temperature of 25 ℃, the INC algorithm achieves a maximum tracked power of 86.09W, with a tracking efficiency of 99.77% under steady-state conditions.

5.2.1 Effect of temperature on tracking results of INC algorithm

First, the impact of temperature on the MPPT algorithm is considered.[20] The conditions set are as follows: maintaining a light intensity of 1000 W/m², with simulations performed at temperatures of 0 ℃, 25 ℃, 45 ℃, and 75 ℃ for comparison. The impact of temperature is shown in Fig. 10. As the temperature increases, there is little effect on power tracking, but a significant impact on voltage. At higher temperatures, although there is a slight fluctuation in power tracking, it eventually stabilizes at the maximum power point of the

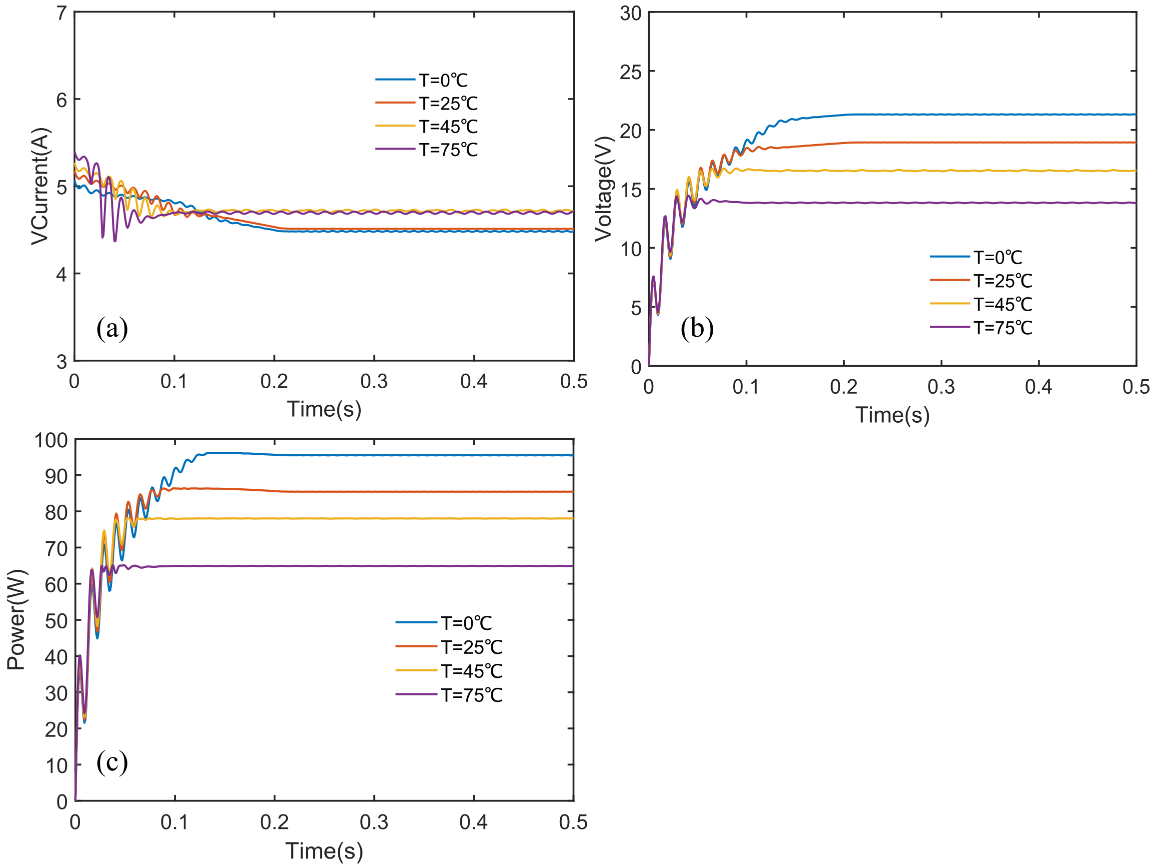

Fig. 10: Effect of different temperatures on INC algorithm tracking (a) t-I plot, (b) t-V plot, and (c) t-P plot.

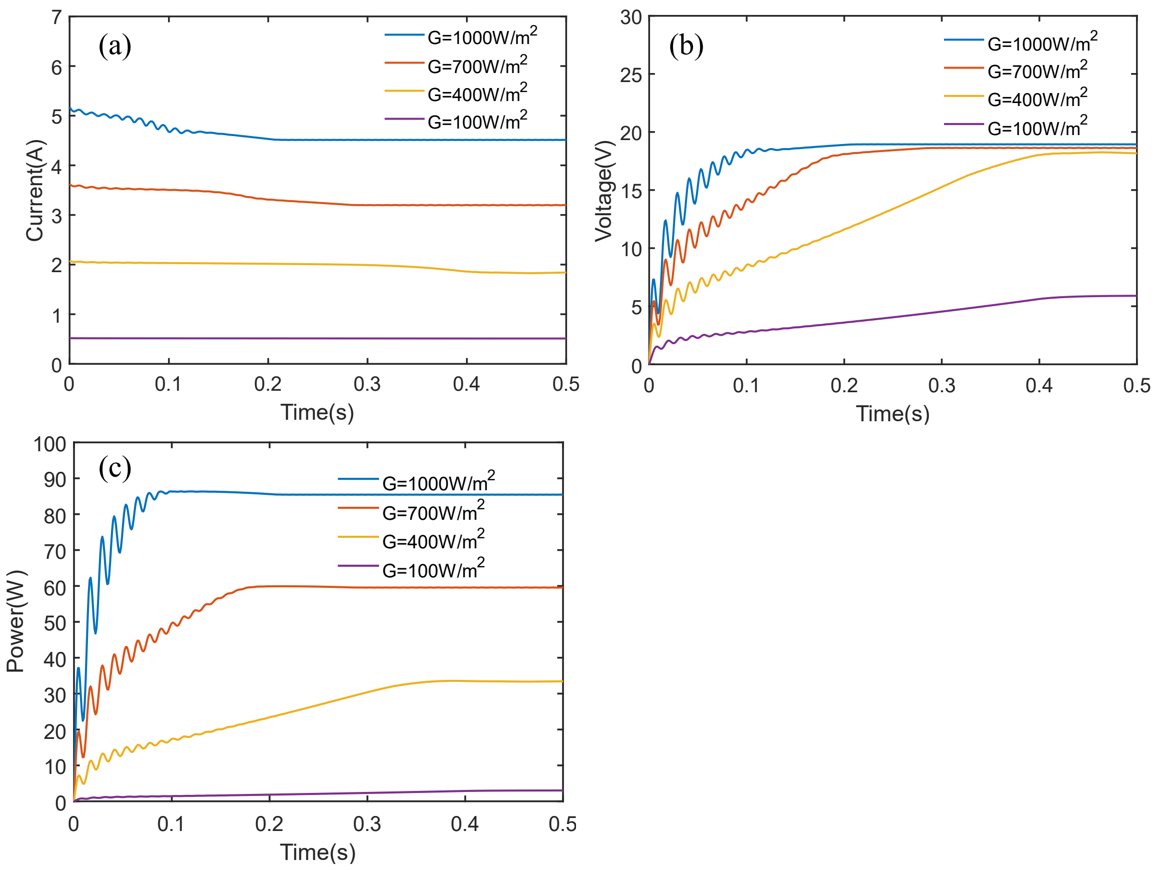

Fig. 11: Effect of different light intensity on INC algorithm tracking (a) t-I plot, (b) t-V plot, and (c) t-P plot.

current operating state. The temperature difference clearly shows that high temperatures have a greater impact on the INC algorithm system than low temperatures.

5.2.2 Effect of light intensity on the tracking results of INC algorithm

Considering that the outdoor conditions are not always clear, there are times when dark clouds or other shading objects cause shadows on the PV cells. Thus, simulation experiments with different light intensities under uniform illumination are conducted on the MPPT algorithm to verify the effectiveness of the algorithm and the model. As shown in Fig. 11, the model is given three light intensities of 1000 W/m^2, 500 W/m^2, and 200 W/m^2, and the temperature is kept at 25 ℃. The simulation effects of different light intensities performed under stable conditions are shown in Fig. 11.

Comparison of Fig. 10(c) and Fig. 11(c) shows that changes in light intensity have a greater effect on the power of the PV cell than that caused by temperature, and the same effect on voltage and current. After the light intensity decreases to a certain level, the Boost circuit has almost no provisioning effect on the current and only controls the voltage. This is because the photogenerated current of the PV cell is inherently low under low light conditions. Even if the INC algorithm adjusts the voltage to increase the power output, it can only maximize the output power of the cell, but the current itself is limited by the light intensity and cannot be increased beyond what the light conditions can provide.

5.2.3 Dynamic input

Considering that the external natural environment does not remain constant, it is necessary to perform a simulation with input conditions that change over time. The following simulation dynamically adjusts the temperature and light intensity inputs in steps, and compares the results with the traditional P&O and CV algorithms.

As shown in Fig. 12, the given conditions are: 1000 W/m², 700 W/m², 400 W/m², and 100 W/m², with a step interval of 0.5s. These simulations are conducted while maintaining a constant temperature of 25 °C to keep the variable single. Fig. 12(a) shows the curve of current variation with changing light intensity. It can be seen that the change in light intensity has a significant impact on current, and the same applies to voltage. The power values tracked by the INC, P&O, and CV algorithms on the first pass are 86.26W, 85.44W, and 75.88W, respectively, with times of 0.106s, 0.232s, and 0.053s. The tracking efficiency is 99.77%, 99.01%, and 87.93%, respectively. On the second tracking, the powers are 59.81W, 59.79W, and 53.02W, with tracking times of 0.058s, 0.153s, and 0.253s, respectively. The power tracked on the third and fourth passes is still optimal with the INC algorithm, with relatively shorter tracking times. Overall, in terms of the impact of external light intensity changes, the performance of the INC algorithm in MPPT is superior to the other two algorithms.

As shown in Fig. 13, the dynamic input conditions are such that the temperature changes over time: four cases are

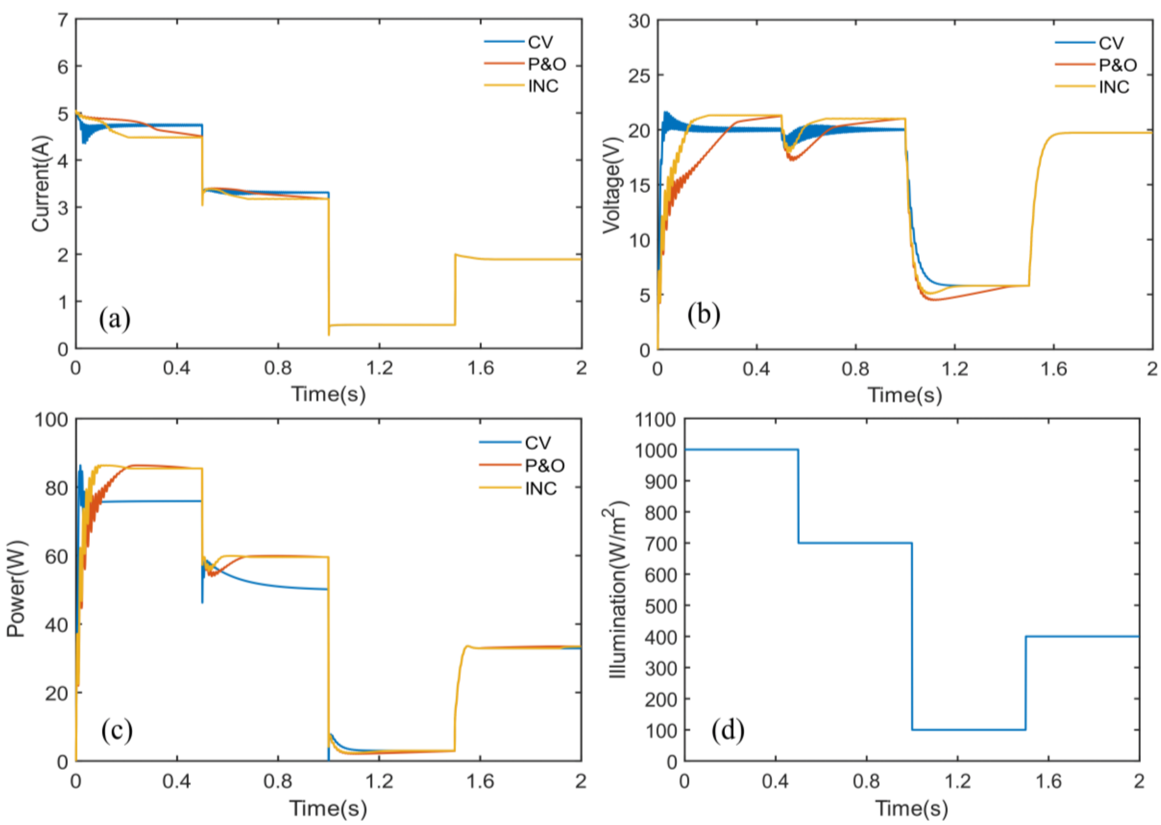

Fig. 12: Effect of dynamically varying light intensity on INC algorithm (a) t-I plot (b) t-V plot (c) t-P plot (d) t-G plot.

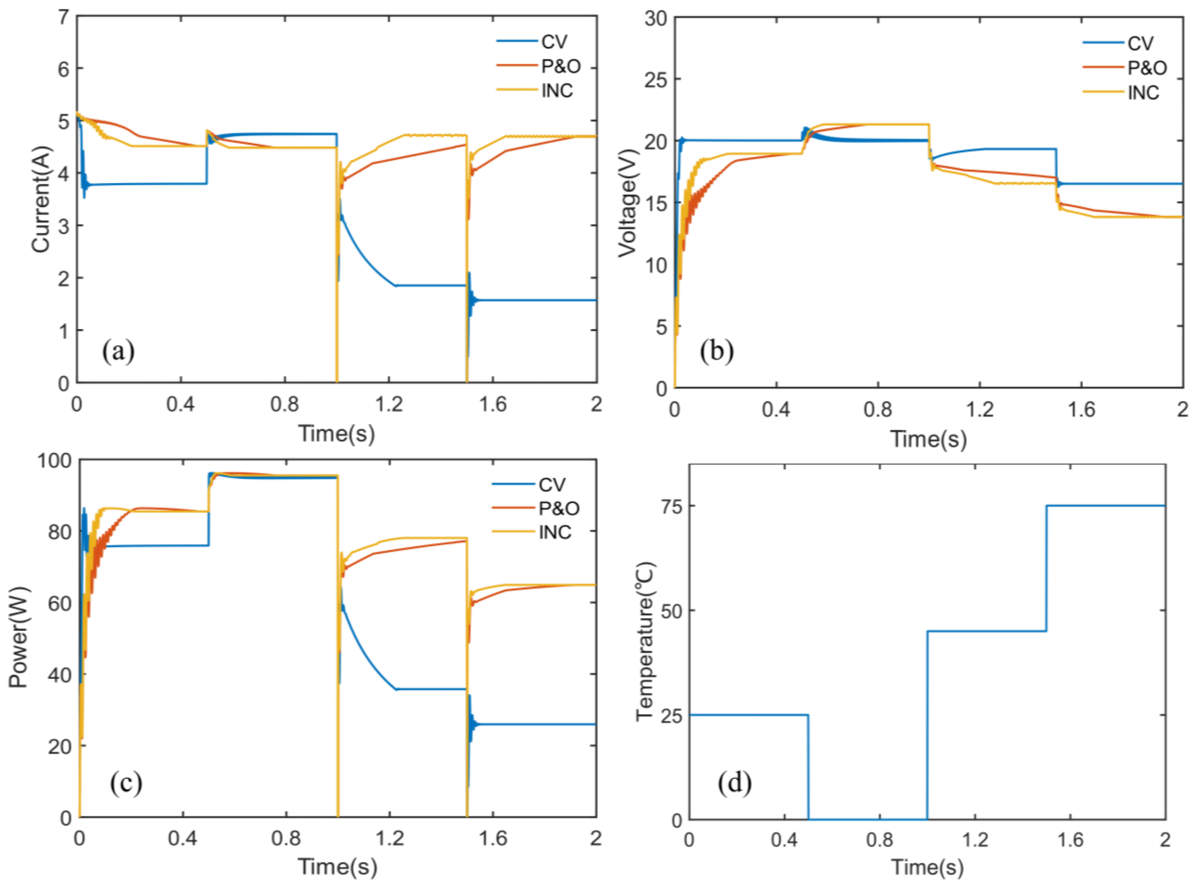

Fig. 13: Dynamically varying temperature effect on INC algorithm (a) t-I plot, (b) t-V plot, (c) t-P plot, and (d) t-T plot.

considered 25 °C, 0 °C, 45 °C, and 75 °C at 0.5s intervals. In this scenario, the light intensity is kept constant at 1000 W/m². It is clear that the impact of temperature changes on the system's output is somewhat smaller compared to the effect of light intensity changes. However, local results do change.

It can be seen that, except for the CV algorithm, the output current of the photovoltaic panel in the other two algorithms does not change significantly with increasing temperature. On the contrary, when the temperature changes, the output voltage of the photovoltaic panel varies more, as temperature changes have the most significant impact on voltage, which can be observed from the photovoltaic characteristics analysis section.

After the first temperature change, the maximum power tracked by the INC, P&O, and CV algorithms were 9603W, 95.89W, and 94.03W, with tracking times of 0.05s, 0.053s, and 0.059s, respectively. After the second temperature change, the maximum power values were 77.04W, 74.20W, and 35.75W, with tracking times of 0.169s, 0.231s, and 0.228s, respectively. After the third temperature change, the maximum powers tracked by the three algorithms were 64.67W, 63.08W, and 25.98W, with convergence times of 0.122s, 0.258s, and 0.049s, respectively.

From this, it can be observed that when the external temperature fluctuates significantly, the INC algorithm reaches a stable state first, demonstrating the best robustness. The P&O algorithm comes second, with the maximum power it converges to only slightly lower than that of the INC algorithm. Lastly, the CV algorithm, although able to converge, tends to get trapped in local maxima, causing power loss.

In summary, while changes in light intensity or temperature cause power fluctuations, the INC algorithm can still track well, and the tracking time remains within an acceptable range. It is also noted that even though the temperature change was larger during the second test, the tracking time was still shorter than when the light intensity changed. Therefore, light intensity is the key factor causing power changes in the photovoltaic panel and is a critical factor that the algorithm and model must consider.

Finally, environmental factors do not change in isolation; in many cases, both temperature and light intensity change simultaneously. Therefore, simulations and testing of the algorithm and model must account for such scenarios.

In Fig. 14, the variable conditions set are as follows: light intensity changes sequentially from 1000 W/m², 700 W/m², 100 W/m², to 400 W/m², with a time interval of 0.5s. The temperature changes sequentially from 25 °C, 0 °C, 45 °C, to 75 °C, with the same time interval of 0.5s.

From Fig. 14, it can be observed that the power drop after the second temperature change, when combined with the light intensity variation, is particularly severe. However, due to the increase in both temperature and light intensity, the convergence speed of all algorithms is relatively fast, and the maximum power tracked by each algorithm is quite similar.

In the first tracking, the fastest convergence time is 0.039s

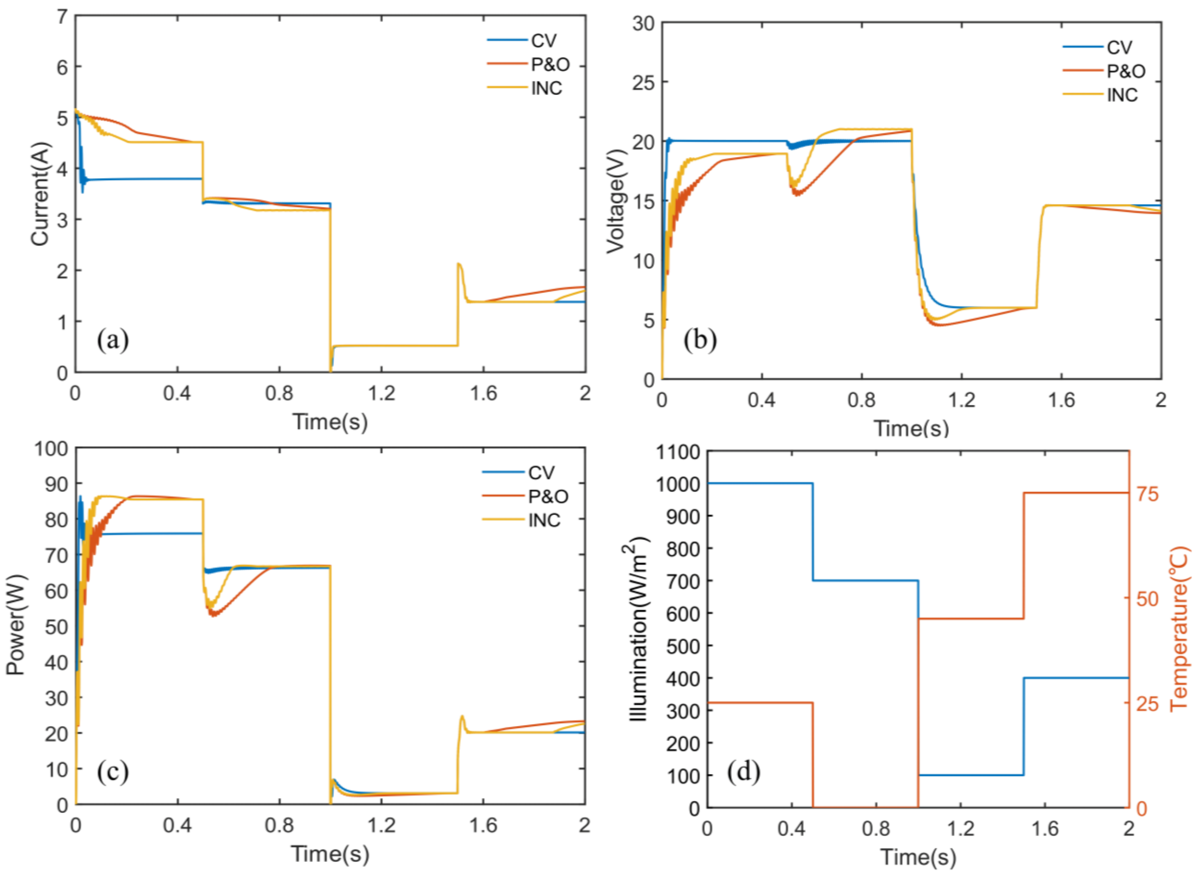

Fig. 14: Effect of simultaneous changes in light intensity and temperature on the INC algorithm (a) t-I plot, (b) t-V plot, (c) t-P plot, and (d) t-T plot and t-G plot.

for the INC algorithm, with a maximum power of 75.09W. The slowest convergence time is for the P&O algorithm, at 0.229s, with a convergence power of 85.44W. In the second tracking, the fastest convergence time is 0.132s, with a maximum power of 66.76W, while the P&O algorithm converges the slowest, with a maximum power of 75.08W. The CV algorithm, on the other hand, is in an oscillation state.

After the final change, the INC algorithm maintains the maximum power for the longest time, while the P&O algorithm disrupts the convergence state first, and the CV algorithm remains at a constant power state.

6. Conclusion

This paper conducts a comparative study of three classic MPPT algorithms, Perturb and Observe (P&O), Constant Voltage (CV), and Incremental Conductance (INC), focusing on their dynamic performance and steady-state characteristics under different environmental conditions. The results indicate significant differences in the performance of these algorithms when light intensity and temperature change.

The P&O algorithm, due to its periodic perturbation, exhibits steady-state power oscillations. In cases of rapid light intensity changes, it may misjudge the direction, leading to an increase in power loss. The CV algorithm, although simple in structure, fails to adapt to environmental changes, resulting in an inability to accurately track the Maximum Power Point (MPP), especially under conditions with significant temperature variations, where it experiences larger errors. In contrast, the INC algorithm, by calculating the relationship between incremental conductance and instantaneous conductance, more accurately determines the MPP position. It provides better dynamic response in the presence of light intensity and temperature changes, reduces steady-state oscillations, and improves system efficiency.

Through MATLAB/Simulink simulation validation, it was found that under the same environmental conditions, the INC algorithm consistently outperforms the P&O and CV algorithms in power tracking efficiency. Particularly in cases of rapid light intensity changes, the INC algorithm can adjust the duty cycle more quickly, achieving a more stable maximum power point tracking. Furthermore, the INC algorithm exhibits lower power loss in steady-state conditions, demonstrating better stability compared to P&O and higher tracking accuracy compared to CV.

Although the INC algorithm performed best in this study, there is still room for improvement. For example, under rapidly changing operating conditions, the step size selection in the INC algorithm has a significant impact on tracking speed and steady-state error. Additionally, in later stages of temperature and light intensity changes, there may be instances where the algorithm fails to maintain the convergence equilibrium. Incorporating adaptive step size or intelligent control methods could further improve its tracking performance. Furthermore, for specific applications, such as MPPT in partially shaded environments, heuristic optimization algorithms, such as Particle Swarm Optimization, Genetic Algorithms, *etc*., should be considered to avoid local optima.

Overall, this study demonstrates that the INC algorithm offers superior performance in photovoltaic MPPT, making it suitable for applications that require high dynamic response and steady-state efficiency. However, each MPPT algorithm has its own strengths and weaknesses. In practical applications, the most suitable MPPT control strategy should be chosen based on the specific needs of the photovoltaic system, balancing computational complexity, hardware cost, and tracking accuracy. Future research could further explore MPPT algorithms based on intelligent optimization to further enhance the overall performance of photovoltaic systems.

This study mainly simulates the performance of the photovoltaic system under different light intensities to validate the effectiveness of the MPPT algorithm under ideal conditions. However, photovoltaic systems in real-world environments are affected by various factors, such as clouds, obstructions, and the aging of photovoltaic components, all of which can significantly alter the output characteristics of the system. Therefore, the results of this study may have certain deviations and cannot fully and accurately reflect the performance of photovoltaic systems in real-world conditions.

Conflict of Interest

There is no conflict of interest.

Supporting Information

Not applicable.

References

[1] A. Kingmaneerat, T. Ratniyomchai, W. Saikong, C. Techawatcharapaikul, T. Kulworawanichpong, Reducing hydrogen consumption by using regenerative braking energy for hydrogen fuel-cell electric bus vehicles, *Engineered Science*, 2025, **33**, 1334, doi: 10.30919/es1334.

[2] H. Wang, L. Li, H. Ye, W. Zhao, Enhancing MPPT efficiency in PV systems under partial shading: a hybrid POA&PO approach for rapid and accurate energy harvesting, *International Journal of Electrical Power & Energy Systems*, 2024, **162**, 110260, doi: 10.1016/j.ijepes.2024.110260.

[3] M. L. Katche, A. B. Makokha, S. O. Zachary, M. S. Adaramola, A comprehensive review of maximum power point tracking (mppt) techniques used in solar pv systems, *Energies*, 2023, **16**, 2206, doi: 10.3390/en16052206.

[4] D. Verma, S. Nema, A. M. Shandilya, S. K. Dash, Maximum power point tracking (MPPT) techniques: Recapitulation in solar photovoltaic systems, *Renewable and Sustainable Energy Reviews*, 2016, **54**, 1018-1034, doi: 10.1016/j.rser.2015.10.068.

[5] P. Livinti, G. Culea, I. V. Banu, S. G. Vernica, Comparative study of a buck DC-DC converter controlled by the MPPT (P&O) algorithm without or with fuzzy logic controller, *Applied Sciences*, 2024, **14**, 7628, doi: 10.3390/app14177628.

[6] Z. Wang. Maximum power point tracking based on constant voltage method combined with variable step conductance increment method, *Science Technology and Engineering*, 2012, **12**, 4638-4642.

[7] P. Li, Research on photovoltaic MPPT control based on variable step-size conductance increment method, *Journal of Jingchu Institute of Technology*, 2024, **39**, 22-30, doi: 10.14151/j.cnki.jclgxyxb.2024.06.010.

[8] Q. Yun, Y. Zhang, S. Wang, Simulation research on off-grid solar photovoltaic power generation system based on Matlab/Simulink, *Journal of Liaoning University of Science and Technology*, 2016, **18**, 19-23, doi: 10.3969/j.issn.1008-3723.2016.03.008.

[9] L. Li, W. Zhao, H. Wang, Z. Xu, Y. Ding, Sand cat swarm optimization based maximum power point tracking technique for photovoltaic system under partial shading conditions, *International Journal of Electrical Power & Energy Systems*, 2024, **161**, 110203, doi: 10.1016/j.ijepes.2024.110203.

[10] G. B. Wereda, I. M. Diaaeldin, O. A. M. Omar, M. A. Attia, A. O. Badr, A novel optimization approach using chaos game optimization algorithm for parameters estimation of photovoltaic cells, *Sustainability*, 2025, **17**, 1609, doi: 10.3390/su17041609.

[11] W. Zhou, H. Yang, Z. Fang, A novel model for photovoltaic array performance prediction, *Applied Energy*, 2007, **84**, 1187-1198, doi: 10.1016/j.apenergy.2007.04.006.

[12] C. Wang, Y. Wen, J. Sun, J. Zhou, Recent progress on optical frequency conversion in nonlinear metasurfaces and nanophotonics, *ES Materials & Manufacturing*, 2022, **17**, 1-13, doi: 10.30919/esmm5f655.

[13] J. A. Ramírez Torres, O. Lastres Danguillecourt, R. A. González Domínguez, G. R. Ibáñez Duharte, L. E. Verea Valladares, J. Pantoja Enríquez, J. A. Enríquez Santiago, A. López López, A. Verde Añorve, Development and implementation of the MPPT based on incremental conductance for voltage and frequency control in single-stage DC-AC converters, *Energies*, 2025, **18**, 184, doi: 10.3390/en18010184.

[14] C. Guo, Y. Tang, S. Lin, Maximum power point tracking strategy based on fuzzy control with variable step-size conductance increment method, *Modern Electronic Technology*, 2022, **45**, 145-151, doi: 10.16652/j.issn.1004-373x.2022.19.027.

[15] J. Kaur, H. D. Shelke, S. R. Jadkar, H. M. Pathan, R. Kumar, Optimization of photovoltaic characteristics of CIGS/Si heterojunction solar cells, *ES Energy & Environment*, 2022, **17**, 56-63, doi: 10.30919/esee8c743.

[16] J. Cui, Y. Ji, Research on maximum power point tracking of photovoltaic based on neural network algorithm, *Automation*

Application, 2024, **65**, 146-149, doi: 10.19769/j.zdhy.2024.13.040.
[17] Z. Liu, H. Wang, M. Zhou, Y. Qian, Global maximum power point tracking algorithm based on conductance increment method, *Journal of Electrical Engineering*, 2023, **18**, 245-253, doi: 10.11985/2023.02.025.
[18] J. Singh, Z. Din, Energy efficient data aggregation and density-based spatial clustering of applications with noise for activity monitoring in wireless sensor networks, *Engineered Science*, 2022, **19**, 144-153, doi: 10.30919/es8d694.
[19] E. Şehirli, Comparison of the input filter effect to PV panel by SEPIC MPPT converter, *Energy Reports*, 2023, **9**, 34-50, doi: 10.1016/j.egyr.2023.05.238.
[20] J. Wang, Research on maximum power point tracking algorithm for photovoltaic power generation system based on MATLAB/Simulink, *Power Generation Equipment*, 2023, **37**, 98-103, doi: 10.19806/j.cnki.fdsb.2023.02.005.