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A PV MPPT control method based on async-PSO and INC algorithm under shading condition

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For the time being, solar energy has received considerable attention and development on account of its distinct advantages, such as rich reserves and no geographical restrictions. Nevertheless, in practical applications, the photovoltaic module is easily affected by external environments, which gives rise to a decrease in photovoltaic power. The maximum power point tracking (MPPT) technology for PV power system is an effective method to elevate the efficacy of photovoltaic electricity conversion. The frequently used control methods include the perturb and observe (P&O) algorithm and the incremental conductance (INC) method, and so forth; these methods vary tremendously in terms of the required parameters, algorithm complexity, tracking speed, tracking accuracy, hardware requirements etc. This work puts forth a MPPT control method on the basis of Async-PSO and INC algorithm to achieve a better performance in the MPPT. To reflect the change of light amplitude and temperature in a day, the temperature varies from 25℃ to 60℃ and irradiance from 450W/m^2 to 900W/m^2. An extensively used mono-crystalline silicon PV module with 240W was considered as the research object to compare the capability of the recommended MPPT control method. MATLAB/Simulink software was adopted to model and simulate the algorithm. Aside from that, comprehensive comparisons were made with other MPPT methods to test and verify the recommended algorithm has significantly improved the tracking speed and accuracy at the maximum power point with smaller oscillations under various conditions.

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Keywords: Photovoltaic, MPPT, Async-PSO, Variable step-size, Shading

1. Introduction

In response to environmental pollution, global climate change and energy strategies, countries worldwide are actively promoting the transformation of clean, sustainable energy and low-carbon systems [1]. Europe puts forward a road map to achieve 100% renewable energy power system in Europe and North Africa by 2050[2]. In 2021, solar photovoltaic capacity increased by 175GW, reached a cumulative total of approximately 942GW [3], solar energy is regarded as the most promising source of energy. The photovoltaic energy is favorably featured by its high efficiency, clean and pollution-free nature, vast resources and minimal maintenance costs, etc. [4].

The photovoltaic cell's input and output characteristics exhibit a nonlinear correlation in the photovoltaic power system. The power output of Photovoltaic is tightly correlated with the change in light intensity, temperature, and load [5]. How to heighten the light conversion efficiency and lower the cost of electricity by source of photovoltaic has always been an imperative issue at present [6-9]. The research of MPPT aims at enabling the PV power system to work at its MPP quickly and continuously, maximizing the photoelectric conversion efficiency, reducing energy loss triggered by oscillations, heightening the efficiency and benefits of PV power generation, promoting the widespread adoption and application of photovoltaic power of large-scale, high-efficiency and high-benefit [10].

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This research is intended to describe the procedures and methods that will be employed to conduct dissertation research on photovoltaic maximum power point tracking technology. This work primarily analysed and probed into the MPPT control methods of photovoltaic power system. Subsequently, this work built a mathematical model in MATLAB/Simulink platform for simulation analysis and verification. Afterwards, this research cconstructed an engineering model of photovoltaic and analysed its working principle. A frequently used mono-crystalline silicon photovoltaic module was selected as the research object to analyse the output characteristic curves of P-U and I-U under different temperature and irradiation. The Async-PSO and INC aalgorithm was adopted, and the algorithm is adopted to track the MPP of the selected photovoltaic model and compared it with other MPPT control methods to test and verify its advantages in the maximum power point tracking process.

2. PV system model

2.1. PV cell model

In general, photovoltaic cells are instruments that convert the energy of light into electricity. On this basis, a photovoltaic cell's mathematical model is founded on the physics of semiconductor materials and the principles of electrochemistry. A current source in parallel with a diode can represent the basic model of a photovoltaic cell. The current source represents the photo-current generated by light absorption in the semiconductor material; the diode represents the P-N junction's current-voltage characteristics that form the photovoltaic cell; Figure 1 demonstrates the equivalent circuit of a PV cell [11].

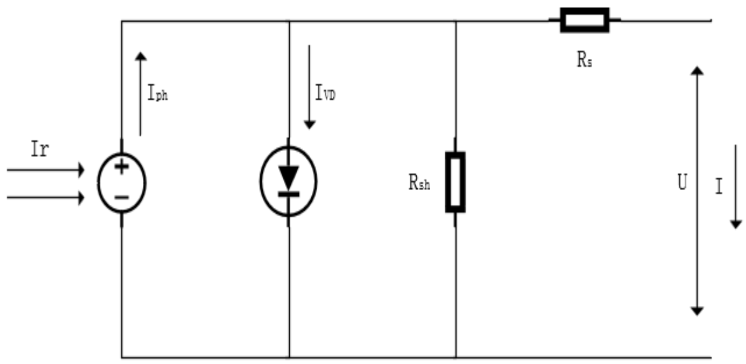

Fig. 1. Equivalent Circuit of Photovoltaic Cell.

In accordance with Figure 1, the mathematical model of the photovoltaic cell is exhibited in equations (1), (2), (3), (4) and (5).

$$\mathbf{I = I_{ph} - I_{VD} - I_{sh}} \tag{1}$$

$$\mathbf{I_{ph} = I_{SC} \times \frac{G}{G_{ref}}} \tag{2}$$

$$\mathbf{I_{VD} = I_0 \left\{ \exp \left| q \left(\frac{U + IR_s}{nKT} \right) \right| - 1 \right\}} \tag{3}$$

$$\mathbf{I_{sh} = \frac{U + IR_s}{R_{sh}}} \tag{4}$$

$$\mathbf{P} = \mathbf{I} \times (\mathbf{U} - \mathbf{U_{OC}} + \mathbf{IR_S}) \tag{5}$$

Here, I - Current generated by photovoltaic cell;
I_{ph} - Photo-current generated by absorbed light;
I_{VD} - Current flowing through the diode;
I_{SC} - Short-circuit current of the PV cell;
G - Irradiance of the incident light;
G_{ref} - Reference irradiance, typically 1000 W/m^2;
I_0 - Reverse saturation current of the diode;
q - Electric charge of the electron, 1.6×10^{-19}C;
U - Voltage across the photovoltaic cell;
R_s - Series resistance of photovoltaic cell;
n - Diode constant factor;
K - Boltzmann Constant, 1.38×10^{-23}J/K;
T - Thermodynamic temperature;
R_{sh} - Parallel resistance of photovoltaic cell;
P - The power output of photovoltaic cell;
U_{OC} - Open-circuit voltage of the photovoltaic cell.

It's paramount to note that the performance of a photovoltaic cell is affected by multifarious factors such as temperature, the spectral distribution of the incident light, and shading effects [12]. Consequently, the above mathematical model provides a basic framework for better understanding the behaviour of photovoltaic cells.

This work takes an extensively used mono-crystalline silicon PV panel as the research object to compare the capability of the recommended MPPT control methods. Besides, the model of the photovoltaic module is M60-240.

Table 1. Standard Parameters of M60-240 (1000W/㎡, 25℃).

Module	M60-240
Cells Per Module	60
Maximum Power（P_{max}）	240W
Voltage at Maximum Power Point（V_{mp}）	36.84V
Current at Maximum Power Point（I_{mp}）	8.32A
Open Circuit Voltage（V_{oc}）	30.72V
Short-Circuit Current（I_{sc}）	7.83A
Temperature Coefficient of V_{oc}	-0.359%/℃
Temperature Coefficient of I_{sc}	0.096995%/℃

Simultaneously, the Current-Voltage and Power-Voltage characteristic curves of M60-240 under different irradiance (900W/m^2, 750W/m^2, 600W/m^2) at 25°C, as displayed in Figure 2.

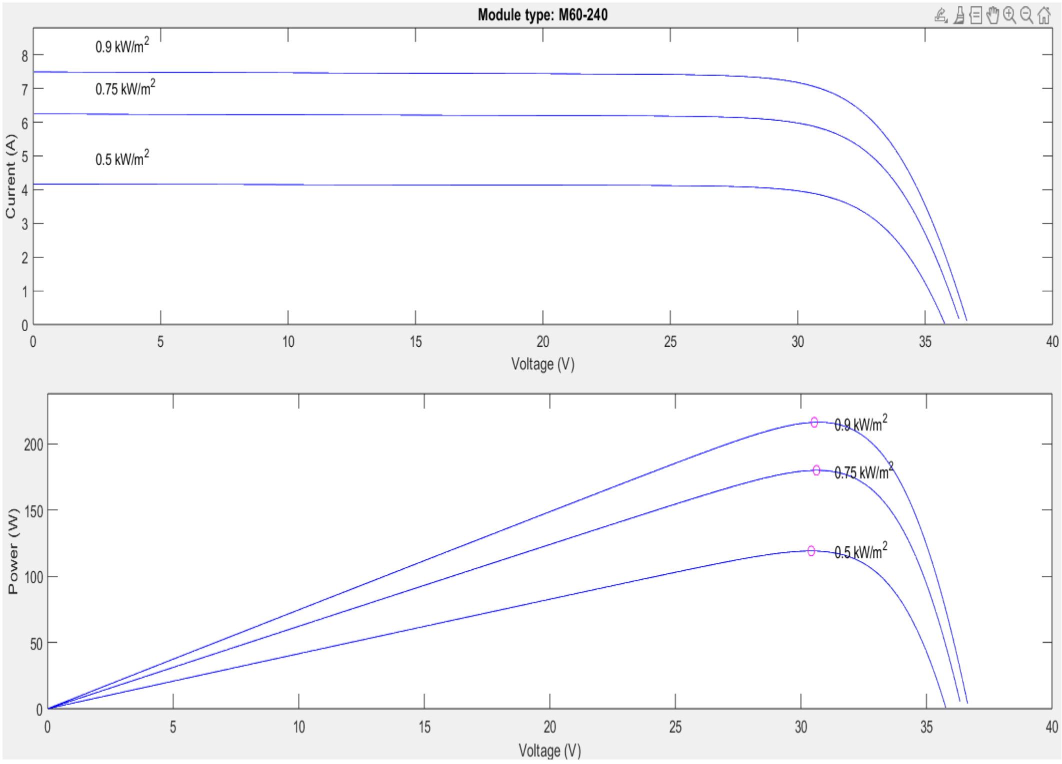

Fig. 2. Characteristic Curves of M60-240 under Different Irradiance at 25℃.

As Figure 2 illustrates, the light intensity imposes trivial influence on the open-circuit voltage of the photovoltaic cell at a constant temperature; when light intensity increases or decreases, the open-circuit voltages are essentially unaffected. The output current of the photovoltaic cell will increase with the augment in light intensity. What's more, the maximum power output of the photovoltaic cell will increase with the increment in light intensity. Although the MPP is different, the corresponding voltage at the MPP is basically the same [13]. Furthermore, Figure 3 depicts the P-U and I-U characteristic curves of M60-240 at varied temperatures (30°C, 45°C, 60°C) under 1000W/m^2 of irradiance.

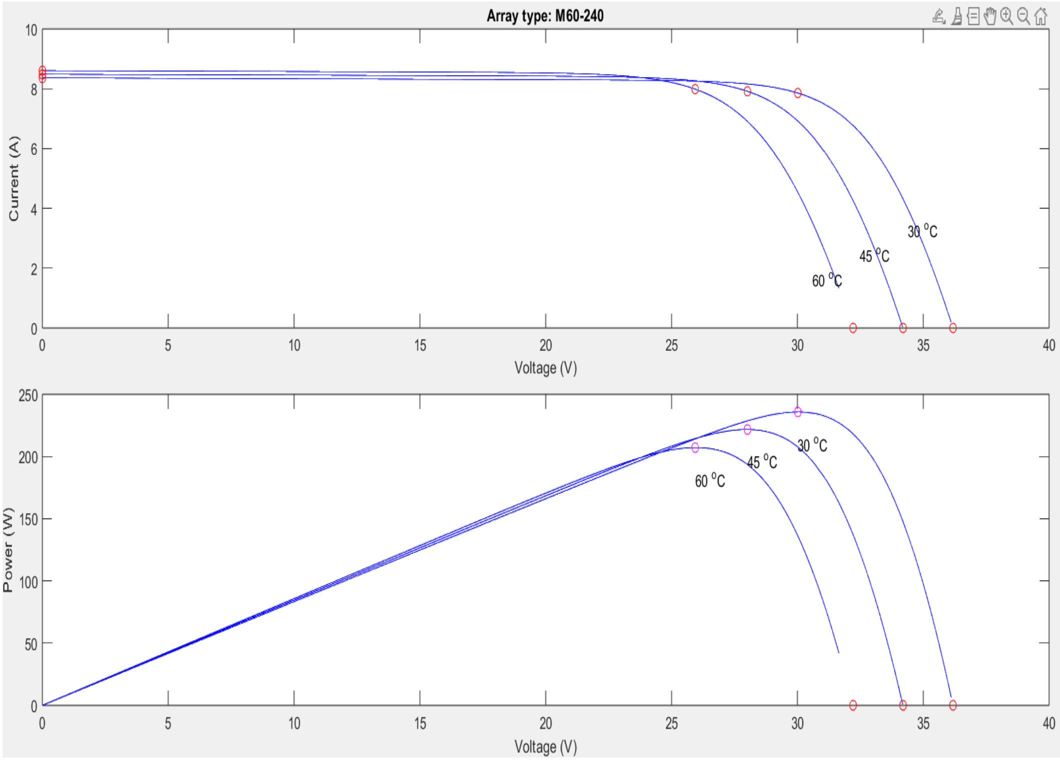

Fig. 3. Characteristic Curves of M60-240 at Different Temperatures under 1000W/m².

As depicted in Figure 3, the temperature has less impact on the output current, which decreases as the temperature rises. In contrast, the temperature can exert a striking influence on on open-circuit voltage. The open-circuit voltage will decrease as the current increase [13]. As a result, if the temperature rises sharply, the maximum power output of the solar cell will decrease accordingly [14].

2.2. Partial shading conditions

Photovoltaic arrays are typically installed in outdoor open areas where they may experience interference from clouds or other factors that affect the intensity of the solar radiation, which triggers uneven illumination of the PV arrays. As a result, the output curve of the PV arrays will exhibit multiple maximum power points [15].

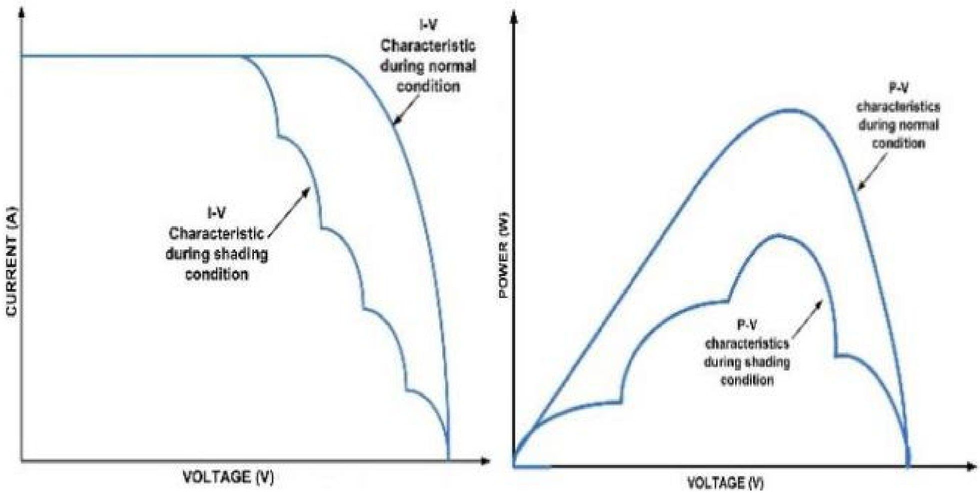

Fig. 4. Characteristic curves under partial shading conditions.

2.3. DC-DC Converter

It's noteworthy that the photovoltaic cell has a specific internal resistance. To be specific, it is equivalent to the load impedance and output impedance by the maximum power transmission theory; in a photovoltaic power generation system, it's essential build a DC-DC converter between the photovoltaic cell and its load to maintain the output always at the maximum power point [16].

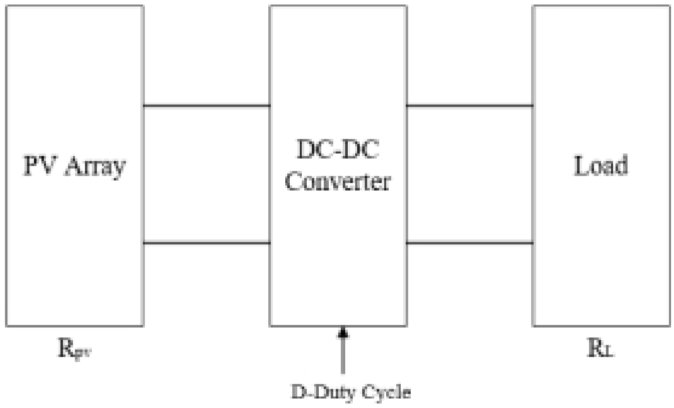

Fig. 5. Connecting Diagram of DC-DC Converter.

Assuming the electronic switch tube operates in an ideal state, then [9]:

$$\mathbf{U_L = \frac{U_{PV}}{1-D}} \tag{6}$$

In the formula:

U_L – The output voltage of PV module;

U_{PV} – The output voltage of PV cell;

D – Duty cycle.

When the circuit operates under ideal conditions, in line with the law of energy conservation, the power input and output of the system are theoretically equal, then [9]:

$$\mathbf{\frac{U_{PV}^2}{R_{PV}} = \frac{U_L^2}{R_L}} \tag{7}$$

In the formula:

R_{PV} - Internal resistance of Photovoltaic module；

R_L - External load resistance.

When the light intensity changes, the resistance value of R_{PV} will also change. In such case, the IGBT needs to be periodically turned off through the MPPT control algorithm. Then the duty cycle is adjusted to make the equivalent resistance and the load resistance of the circuit equal so that the PV power system can work at the MPP, thus realizing MPPT control [17].

3. MPPT Control Methods

3.1. The Principle of MPPT

In a PV power system, the characteristic curve of the PV cell under a constant environment is a single-peak curve. The highest point on the nonlinear output curve is the MPP [18]. The MPPT detects the photovoltaic array's output power in real-time, and the appropriate control method is adopted to track the MPP of the PV in real-time. The MPP of the photovoltaic cell will change with the variability of external environmental factors such as temperature and irradiation. In addition, its voltage-current and volt-watt characteristics curve shows extreme non-linearity [19].

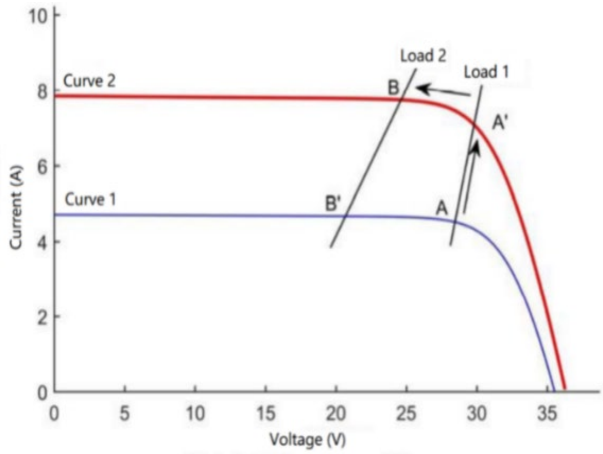

Fig. 6. Schematic Diagram of MPPT.

The two curves in Figure 6 are the current-voltage characteristic curves of the photovoltaic cell under different light intensities; points A and B are the maximum power points under different solar irradiance and load conditions [12]. If the light intensity decreases from irradiance curve 2 to irradiance curve 1 while the load remains constant, the power output will shift from B to B'; nonetheless, the new MPP should be at point A. As a consequence, the load must be adjusted from load 2 to load 1, so as to maintain the maximum power output when the light intensity decreases. Analogously, when the light intensity increase, the MPP will also change, and the system can be adjusted to work at the MPP by adjusting the load.

3.2. Async-PSO Algorithm

Normally speaking, asynchronous Particle Swarm Optimization (APSO) is an evolutionary algorithm used for optimizing the solutions of continuous functions[20]. It is a variant of Particle Swarm Optimization (PSO)[21], where each particle updates its position in a random order. Each particle in the APSO algorithm has a local best solution and a global best solution[22]. In each iteration, each particle updates its position on the basis of its current velocity and the distance from the global and local best solutions. Once the position update is complete, the particle evaluates the fitness of its new position and updates its local best solution if the fitness is better. Apart from that, if the fitness of the new position is better than any previous best fitness of any other particle in the swarm, it becomes the global best solution. In contrast to standard PSO, APSO does not update all particle positions in every iteration. Instead, the particles update their positions in arbitrary order to avoid the problem of collective behavior and prevent getting trapped in local optima. This gives rise to faster convergence rates and better performance in high-dimensional optimization problems.

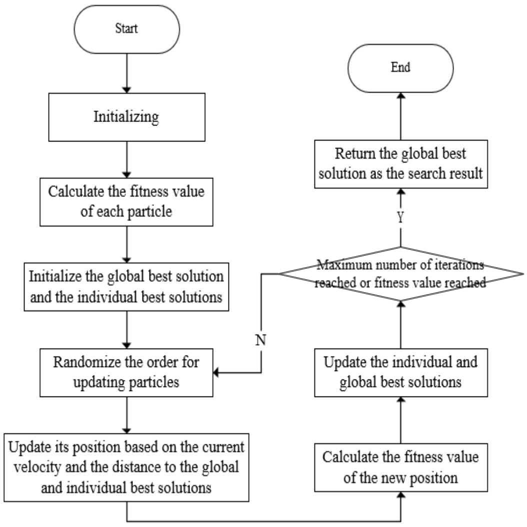

Fig. 7. The Flowchart of the Async-PSO Algorithm.

To test the Async-PSO algorithm's effectiveness, different test functions with multi-modal characteristics are selected for verification.

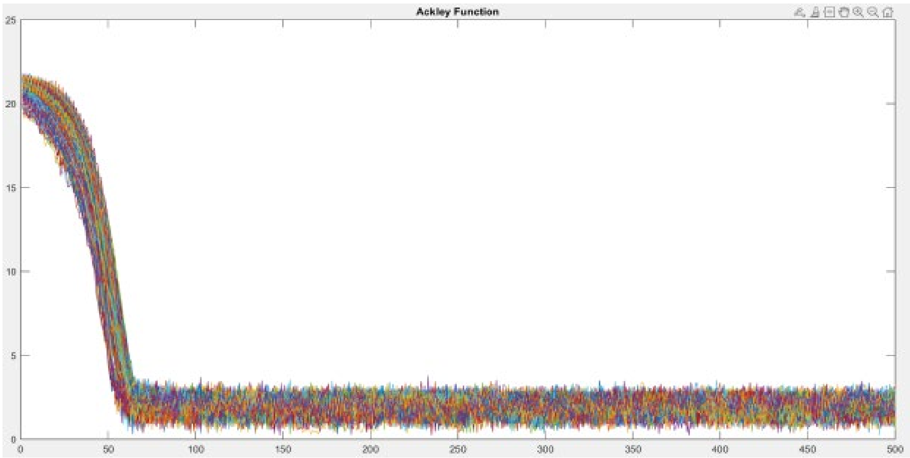

Fig. 8. The Iterative Curve of Ackley Function.

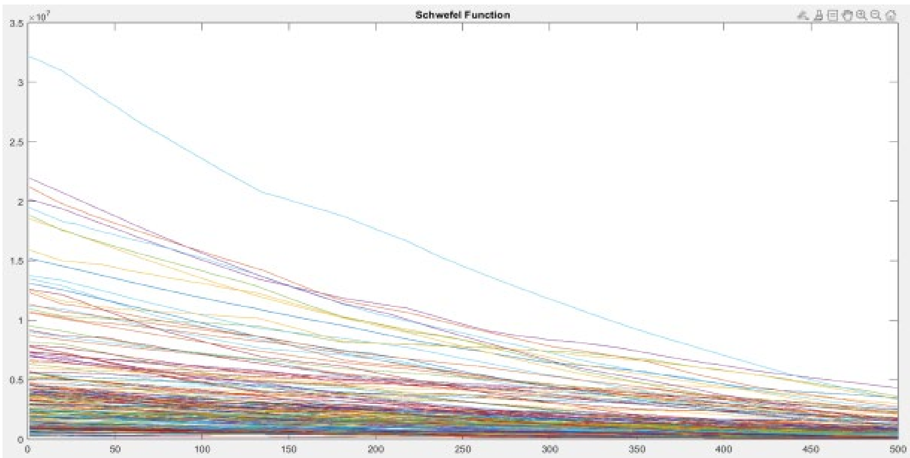

Fig. 9. The Iterative Curve of Schwefel Function.

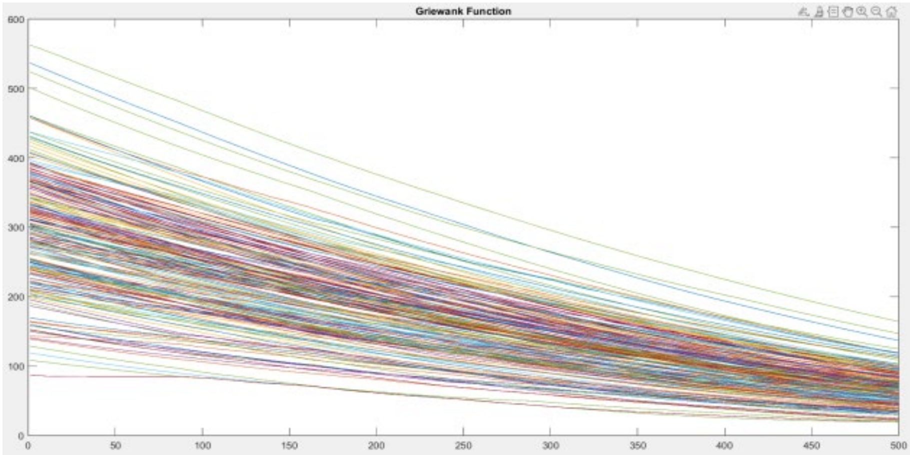

Fig. 10. The Iterative Curve of Griewank Function.

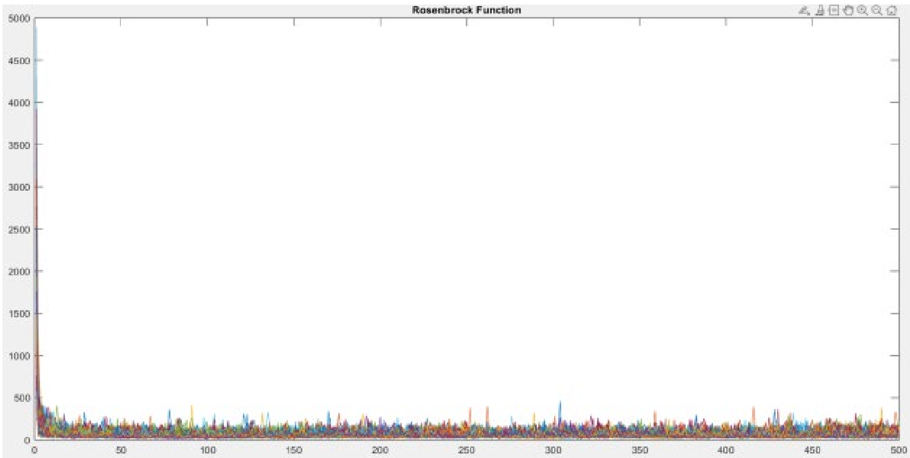

Fig. 11. The Iterative Curve of Rosenbrock Function.

3.3. The Variable Step-Size INC method

The INC method typically employs a fixed step size for maximal power point tracking, which does not meet the requirements for tracking speed and precision[23]. The selection of step size for a PV system is always inversely proportional to the search speed and precision of the MPP [23]. For sake of reconciling the disparity between tracking speed and steady-state precision, the search area may be subdivided into distinct regions with corresponding step sizes[24]. The P-U curve of a photovoltaic cell has only one extremum point. Clearly, the closer the operating voltage U of the system is to the MPP voltage U_m, the smaller the value of $|dP/dU|$ will be, with a minimum value of zero[25]. In the INC method simulation module, the default step size $\Delta D=0.002$, let $dP=dUdI=\Delta U\Delta I$, and slope=dP/dU. If $|slope|\geq 4$, the step size is $\Delta D_1=10*\Delta D$; if $|slope|<4$, the step size is the default step size $\Delta D=0.002$. The flowchart of the variable step-size INC method is exhibited in Figure 12.

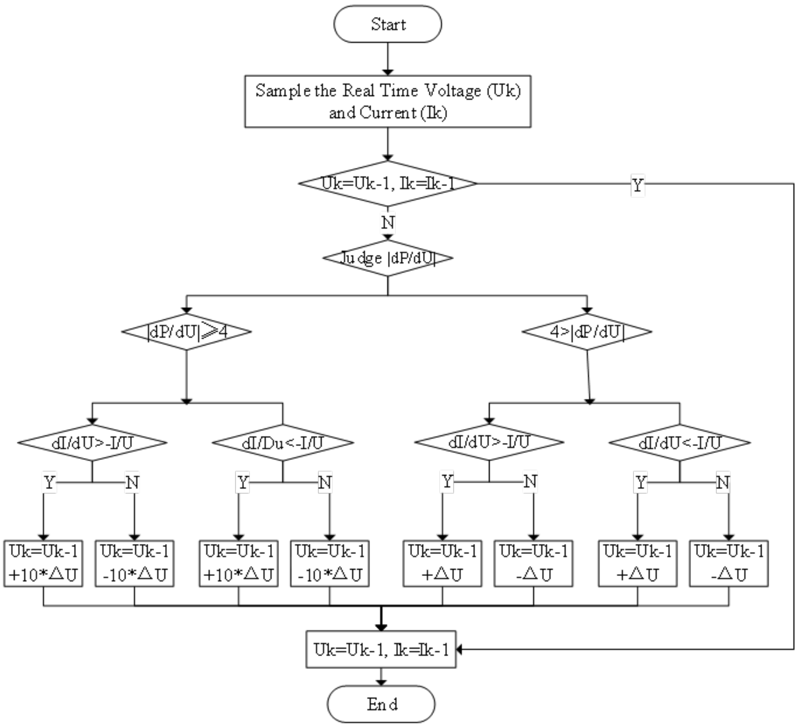

Fig. 12. The Flowchart of Variable Step-Size INC Method.

3.4. The Async-PSO and Variable Step-Size INC Algorithm

This research combines the variable step-size INC method with the Async-PSO algorithm for tracking the MPP of the photovoltaic system, aiming to achieve superior tracking performance. Hence, in the A-B and E-F segments of Figure 13, where the distance from Ump is far, and the power changes significantly with voltage, the INC method with a bigger step size be utilized to track and shorten tracking time while accelerating algorithm tracking speed. The B-C and D-E segments are close to the MPP; the INC method with a smaller step size can be employed to track these two segments to improve tracking accuracy. Finally, the voltage is mostly near the maximum power point in the C-D segment. It's important to note that if the INC method continues to be used, it will bring about oscillation and lower the accuracy of the MPP. Consequently, the Async-PSO algorithm is introduced in this segment to minimize steady-state oscillation at the MPP and improve tracking accuracy. In the recommended algorithm, if $|dP/dU| \geq 1$, use the variable step-size INC method to track the MPP for faster tracking speed. If $|dP/dU| < 1$, use the Async-PSO algorithm to track the MPP for improved tracking accuracy.

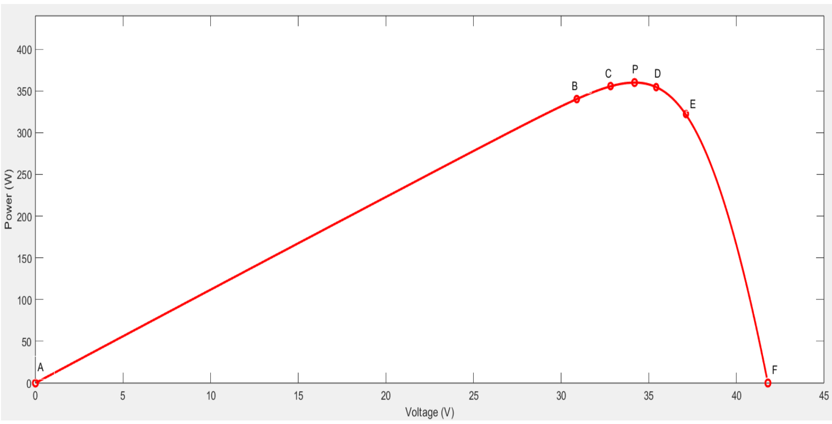

Fig. 13. The P-U characteristic curve of PV.

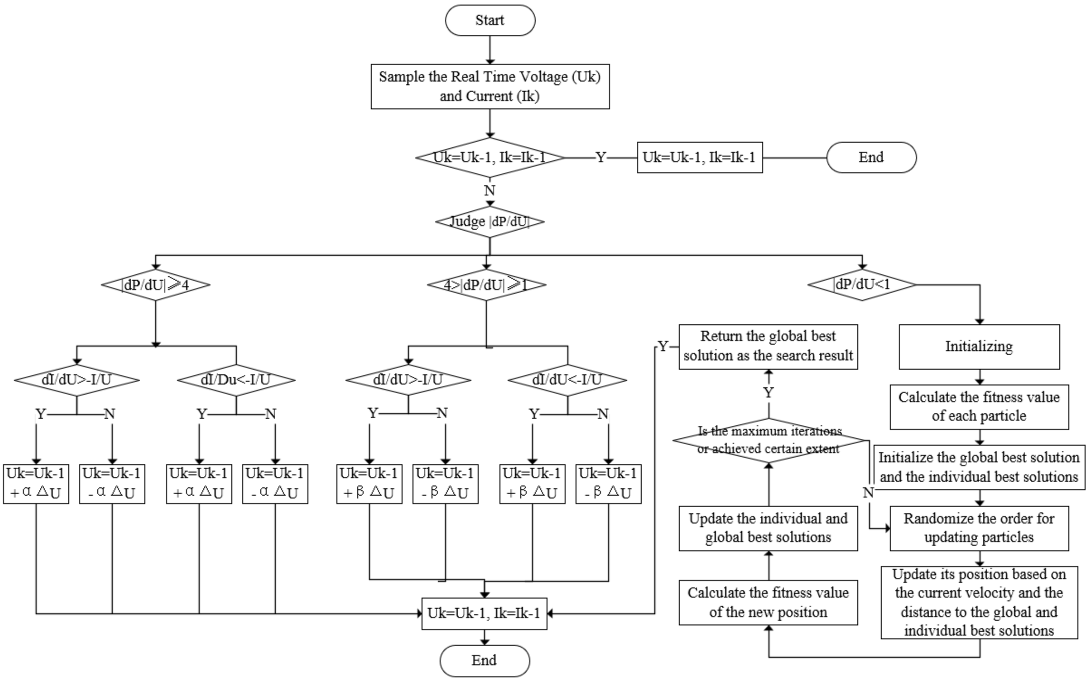

Fig. 14. The Flowchart of Async-PSO and VSINC Algorithm.

5. Results and discussion

A MATLAB/Simulink simulation model of the PV system was developed to delve into the tracking characteristics of MPPT control methods under shading conditions. The entire photovoltaic system simulation model comprises photovoltaic modules, DC-DC converter module, MPPT algorithm module, IGBT module, and observation apparatus, among other components.

Table 2 displays the simulation module parameters of the PV system, and the simulation module is depicted in Figure 15.

Table 2. The Parameters of the Simulation Module of PV System.

Parameters	Value
Maximum Power (P_{max})	240W
Voltage at Maximum Power Point (V_{mp})	30.72V
Current at Maximum Power Point (I_{mp})	7.83A
Open Circuit Voltage (V_{oc})	36.84V
Short-Circuit Current（I_{sc}）	8.32A
The Input Capacitor (C_i)	3300μF
The Output Capacitor (C_o)	3800μF
The Inductor (L)	550μH
Resistance Load (R)	60Ω
The Frequency of PWM	1000HZ

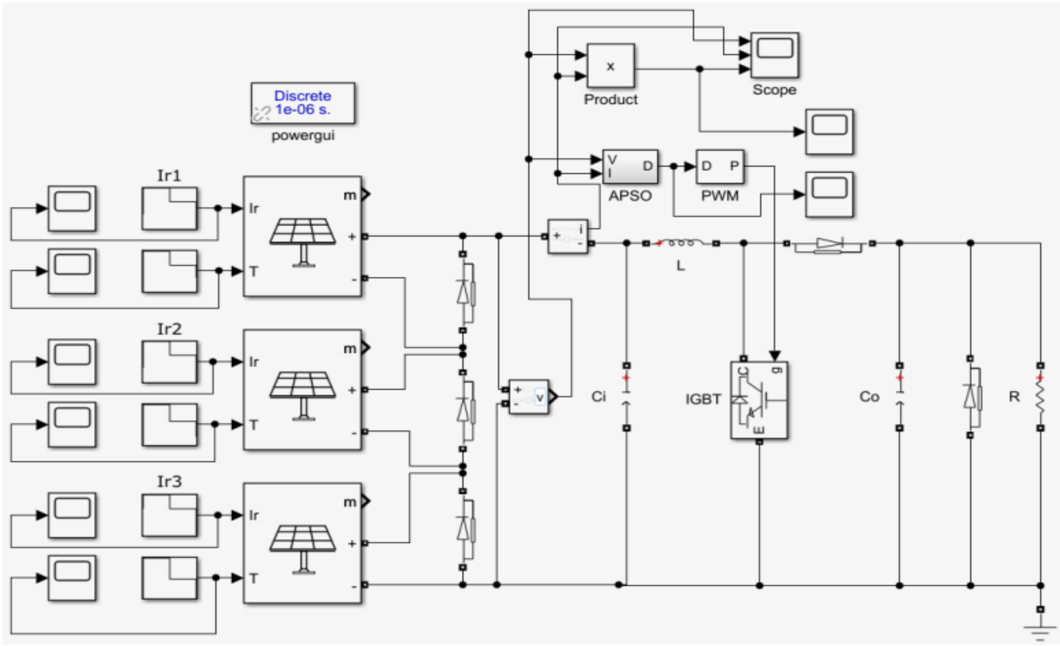

Fig. 15. Simulation Model of PV System.

The simulation time is 1.2S to reflect the change of light amplitude and temperature of the photovoltaic module in a day. The varied irradiation and temperature of each PV array are displayed in Figure 16.

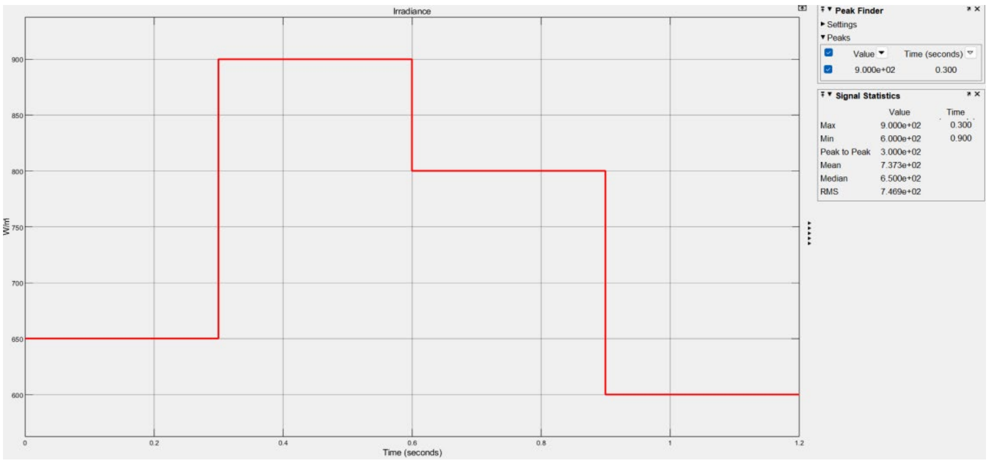

Figure 16 a) The Varied Irradiation and Temperature in the Simulation Module
Varied Temperature_PV Array1

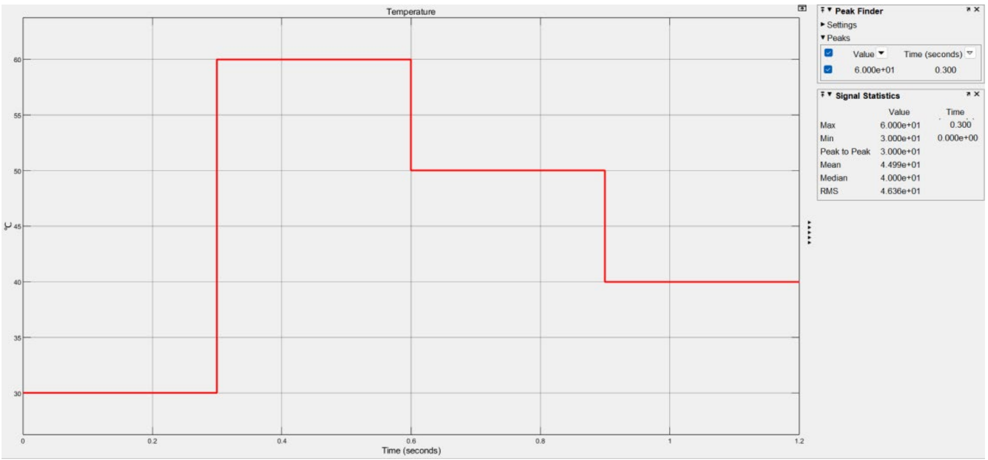

Figure 16 b) The Varied Irradiation and Temperature in the Simulation Module Varied Temperature_PV Array1

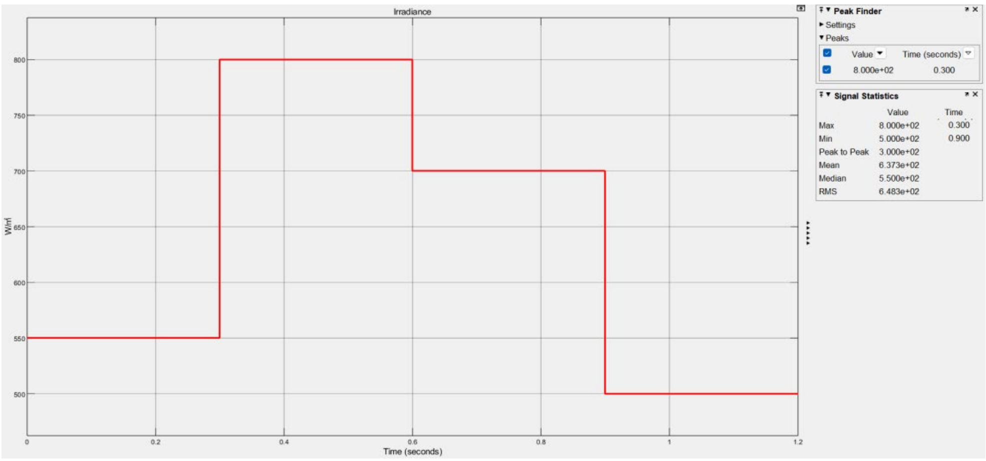

Figure 16 c) The Varied Irradiation and Temperature in the Simulation Module Varied Irradiation_PV Array2

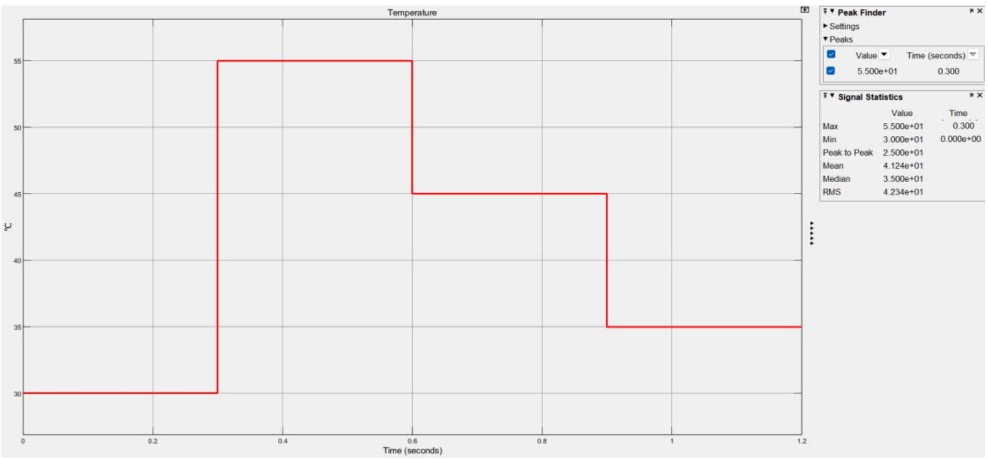

Figure 16 d) The Varied Irradiation and Temperature in the Simulation Module Varied Temperature_PV Array2

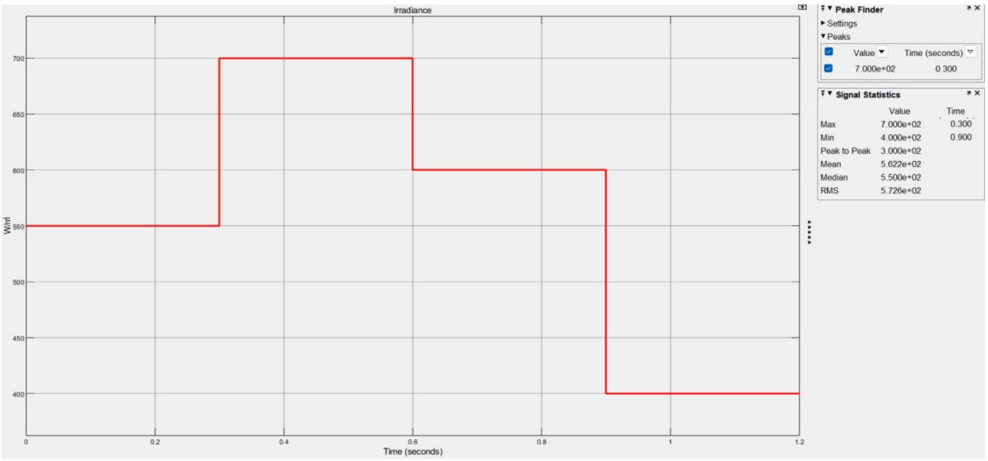

Figure 16 e) The Varied Irradiation and Temperature in the Simulation Module Varied Irradiation_PV Array3

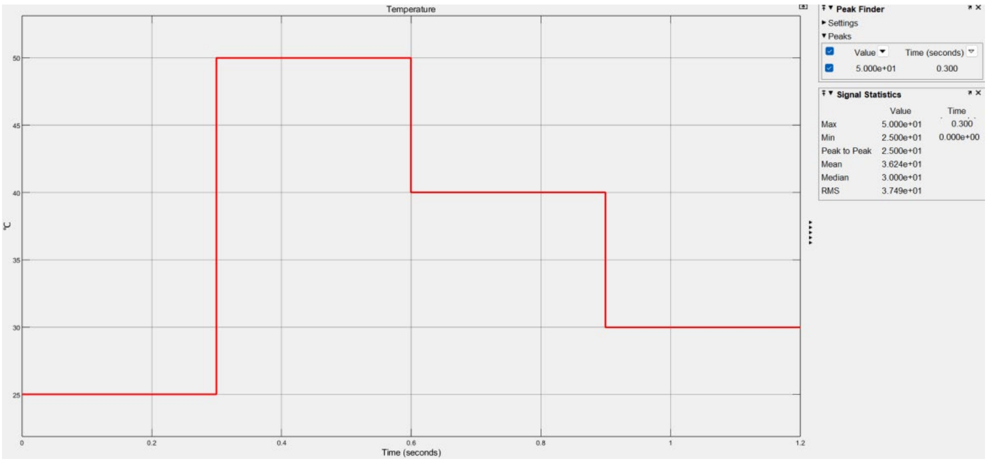

Figure 16 f) The Varied Irradiation and Temperature in the Simulation Module Varied Temperature_PV Array3

The simulation results of MTTP control methods are depicted in Figure 17, Figure 18 and Figure 19.

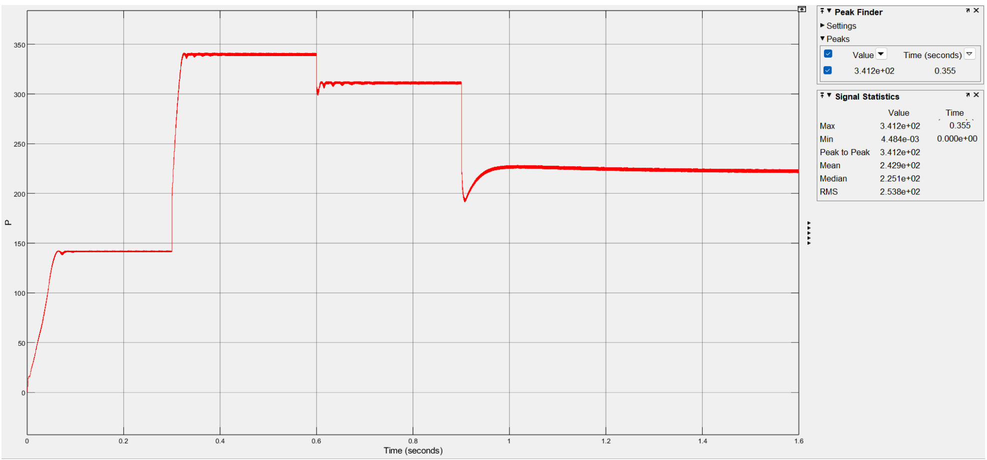

Fig. 17. Simulation Result of the P&O Method.

At 0.355 seconds, the maximum power point is reached with a maximum power of 341.2W. Although the P&O method may have some errors in response to light intensity and temperature changes, it has more desirable tracking performance.

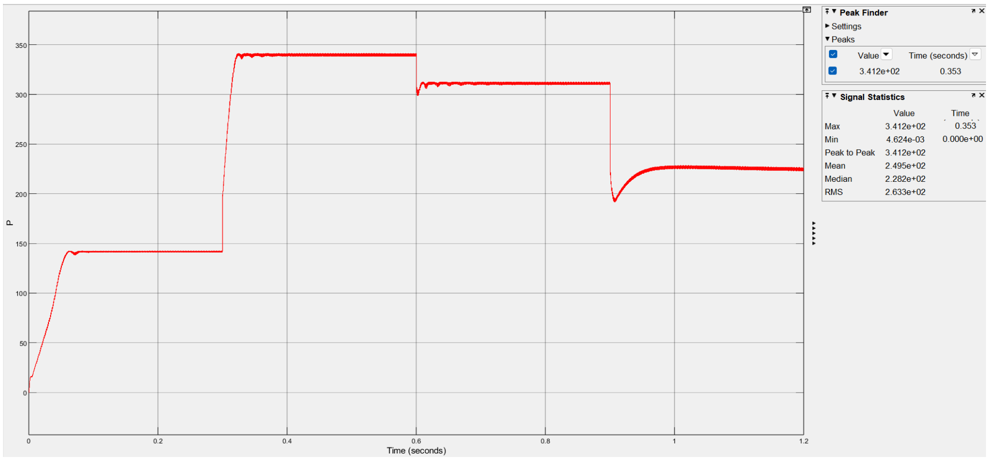

Fig. 18. Simulation Result of the INC Method

At 0.353 seconds, the maximum power point is reached with a maximum power of 341.2W. The INC method has minor errors in response to light intensity and temperature changes and has more superior tracking performance.

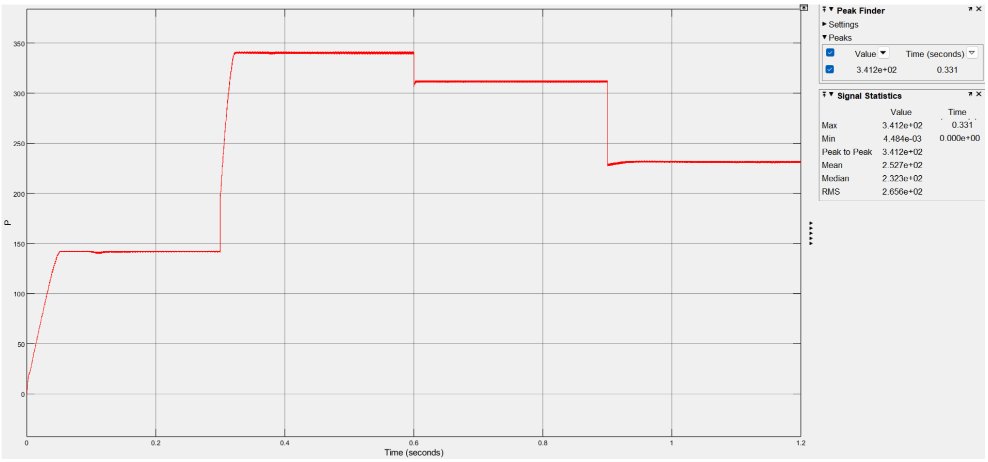

Fig. 19. Simulation Result of Async-PSO and VSINC Algorithm.

At 0.331 seconds, the maximum power point is reached with a maximum power of 341.2W. The Async-PSO and VSINC method has almost no errors in response to light intensity and temperature changes and has much more outstanding tracking performance overall.

Table 3. The Simulation Records.

MPPT control method	The time to reach the maximum power point	The maximum power output	The mean value of power output
P&O	0.355s	341.2W	242.9W
INC	0.353s	341.2W	249.5W
Async-PSO and VSINC	0.331s	341.2W	252.7W

As clearly revealed in the figures and records, the INC and P&O methods have some errors in response to light intensity and temperature changes, affecting their tracking performance. In contrast, the Async-PSO and VSINC Method has almost no errors in response to these changes and has much better tracking performance overall, which evidently demonstrates that the Async-PSO and VSINC method is a more robust and reliable method for maximum power point tracking of multi-peak photovoltaic MPPT.

4. Conclusion

As the global issues of energy shortage and environmental pollution become increasingly prominent, countries worldwide are seeking clean and efficient energy sources. Solar energy is characterized by infinite reserves and no pollution, making it an essential way for the global development of new energy. In some sense, improving solar energy utilization is the key to photovoltaic power generation, so the MPPT control algorithm of PV power has become a research hot spot for academicians around the world.

This work comes up with a novel MPPT control strategy on the basis of an Async-PSO algorithm and variable step-size INC method. Through simulation modelling and experimental analysis, the recommended algorithm can optimize photovoltaic power generation systems' stability and fast-tracking performance, especially for sudden changes in environmental conditions such as partial shading. The research results have pivotal practical significance for pushing ahead solar energy development. However, there are still some shortcomings in this study. For instance, this work's study of the MPPT part in the PV power system is only at the experimental simulation stage. Although the results meet the requirements, virtual application environments still deserve further improvement.

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