A Novel Maximum Power Point Tracking Strategy Based on Enhanced Real-Time Adaptive Step-Size Modified Control for Photovoltaic Systems

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With the development of society, the demand for energy keeps increasing. Solar energy has received widespread concern for its renewable and environmentally friendly advantages. As one of the most efficient solar energy devices, the output power of photovoltaic (PV) cells is easily affected by the external environment. In order to solve the problem of the maximum power output of PV cells, this paper proposed a maximum power point tracking (MPPT) method. Based on the online particle swarm optimization (PSO) variable step length algorithm, the pulse width modulation (PWM) control module parameters are set according to the parameters of the PV cells' output voltage. By dynamically adjusting the output voltage step of the PV cells online, the output of the PV cells is stabilized near the maximum power point (MPP). The simulation results concluded that the method and model could accurately adjust the output voltage according to the external environment changes in real time and reduce the voltage fluctuation at the MPP, providing a new idea to solve the problem of MPPT of PV cells.

Keywords: photovoltaic cell, particle swarm optimization, maximum power point tracking, variable step size, variable carrier

1 INTRODUCTION

The energy demand increases with society's development, yet the increasing depletion of fossil fuels cannot meet long-term growth. Moreover, fossil fuels' application will also bring serious adverse effects, such as the greenhouse effect and environmental pollution (Bavarinos et al., 2021). Therefore, renewable energy has slowly broken traditional energy status with an enhanced eco-friendly philosophy (Zeeshan Tariq et al., 2021). One of the more essential energy sources is PV systems in nature. Over the last decades, governments worldwide are growing the share of PV technology to deal with energy demands competitively. With the advent of modern technology for PV cells, it has been one of the most promising solutions to address growing electricity needs (Pathak and Yadav, 2019). PV cells are a specialized semiconductor diode electronic device that converts light energy into

electrical energy using various chemical and physical phenomena. The voltage output of PV cells is affected by their characteristics, external temperature, and irradiation. What's more, PV cells have only one maximum power output point. Since physical factors such as solar radiation and temperature affect PV cells' performance characteristics, the maximum power point (MPP) of PV cells may be different (Nguyen et al., 2020). The research on MPP of PV cells has become a hot topic.

Currently, the main methods of PV cells maximum power point tracking (MPPT) technology can divide into three categories: 1) mathematical models; 2) self-optimizing control algorithms; 3) intelligent algorithms (Ishaque and Salam, 2013). In (Desai and Patel, 2007), constant voltage tracking (CVT) and constant current tracking (CIT) based on PV cells' mathematical models are applied to predict the voltage or current at the MPP of PV cells under different external conditions such as light intensity and temperature. MPP prediction only needs to detect the parameters such as the light intensity and radiation intensity in the actual operation of PV cells, which can be obtained with the look-up table method and interpolation calculation. In (Serrano-Guerrero et al., 2016), fixed voltage and fixed current methods have the advantages of low computational complexity and fast-tracking of maximum power, yet they have apparent shortcomings. It is challenging to keep PV cells' characteristics unchanged after a long operation as the maximum power is an approximate value, causing error accumulation. In (Liu et al., 2018), an MPPT algorithm is proposed that combines an improved constant voltage algorithm with an enhanced variable step-length incremental conductance algorithm. The self-adaptive topology is designed to make the system get a better working condition. The results show that the mothed could improve the efficiency of PV power generation. On the other hand, the self-optimizing control algorithms' main application is the open-circuit voltage proportional coefficient method (Kumar et al., 2019), the perturb and observe (P and O) method (Alik and Jusoh, 2018), and the conductance increment method (Jeong et al., 2012). The method is mainly realized by self-optimizing maximum power optimization based on PV cells' equivalent and external characteristics while combining control theory (Hossain et al., 2016). In (Zhou et al., 2010), this article pointed out the voltage step is fixed, which will not stop the judgment after finding MPP but will continue to move with the originally fixed-step. If the step size is not selected correctly, large power fluctuations will occur near MPP, causing unnecessary loss of output power. If the step size chosen is short, the power oscillation at MPP will slow down to a certain extent, and the tracking speed will significantly reduce to a certain extent. On the other hand, many intelligent optimization algorithms have been applied to MPPT of PV cells. In (Mansoor et al., 2020), a grass hopper optimization (GHO) algorithm was proposed to solve the problem of MPPT of PV cells in complex environments. The article compared several traditional methods under different conditions and points out the shortcomings of the prior techniques in dealing with complex partial shading conditions. The analysis results show that the GHO algorithm has good robustness, high tracking efficiency, can reduce oscillation, and the tracking effect is within an acceptable range. Hassan et al.

(2020) pointed out that PV cells as a renewable energy source have received more and more attention, but due to changes in the external environment, there are uncertainties in the modeling and MPPT of PV cells. In order to solve this problem, this article proposed an isolated PV system using a push pull converter with the fuzzy logic-based MPPT algorithm. The method achieved smooth tracking of output power near the MPP. A fuzzy logic closed loop controller was introduced to improve the power quality of the AC voltage through a current fed push pull boost converter circuit with a higher conversion ratio. The experimental results show that the method can track the MPP well and reduce the circuit loss. In (Danandeh and Mousavi, 2018), compared with the traditional P and O method, the fuzzy logic control algorithm improves the tracking efficiency, and it also has advantages in robustness and environmental adaptability. The above methods have achieved significant results in MPPT of PV cells. However, the fuzzy control method also have apparent shortcomings, which relies too much on selecting fuzzy rules and rich experience. In (Javed et al., 2019), the article gives a detailed introduction to the single diode, double diode, and PV components system. Then tests the output characteristics of PV cells under the uniform irradiance condition (UIC) and partial shading condition (PSC) conditions. The control circuit commonly used in tracking the PV cells' MPP is explained. The author points out that there are many existing methods for solving the MPPT issue, including the factional short circuit current (FSCC) (Feroz Mirza et al., 2019), hill climbing (HC) (Alajmi et al., 2010) method, incremental conductance (Inc.) (Radjai et al., 2014) technique, and intelligent algorithms and so on. The article focuses on explaining the basic principles of each method, giving many alternative technologies for using intelligent algorithms to solve the MPPT problem. Finally, the paper proves the method through simulation experiments and compared them with each other. The realization of intelligent algorithms such as neural network method and ant colony optimization algorithm often requires a long operation cycle and hardware platform with good performance, which hinders their application in control systems to a certain extent.

In order to better solve the problem of MPPT of PV cells, this paper proposed a PWM variable carrier PV cells power optimization control method based on the online PSO variable step length. The optimal power control strategy based on a real-time change of the voltage step size is adopted, and the optimal voltage value at MPP of each operation is searched online. The voltage step obtained is more accurate, stable than CVT and CIT. Compared to the fixed step method, the step-length of the voltage value optimized with the above control strategy is not static but based on actual conditions. If the output power is far away from MPP, the voltage step-length will change considerably, and the output power closes to MPP, the voltage step-length will vary slightly, which makes the output power value update online in real-time. Finally, realize real-time control power, reduce output fluctuation, and improve tracking accuracy and efficiency. The control method adjusts the carrier module in PWM for different PV cells parameters to generate a better duty cycle signal that controls the switching device to turn on-off and further optimizes the MPPT problem.
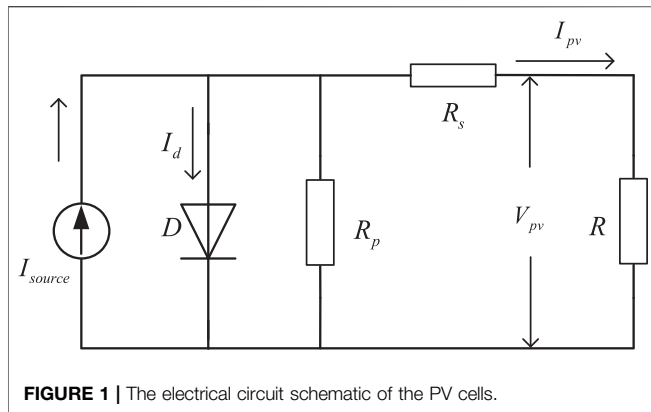
FIGURE 1 | The electrical circuit schematic of the PV cells.

The main contributions of this paper are as follows:

1) A novel technique for MPPT of PV cells is proposed, which can effectively reduce output fluctuations and increase the speed of convergence.
2) The output of PV cells under different external conditions was tested.
3) The comprehensive experiment is used to compare the method with the traditional MPPT method.

The organization of the rest is arranged as follows. **Section 2** describes PV cells' mathematical models and simulates in Matlab. The optimization method of MPP is introduced in **Section 3**. The results and analysis in **Section 4**. **Section 5** presents the conclusions.

2 THE MATHEMATICAL MODEL OF PV CELLS

The photoelectric phenomenon is PN junction of PV cells through certain materials. They can transfer the energy of sunlight photons to electrical power. PV cells are a more effective way to directly use solar energy—the typical equivalent circuit shown in **Figure 1** (Alghamdi et al., 2021). Kirchhoff's current law (KCL) is applied to the equivalent circuit of solar cells in **Figure 1**, and the output equation of the PV cells can be obtained as shown in **Eq. 1**.

$$I_{pv} = I_{source} - I_{sc} \star \left(e^{\frac{V_{pv}}{\eta \star V_t}} - 1 \right) - \frac{V_{pv} + I \star R_s}{R_p} \quad (1)$$

Where I_{ph} is the photocurrent (A), I_{sat} represents the diode saturation current (A), and η is the diode ideal factor. V_t ($V_t = kT/q$) is the thermal voltage (V), k is the Boltzmann constant ($1.38 \times 10^{-23} J/K$), T is the surface temperature of the PV panel (K), and q represents the electron charge ($1.6 \times 10^{19}C$). Some PV cells' parameters are treated approximately to meet actual engineering and research needs. The basic equations describing the $I - V$ characteristic are given in the following equations (Humada et al., 2020).

$$I_{pv} = I_{sc} \star \left[1 - C_1 \star \left(e^{\frac{V_{pv}}{C_2 \star V_{oc}}} - 1 \right) \right] \quad (2)$$

$$C_1 = \left(1 - \frac{I_m}{I_{sc}} \right) \star e^{-\frac{V_m}{C_2 \star V_{oc}}} \quad (3)$$

$$C_2 = \left(\frac{V_m}{V_{oc}} - 1 \right) \Big/ ln\left(1 - \frac{I_m}{I_{sc}} \right) \quad (4)$$

Where I_{pv} is PV cells output current (A), I_{sc} represents PV cells short circuit current (A), I_m is PV cells maximum power point current (A). V_{pv} denotes PV cells output voltage (V), V_m is PV cells maximum power point voltage (V), V_{oc} represents PV cells open circuit voltage (V).

When PV cells work under the nominal condition (temperature $T = 25°C$, irradiation $S = 1000 W/m^2$), the manufacturer datasheet can provide the short-circuit current, the maximum power point current, the open-circuit voltage, and the maximum power point voltage. The values of C_1 and C_2 can be calculated by **Eqs 3**, **4** and then substituting **Eq. 2** to describe the $I - V$ curve of PV cells. But in the real environment, it is difficult for PV cells to work in the reference conditions, and environment temperature T and irradiation S will change with time. In this case, PV cells' parameters are calculated as follows (Deveci and Kasnakoğlu, 2016).

$$I'_{sc} = I_{sc} \star \left\{ \frac{S}{S_{ref}} [1 - \alpha \star (T - T_{ref})] \right\} \quad (5)$$

$$I'_m = I_m \star \left\{ \frac{S}{S_{ref}} [1 - \alpha \star (T - T_{ref})] \right\} \quad (6)$$

$$V'_{oc} = V_{oc} \star \left[1 - \gamma \star (T - T_{ref}) \right]$$
$$\star ln\left[e + \beta \star \left(\frac{S}{S_{ref}} - 1 \right) \right] \quad (7)$$

$$V'_m = V_m \star \left[1 - \gamma \star (T - T_{ref}) \right]$$
$$\star ln\left[e + \beta \star \left(\frac{S}{S_{ref}} - 1 \right) \right] \quad (8)$$

$$C'_1 = \left(1 - \frac{I'_m}{I'_{sc}} \right) \star e^{-\frac{V'_m}{C'_2 \star V'_{oc}}} \quad (9)$$

$$C'_2 = \left(\frac{V'_m}{V'_{oc}} - 1 \right) \star \left[ln\left(1 - \frac{I'_m}{I'_{sc}} \right) \right]^{-1} \quad (10)$$

Where, T and S are the nominal temperature and the nominal irradiation. α, β, γ are battery parameters and coefficients under standard conditions.

According to **Eq. 2** ~ **Eq. 10**, the model of PV cells can be established by using Matlab/Simulink (Xiao et al., 2012). The internal structure is shown in **Figure 2**. The battery contains some parameters: T_{ref}, S_{ref}, I'_{sc}, I'_m, V'_{oc}, V'_m, and α, β, γ, which given by manufacturer datasheet. The external input parameters are the temperature T, the irradiation S, the input voltage V_{pv} in the current environment, and the output current I_{pv}.
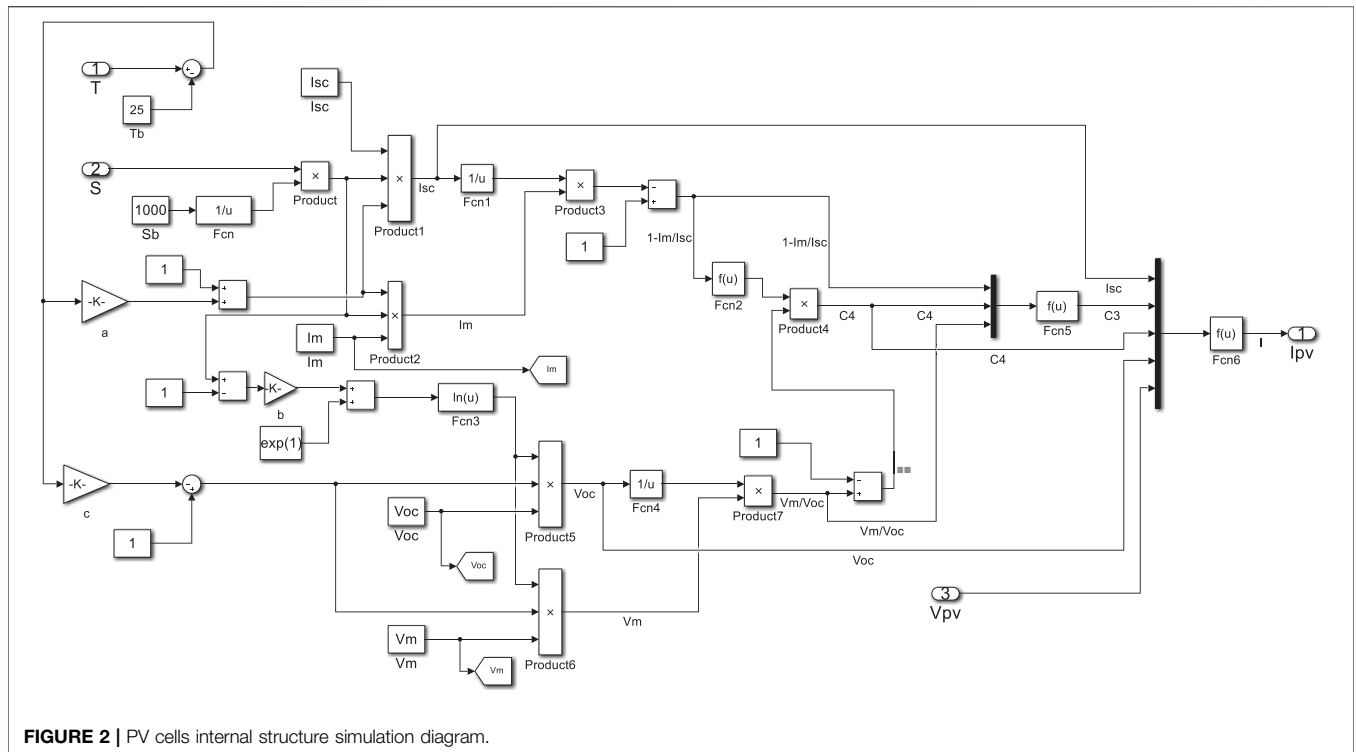
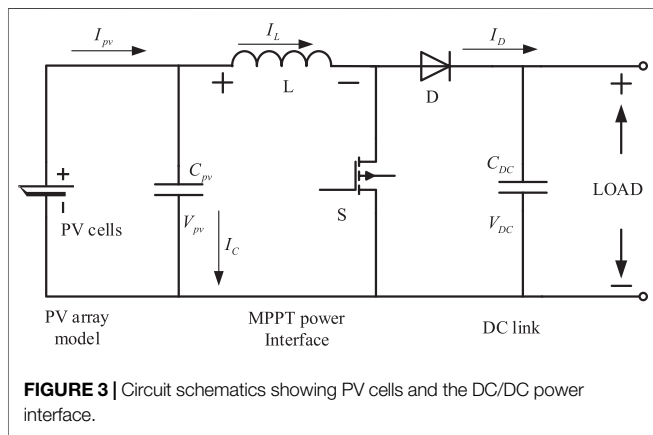**FIGURE 2 |** PV cells internal structure simulation diagram.

FIGURE 3 | Circuit schematics showing PV cells and the DC/DC power interface.

3 MPPT OF PV CELLS

3.1 The Application of the Boost Circuit in MPPT

Under certain temperatures and light conditions, the output curve of the PV cells is always changing. When PV cells work at the MPP, the output power $P_{out} = P_m$ to go along with $V_{pv} = V_m$ and $I_{pv} = I_m$. However, PV cells can work at MPP depends on the load because the external environmental factors usually can't be changed artificially. During the working process of PV cells, the temperature and irradiation are constantly changing, so the output characteristics of PV cells and MPP will change accordingly. In order to find MPP quickly and make PV cells

work at MPP, it is necessary to change the external load by controlling the terminal voltage of PV cells.

With the development of electronic technology, MPPT control of PV cells is completed generally with a DC-DC conversion circuit. In this paper, the Boost circuit is used as the DC-DC conversion circuit in the PV cells system (Amir et al., 2018), which can be stabilized the system output voltage via adjusting the terminal voltage and output the circuit's voltage for later use. The boost circuit diagram structure is shown in **Figure 3**.

In DC-DC circuit, the impedance relationship is as follows.

$$R_{in} = \frac{V_{in}}{I_{in}} = \frac{V(1-D)}{I/(1-D)} = \frac{V}{I}(1-D)^2 = R(1-D)^2 \qquad (11)$$

Where, R_{in} is the input impedance of the converter. R represents the load impedance of the converter. D denotes the duty cycle of the switching device itself, regardless of the power loss of the Boost circuit itself. It can see from **Eq. 11** that when the load impedance of the Boost circuit remains unchanged, the bigger the duty cycle D, the smaller the input impedance of the Boost circuit, and the smaller the duty cycle D, the larger the input impedance of the Boost circuit (Pires et al., 2016). The equivalent impedance R_m of PV cells can be changed by adjusting the duty cycle D of the switching device. The circuit knowledge knows that when the external circuit's load impedance is equal to PV cells' equivalent impedance, the system has the maximum power output (HA et al., 2016). Therefore, it is necessary to keep the equivalent resistance of the DC-DC conversion circuit always equal to the PV cell's internal resistance and achieve MPPT of PV cells to meet the maximum output.

3.2 Online Variable Step-Length PSO in MPPT

3.2.1 Introduction to the Particle Swarm Optimization

The particle swarm optimization (PSO) algorithm is a swarm intelligence algorithm developed by Kennedy and Eberhardt in 1995 and inspired by the social behavior of flocking birds and schooling fishes (Kennedy and Russell, 1995; del Valle et al., 2008). Compared with other random methods such as a genetic algorithm, particle swarm optimization can quickly get higher-quality solutions, and these solutions have convergence characteristics (Femia et al., 2004). The mathematical description of PSO could be known. Suppose a population of m individuals in an N-dimensional search space $x = (x_1, x_2, \ldots, x_m)^T$, where the position of the ith particle is $x_i = (x_{i,1}, x_{i,2}, \ldots, x_{i,n})^T$, the velocity is $v_i = (v_{i,1}, v_{i,2}, \ldots, v_{i,n})^T$. $p_i = (p_{i,1}, p_{i,2}, \ldots, p_{i,n})^T$ is the local optimum value, and $p_g = (p_{g,1}, p_{g,2}, \ldots, p_{g,n})^T$ represents the global optimum value. When the individual completes a search operation at every generation, it will update its velocity v and position x according to **Eq. 12** and **Eq. 13**, (Bechouat et al., 2015).

$$v_{i,d}^{k+1} = \omega \star v_{i,d}^k + c_1 \star r_1 \star \left(p_{i,d}^k - x_{i,d}^k\right)$$
$$+ c_2 \star r_2 \star \left(p_{g,d}^k - x_{g,d}^k\right) \tag{12}$$

$$x_{i,d}^{k+1} = x_{i,d}^k + v_{i,d}^{k+1} \tag{13}$$

Where, $i = 1, 2, \ldots, n$ and n is the size of the population. d is the dimension of the search space. k represents the iteration number. c_1 is the individual optimal coefficient, c_2 is the individual global coefficient. ω represents the weight of inertia. r_1 and r_2 are random numbers which are uniformly distributed in (0,1). p_1 represents the local optimum and p_g represents the best individual among all the particles at every generation.

3.2.2 Initialization in MPPT System

Considering the system model and the power optimization problem, the number of particle groups can set to 20, and each particle's iteration number is 100. The choice of individual optimal coefficient, global optimal coefficient, and inertia weight is significant to the algorithm's calculation process. The c_1 and c_2 should have a strong self-cognition ability and maintain the information interaction ability between various particles. The choice of inertia weight ω should make the algorithm have excellent searchability. Therefore, considering comprehensively, define the particle individual optimal coefficient $c_1 = 0.5$, the optimal global coefficient $c_2 = 0.5$, and the inertia weight $\omega = 0.8$. The particle represents the output voltage of PV cells, which is initialized randomly at first. The initial position and next position of particles need to be restricted considering the actual situation. The output voltage value of PV cells is specified in $(0, V)$ to make it change within a reasonable range, which is (0, 35.4). Each particle movement's velocity is limited to $(−1, 1)$ to ensure particle search effectiveness.
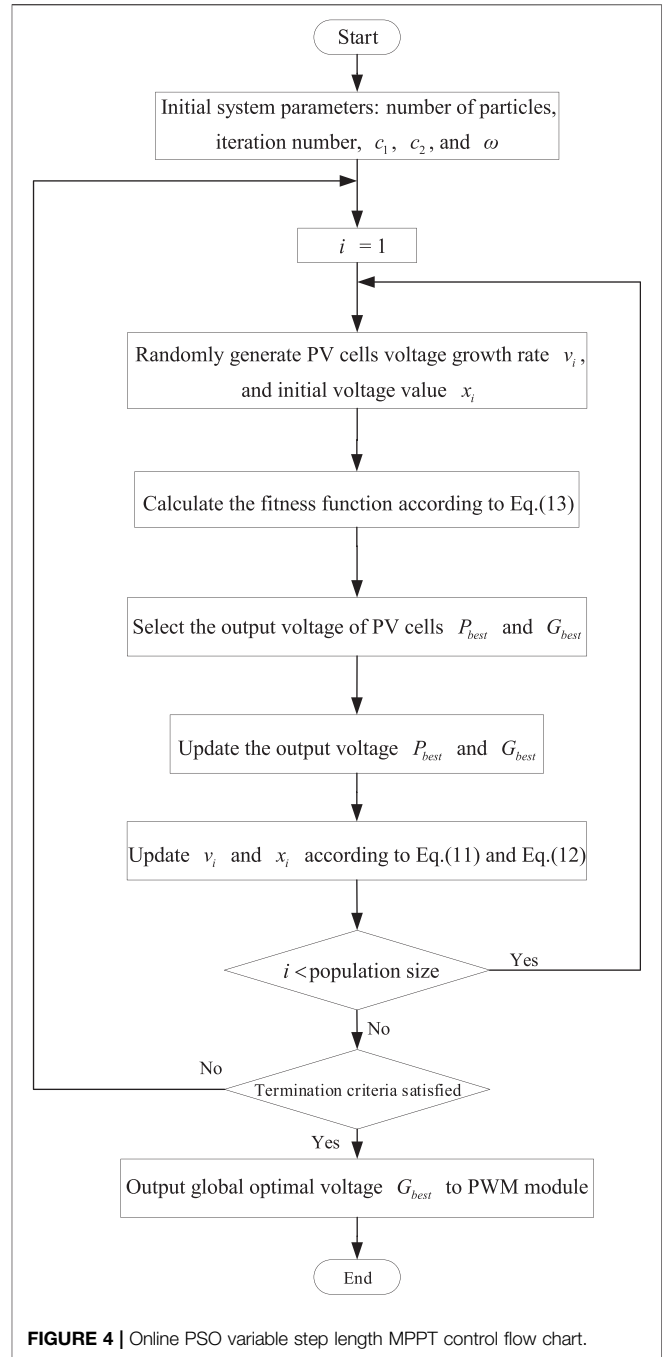

FIGURE 4 | Online PSO variable step length MPPT control flow chart.

After the particles' initialization is completed, the system needs to select an appropriate objective function. In MPPT of PV cells, the output current I_{pv} of the circuit can be calculated according to **Eq. 2 ∼ Eq. 10**, and the fitness function can determine as **Eq. 14**.

$$F = V_{pv} \star \left[1 - \gamma \star (T - T_{ref})\right] \star \ln\left[e + \beta \star \left(\frac{S}{S_{ref}} - 1\right)\right]$$

$$I_{pv} \star \left\{\frac{S}{S_{ref}} \star \left[1 - \alpha \star (T - T_{ref})\right]\right\} \tag{14}$$

3.2.3 Online PSO Variable Step-Length Control

Through the previous analysis, the PV cell's output current I_{pv} is connected as an input of the PSO module, brought into the fitness function to calculate. The PSO is used to perform online random initialization of the particle position, that is, to complete the random value of PV cells voltage online in real-time. Then, calculate the fitness function based on the input current value of PV cells. The optimal voltage value after each particle movement is regarded as the PSO module's output. The PSO module's optimal voltage output value is then used as the input of the PWM module. The processes mentioned above are all completed online in real-time to achieve real-time online control of PV cells' output power.

In the PWM module, the voltage step-length is updated online instead of constant since the voltage input will change relative to the last voltage every time. Then, setting corresponding carrier parameters and combining the real-time input voltage value, the switching device's duty ratio signal is synthesized to realize the switching device's conduction and turn-off functions in the circuit. When $I_{pv} = I_m$ and $V_{pv} = V_m$, the output power $P_{out} = P_m$. Meanwhile, if $V_{pv} < V_m$, the power P_{out} will increase with the increase of the voltage. At this time, the PSO module needs to increase the voltage output. That is, increasing the step-length of the voltage. If $V_{pv} > V_m$, the power P_{out} will decrease as the voltage increases. It is necessary to reduce the voltage output through the PSO module, that is, reducing the voltage step-length. Finally, it is converted into the signal's duty cycle for controlling the switching device in the PWM module. Among them, the output current I_{pv} of PV cells is sampled in real-time in each period, and the voltage of PV cells is randomly selected by PSO and real-time online update in each optimization. The output voltage will also affect the output current so that PSO is used to adjust the optimization step until the output current I_{pv} and output voltage V_{pv} corresponding to the maximum power P_m are found. The MPPT control method using online PSO to change the voltage step-length is shown in **Figure 4**.

3.3 Variable Carrier PWM in MPPT

In order to obtain a better control effect and stabilize the output power of PV cells near the maximum power point, it is necessary to control the duty cycle signal generated by the PWM module. The PWM module's working principle is to sample the optimal voltage value output by PSO, and this voltage value is the input signal of the PWM module. When this voltage signal is input, it is converted into the duty cycle signal controlling the switching device to turn off or turn on through the zero-order holder and other corresponding links.

When the voltage signal is available, it is combined with the set carrier signal. Then the corresponding conversion is carried out through the following links to generate the corresponding duty cycle signal. Since the signal is collected and changed in real-time, the PSO module's voltage signal output will not be constant but will constantly be updated and changed in real-time. So, the voltage value input to the PWM module is also continually changing. Completes the maximum power control of PV cells

using variable step PSO and realizes the change of the output voltage step-length. For battery modules with different parameters or PV cells with variable parameters, if a constant carrier wave is used to generate the duty cycle signal for controlling the switching device, the maximum power point tracking effect is relatively low. Therefore, the relationship between the carrier signal and the corresponding parameters of PV cells are searched. Through a lot of experiments and observations, it is found that the relationship between the PWM carrier module and the voltage of PV cells at MPP has a relationship as **Eq. 15**.

$$A = 2 * V_m \tag{15}$$

Where: A is the amplitude of the carrier wave in the PWM module, and V_m is the maximum power point voltage of PV cells.

4 MPPT SIMULATION ANALYSIS OF PV CELLS

4.1 System Simulation Model and Parameters

The above analysis and the system's simulation model are established in the Matlab/Simulink based on the mathematical model, as shown in **Figure 5**. In the simulation, the parameters of PV cells under standard conditions and Boost current parameters are illustrated in **Table 1**. The module structure diagram of PWM wave generation is shown in **Figure 6**. The parameters of the PWM module are: the sampling period of the zero-order holder is 0.0005.

4.2 Results When the Temperature Changes

Figure 7 shows the variation curve of PV cells' online output current I_{pv}, voltage V_{pv}, power P_{out}, Boost circuit output voltage V_{out} when the temperature changes. In the simulation model, the temperature parameter PV cells reduces from $50°C$ to $25°C$ in $0.3\ s$ and to $15°C$ in $0.7\ s$. It can be known from **Figure 7**. In different temperature conditions, the output of PV cells can stabilize in real-time, and MPP can be well tracked. The change of temperature has little effect on the output of PV cells. When the temperature drops and PV cells achieve MPPT, the output current and voltage both increase slightly, the maximum output power is also increased slightly. The output voltage of the Boost circuit increased. For detailed data, please refer to the **Supplementary Material**.

4.3 Results When the Irradiation Changes

Figure 8 shows the variation curve of the output current I_{pv}, voltage V_{pv}, PV cells' output power P_{out}, and the Boost circuit output voltage V_{out} under the change of irradiation. In the simulation model, the irradiation parameter of PV cells reduced from $1200\ W/m^2$ to $1000\ W/m^2$ at $0.3\ s$ and to $800\ W/m^2$ at $0.7\ s$. The output of PV cells can stabilize in real-time with the irradiation changes, and MPP can be well tracked. The irradiation has a more significant impact on the output of PV cells. When light intensity dropping and PV cells tracking MPP, the output of current and voltage all decrease to some extent, and the maximum output power decrease significantly. The output
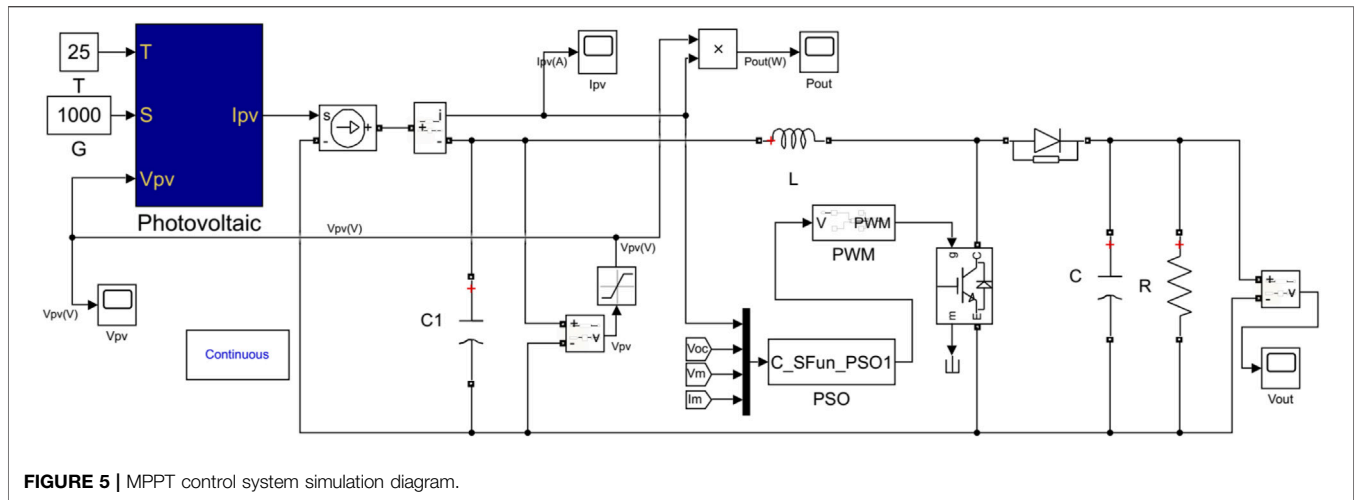
FIGURE 5 | MPPT control system simulation diagram.

TABLE 1 | System simulation parameters.

| Parameters	Values
Maximum power P_m (M)	200
Voltage V_m, max power (V)	28.80
Current I_m, max power (A)	6.94
Open circuit voltage V_{oc} (V)	35.40
Short circuit current I_{sc} (A)	7.44
Nominal temperature T (°C)	25.00
Nominal insolation S (W/m^2)	1000.00
Temperature coefficient of current change α (A/°C)	0.0025
Temperature coefficient of voltage change β (V/°C)	0.00288
Insolation coefficient of voltage change γ ($V \cdot W/m^2$)	0.05
Boost circuit: L (H)	10×10^{-3}
Boost circuit: C_{DC} (F)	300×10^{-5}
Boost circuit: C_{pv} (F)	10×10^{-5}
Boost circuit: R (Ω)	20
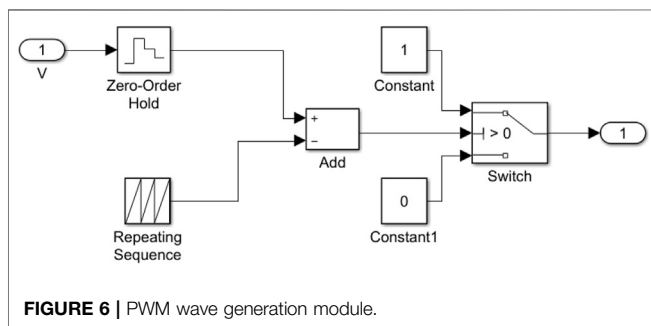
FIGURE 6 | PWM wave generation module.

voltage of the Boost circuit significantly reduces. For detailed data, please refer to the **Supplementary Material**.

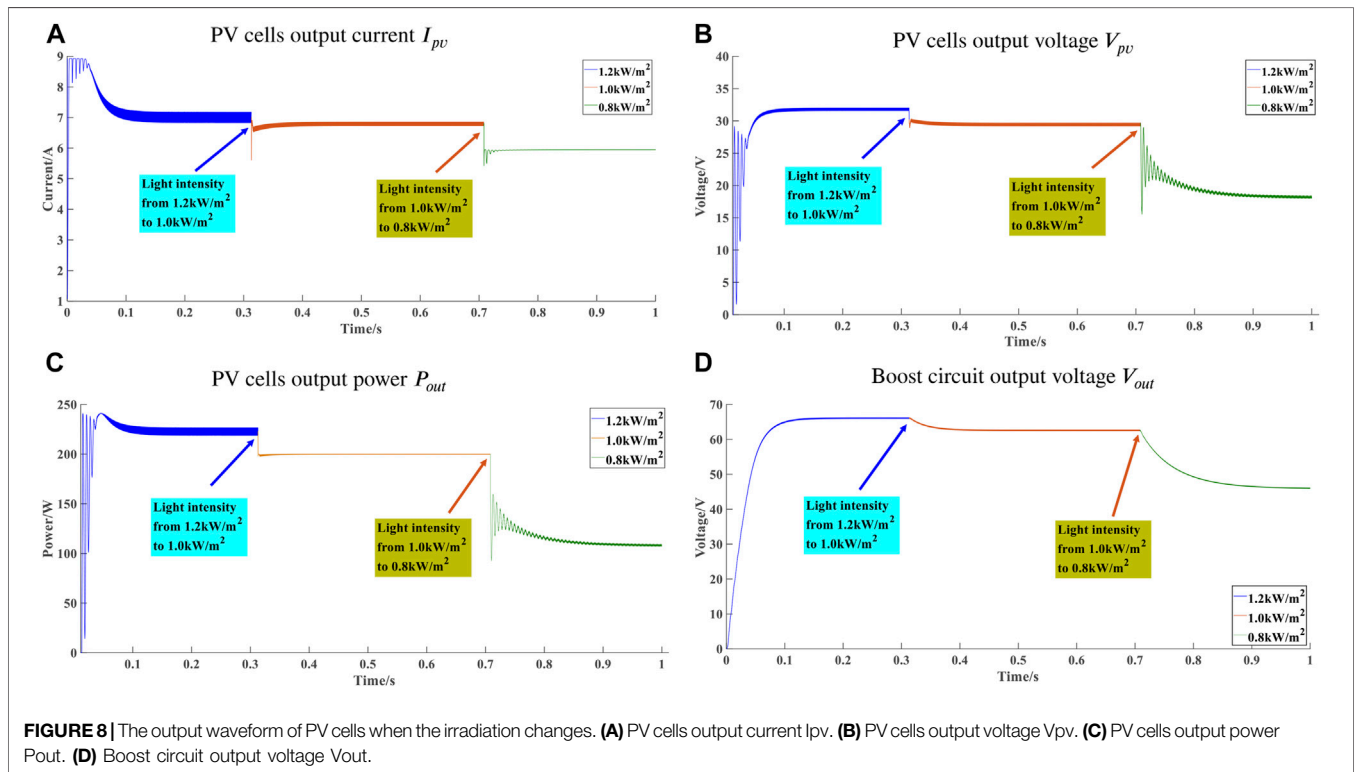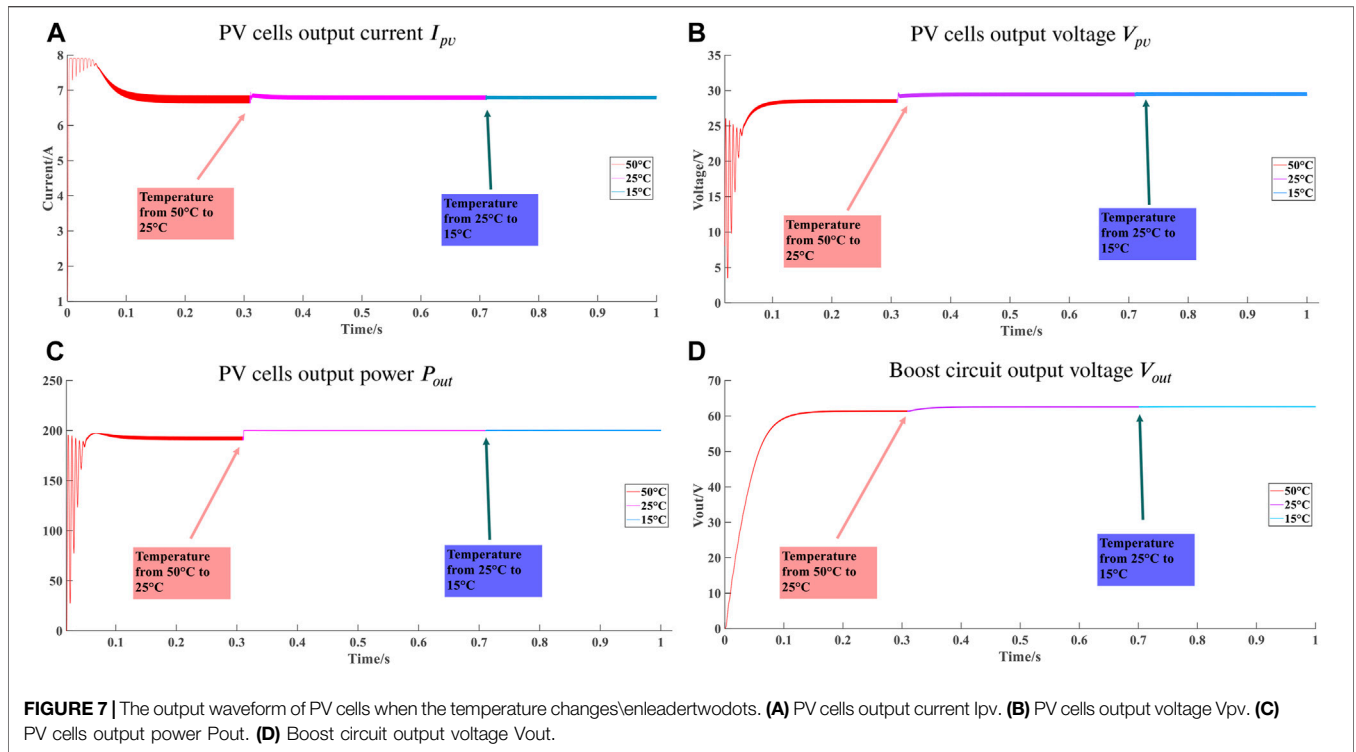## 4.4 Analysis of Comparative Results

The above analysis results are consistent with the analysis of the characteristics of PV cells. In addition, to further illustrate the role of the method used for MPPT, **Table 2** lists the maximum (MAX)/minimum (Min) fluctuations and rates of change

between the PV cells output at MPP and the given parameters under the standard conditions. When the method proposed in this paper is used to MPPT of PV cells under standard conditions, the maximum and minimum fluctuations of output current I_{pv}, output voltage V_{pv} and output power P_{pv} obtained are all within a controllable range. Compared with the rated values, the relative error between them is small, and the error accounts for a considerable proportion of the rated values, which can meet the actual demand.

In order to illustrate the effect of the proposed method to reduce the fluctuation in the process of MPPT. Compared with the traditional P and O method, the results are shown in **Figure 9**. As can be seen from the figure, when the system is tracking MPP, the online PSO method can reduce the fluctuation at the beginning of the system, and reach MPP at a faster convergence. When the system reaches MPP, the online PSO method can reduce the output fluctuation of the system and has a more stable output waveform than the traditional P and O method. The stability of I_{pv}, V_{pv}, P_{out}, V_{out} has a smaller fluctuation range. The method adopted in this paper has shorter adjustment time, higher tracking accuracy, faster response speed, better real-time, and better control effects when the process of MPPT.

5 CONCLUSION

This paper proposed a PWM variable carrier power optimization control scheme based on the online PSO variable step size. A general model of PV cells was established through the analysis of the PV cells model and practical mathematical expressions, and the model was simulated and analyzed. Online PSO varible step length was used to change the step length of the output voltage. Real-time online optimization control of the PV cells' MPP is realized by controlling the Boost circuit switching device's duty cycle. Analyzed the specific realization principle and gave the realization process, and got a better control effect at MPP. The product was compared with the traditional P and O method. The results illustrate that the control strategy and the optimization module can judge MPP in real-time, find the optimal voltage

FIGURE 7 | The output waveform of PV cells when the temperature changes\enleadertwodots. **(A)** PV cells output current Ipv. **(B)** PV cells output voltage Vpv. **(C)** PV cells output power Pout. **(D)** Boost circuit output voltage Vout.

FIGURE 8 | The output waveform of PV cells when the irradiation changes. **(A)** PV cells output current Ipv. **(B)** PV cells output voltage Vpv. **(C)** PV cells output power Pout. **(D)** Boost circuit output voltage Vout.
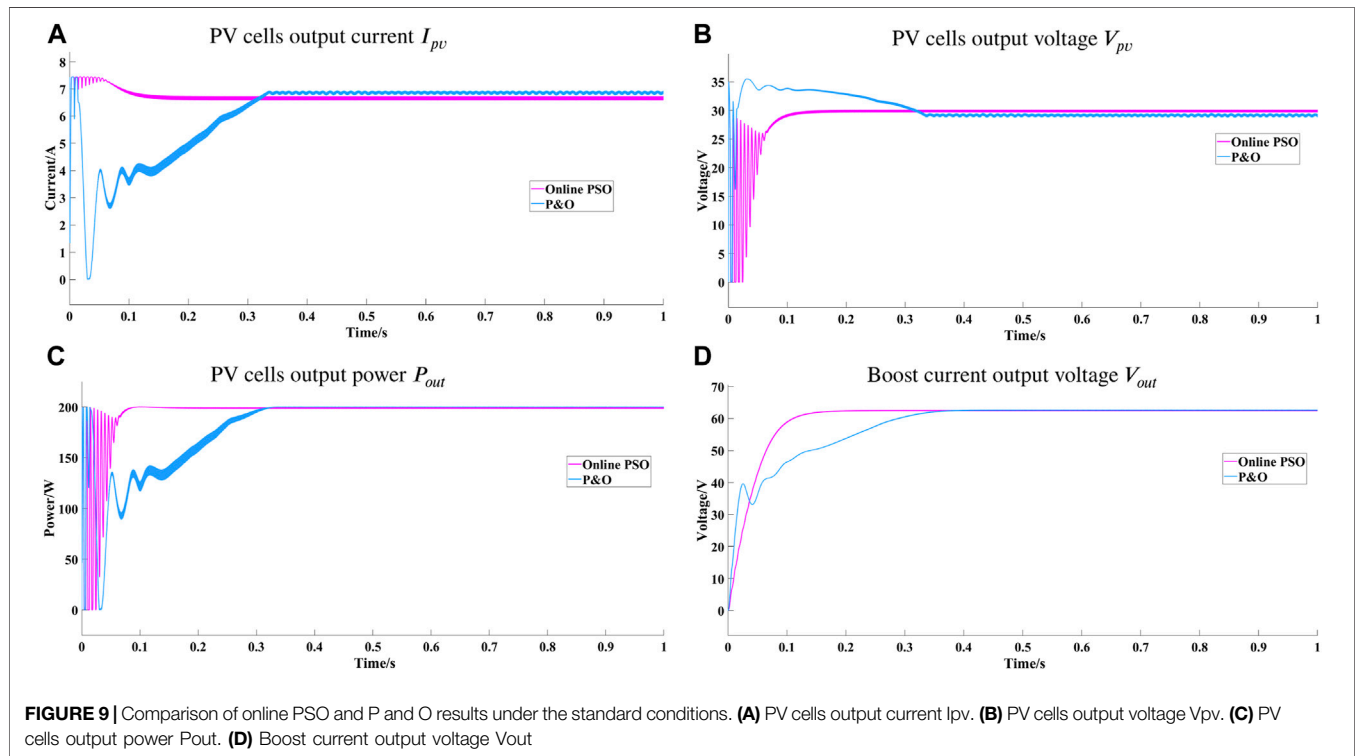
value online, and change the step length of the output voltage. Finally, the PV cells' output power can be stabilized at MPP. The output voltage of the Boost circuit can change with the change of the external environment to achieve an excellent real-time online tracking effect.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding authors.

TABLE 2 | Error between measured data and simulated data under the standard conditions.

Conditions	Parameters	Measured data	Simulated data			Error		Proportion	
			Max	*Min*	*Mean*	*Max*	*Min*	*Max*	*Min*
$T = 25\ °C$	I_{pv} (A)	6.94	6.735	6.584	6.674	0.205	0.356	2.954%	5.130%
$S = 1000\ W/m^2$	V_{pv} (V)	28.8	30.13	29.65	29.89	1.33	0.85	4.618%	2.951%
	P_{out} (W)	200	199.7	198.4	199.1	0.3	1.6	0.15%	0.8%

FIGURE 9 | Comparison of online PSO and P and O results under the standard conditions. **(A)** PV cells output current Ipv. **(B)** PV cells output voltage Vpv. **(C)** PV cells output power Pout. **(D)** Boost current output voltage Vout

AUTHOR CONTRIBUTIONS

JZ: Methodology, Investigation, Writing-review and editing. YZ: Investigation, Conceptualization. SZ: Methodology, Investigation. YG: Software, Validation. ZY: Software, Funding acquisition, Writing-review and editing. WF: Investigation, Funding acquisition.

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NOMENCLATURE

A carrier wave amplitude

CIV constant current tracking

CVT constant voltage tracking

D switching device duty cycle

F objective function

I_m PV cells maximum power point current

I_{pv} PV cells output current

I_{sc} PV cells short circuit current

I_{source} photocurrent

Max maximum

Min minimum

MPP miximum power point

$MPPT$ miximum power point tracking

P_m maximum power point power

P_{out} PV cells output power

PSO particle swarm optimization

P and O perturb and observe method

PV photovoltaic

PWM pulse width modulation

R converter load impedance

rand random numbers in **(0,1)**

R_{in} converter input impedance

R_m PV cells equivalent impedance

S irradiation

T temperature

V_m PV cells maximum power point voltage

V_{oc} PV cells open circuit voltage

V_{out} Boost circuit output voltage

V_{pv} PV cells output voltage

V_t thermal voltage

α battery parameters

β battery parameters

γ battery coefficients