

Simulation and Analysis of Power-point Tracking via Photovoltaic Sensors

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The photovoltaic (PV) cell is the basic component of a solar power system as it converts light energy into electricity by the PV effect. To increase the efficiency of conversion, the maximum power point (MPP) of the battery must be tracked in real time. We have established a system model based on the main characteristics of the PV power generation system and PV cells that considers the nonlinearity of the PV cell output. The mathematical model of a PV array is established by MATLAB/Simulink and combined with the common equivalent circuit of a PV cell and the mathematical model of PV power generation. This model enables the maximum power point tracking (MPPT) control of the PV cell through the simulation of its current-voltage ($I-V$) characteristic curve, which shows the cell's operation within its electrical circuit. We propose a MPPT control algorithm based on this model as an improved perturbation observation method. This algorithm controls the working current of the inverter of the PV cell using a PV sensor. Changes in light intensity or working temperature do not affect the ability of the tracking system to reliably track the MPP. This method does not need complex analysis and the control is based on a simple principle. Simulation results show that the algorithm has good dynamic performance in a steady state. The proposed method can track the MPP and improve the PV power generation efficiency by reflecting changes in illumination intensity with time.

1. Introduction

The progress of science and technology and the improvement of people's living standards require more energy than before, which can no longer be satisfied with traditional fossil fuel power generation. Therefore, the large-scale development and utilization of new forms of energy are necessary to protect the environment and achieve sustainable development. The depletion and environmental problems of fossil fuels have led to the development of renewable energy sources. Among the sources, photovoltaic (PV) power (solar power) generation has attracted

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much research interest as it is easier to install solar power plants and obtain energy with much fewer geographical limitations on the plants than for other renewable energy sources. Therefore, large-scale PV power plants have been developed rapidly and have become increasingly popular. This has contributed to the rapid development of PV cells as the essential component of these systems. However, the output of PV power generation systems is significantly affected by light intensity and temperature, which does not allow stable power generation.

To solve this problem by improving the efficiency of systems, the maximum power point tracking (MPPT) method has been proposed. The principle of MPPT is to maximize the energy transfer from PV cells, which depends on the incidence angle of sunlight, the temperature of the PV cell, and the electrical properties of the system, by using various sensing technologies. To collect the maximum power from a PV power generation system using MPPT, several components, such as a sliding mode controller (SMC), a voltage source inverter (VSI) and grid design, and a PV generator (PVG) are required.⁽¹⁾ These are integrated into the system to display its motion trajectory with the inverter topology that is used in an algorithm to optimize the maximum power point (MPP).

The module for motion trajectory includes a calendar chip that calculates the current position and height of the sun using the current time and local latitude and longitude. The microcontroller drives motors to move the PV panels to receive the maximum incidence of sunlight.⁽²⁾ The PV array and inverter are important for improving the power conversion rate in MPPT because decreasing the number of electronic devices and having a compact structure will enable simple control, low power consumption, and, accordingly, high conversion efficiency.⁽³⁾ This is related to the algorithm that controls the system efficiently. Previous research on algorithms for MPPT mainly adopted the MATLAB/Simulink platform.⁽⁴⁾ The hill-climbing algorithm was proposed for boosting circuit operation and achieving effective MPPT,⁽⁵⁾ which is regarded as simple and effective. This method combines simplified particle swarm optimization and the step-size perturbation observation method to ensure a fast, simple, and efficient process with limited hardware resources.

In this study, we propose a new design of a view-based motion trajectory system and a mathematical model for improving the efficiency of the PV automatic tracking system. The system replaces the traditional trajectory system with the view-based system. The new model provides optimal and stable PV arrays and an accurate simulation of the PV power generation system that improves the power generation and decreases the current loss due to the transmission between components of the PV power generation system.

2. Methods

2.1 Basic principle of MPPT

MPPT is a dynamic and self-optimizing process that matches the internal resistance of the PV battery. Its function is the real-time detection of the voltage of the power generated by the PV panel to monitor the peak voltage and current of the PV power generation system. The high voltage allows the high efficiency of the battery pack, which is the purpose of using MPPT.^(6,7)

The factory-set peak voltage (V_{pp}) and ambient reference temperature of a solar panel are about 17 V and 25 °C in general, respectively. Under ideal conditions, the charge and discharge efficiencies of the solar controller increase by about 50% with MPPT.⁽⁸⁾ Recent MPPT algorithms adopt various methods such as fixed voltage, disturbance observation, incremental conductivity, and fuzzy logic control methods.⁽⁹⁾ Figure 1 shows a schematic diagram of an MPPT system that includes a PV module, a DC-DC converter circuit, and a pulse-width modulation control circuit.

2.2 Control algorithm

The disturbance observation method is often applied to the control of MPPT to improve the system power oscillation near the MPP of a PV battery by reducing the perturbation step size.⁽¹⁰⁾ This method is not efficient in maintaining a balance between tracking speed and obtained power so it has limited applications. When the step size is large, the tracking speed increases, and operating points vary greatly near the MPP, which results in a large loss of output power but accurate tracking.⁽¹¹⁾ If the step size is small, the range of operating points decreases near the MPP, resulting in a small power loss and an increased number of disturbances. This increases the tracking time,⁽¹²⁾ and the power–voltage ($P-U$) characteristic curve satisfies $\Delta P/\Delta U = 0$ near the MPP. To simplify the calculation, $\Delta P/\Delta U$ is replaced with a certain voltage increment.⁽¹³⁾

When the duty cycle decreases, U increases by ΔU to U_1 ($U_1 = U + \Delta U$).

- (1) When $P_k > P_{k-1}$, the operation mode is located on the left side of the MPP and the disturbance direction remains unchanged.
- (2) When $P_k < P_{k-1}$, the operation mode is located on the right side of the MPP and the disturbance direction changes.

When the duty cycle increases, U decreases by ΔU to U_1 ($U_1 = U - \Delta U$).

- (1) When $P_k > P_{k-1}$, the operation mode is located on the right side of the MPP and the disturbance direction remains unchanged.
- (2) When $P_k < P_{k-1}$, the operation mode is located on the left side of the MPP and the disturbance direction changes.

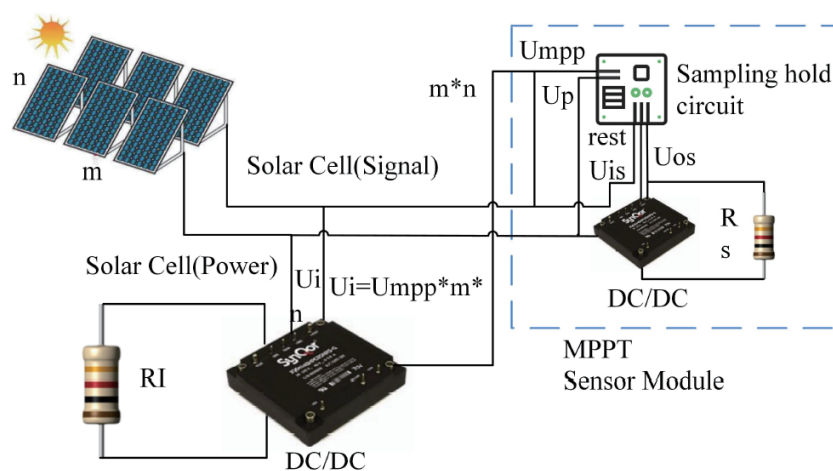


Fig. 1. (Color) Schematic diagram of MPPT system.

2.3 Mathematical model

A solar PV power generation system transforms solar energy into electric energy through the PV effect of solar cells and stores the energy in the battery. Since the battery is connected to the load at both ends, current flows through the load to produce output power as shown in Fig. 2.

Figure 3 shows a circuit of the battery of the PV power generation system. According to Kirchhoff's current law and Kirchhoff's voltage law, the mathematical model of current and voltage is defined as⁽⁵⁾

$$I_L = I_{ph} - I_D - I_{sh}. \tag{1}$$

When R_s is small and R_{sh} is large, they have a negligible effect on the output of the battery. Therefore, in the analysis of the actual circuit, R_s or R_{sh} can be ignored.⁽⁵⁾ When R_{sh} of the equivalent circuit in Fig. 3 reaches several thousand ohms, its effect on the circuit can also be neglected. Thereby, the circuit model is simplified to that shown in Fig. 4, and the output characteristic is expressed as

$$I_L = I_{ph} - I_D \left[\exp\left(\frac{q(V_{oc} + I_L R_s)}{AKT}\right) - 1 \right]. \tag{2}$$

According to Eq. (2), the output voltage and current for the battery are affected by light intensity and temperature, which have a linear relationship with I_{ph} .⁽⁵⁾ The relationship between light intensity and temperature is defined as

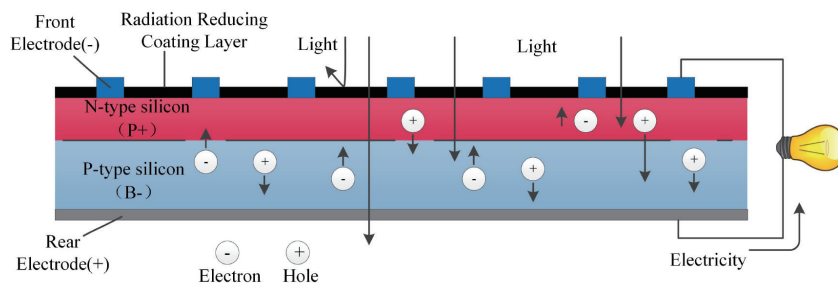


Fig. 2. (Color) Schematic diagram of a PV cell.

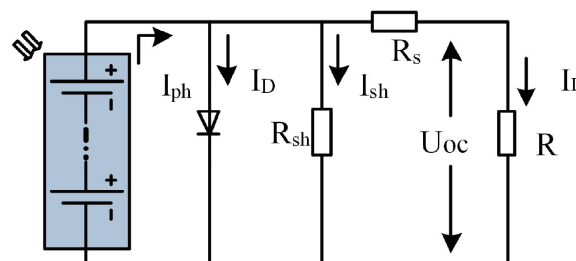


Fig. 3. (Color) Circuit model of the battery of the PV power generation system.

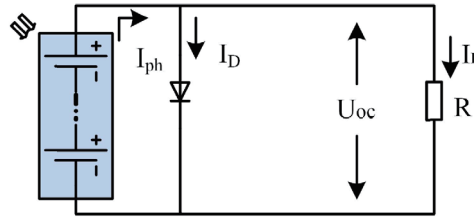


Fig. 4. (Color online) Simplified circuit model of the battery of the PV power generation system.

$$U_{OC} = \frac{AKT}{q} \ln \left(\frac{I_{ph}}{I_D} + 1 \right), \quad (3)$$

where AKT is the temperature coefficient of the open-circuit voltage and U_{OC} is the open-circuit voltage for the benchmark test (light intensity $G = 1000 \text{ W/m}^2$ and temperature = $25 \text{ }^\circ\text{C}$).⁽¹⁴⁾

3. Results and Discussion

3.1 Parameters of simulation

A MATLAB/Simulink simulation of the battery of the PV power generation system based on the above equations was established. The parameters of the battery are shown in Table 1.

The output characteristics of the voltage and current of the battery are determined by ambient temperature (T) and light intensity (G). The model of the battery was simulated by using different values of G and T , whose standard values were 1000 W/m^2 and $25 \text{ }^\circ\text{C}$, respectively. By setting $G = 1000 \text{ W/m}^2$, T values of 5, 15, 25, 30, and $40 \text{ }^\circ\text{C}$ were used to obtain the simulated values of the parameters. The obtained results are shown in Table 2.

The simulated values of the parameters were calculated with $T = 25 \text{ }^\circ\text{C}$ and $G = 200, 400, 600, 800, \text{ and } 1000 \text{ W/m}^2$. The obtained results are shown in Table 3.

Table 1
Parameters of battery of PV power generation system used in simulation.

Parameter	Value
V_{OC}	21.6 V
V_m	17.2 V
I_{SC}	3.41 A
I_m	3.19 A
α	0.015
β	-0.07
R	2Ω

Table 2
Simulated values of parameters obtained by model with G fixed at 1000 W/m^2 .

T ($^\circ\text{C}$)	V_{OC} (V)	V_m (V)	I_{SC} (A)	I_m (A)
5	35.6	31.2	3.11	2.89
15	28.6	24.2	3.26	3.04
25	21.6	17.2	3.41	3.19
30	18.1	13.7	3.335	3.265
40	11.1	6.7	3.185	3.415

Table 3
 Simulated values of parameters obtained by model with T fixed at 25 °C.

G (W/m ²)	V_{OC} (V)	V_m (V)	I_{SC} (A)	I_m (A)
200	21.6	17.2	0.638	0.682
400	21.6	17.2	1.364	1.276
600	21.6	17.2	2.046	1.914
800	21.6	17.2	2.728	2.552
1000	21.6	17.2	3.41	3.19

3.2 Simulation results

3.2.1 $V-I$ and $P-U$ relationships

The simulated results were plotted as $V-I$ and $P-U$ curves for different values of sunlight intensity and temperature. Figures 5 and 6 show the simulation results of $I-V$ and $P-U$ curves at $T = 25$ °C with G values of 200, 400, 600, 800, and 1000 W/m².⁽¹⁵⁾ With the solar radiation intensity (G) fixed at 1000 W/m², the ambient temperature was lowered from 40 to 5 °C. It was

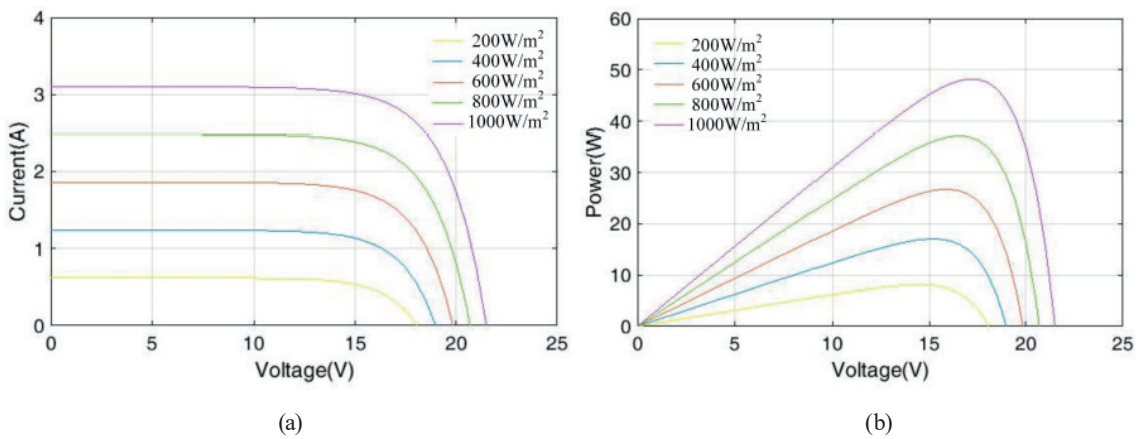


Fig. 5. $I-V$ and $P-U$ curves of simulated PV power regulation system at $T = 25$ °C and different light intensities.

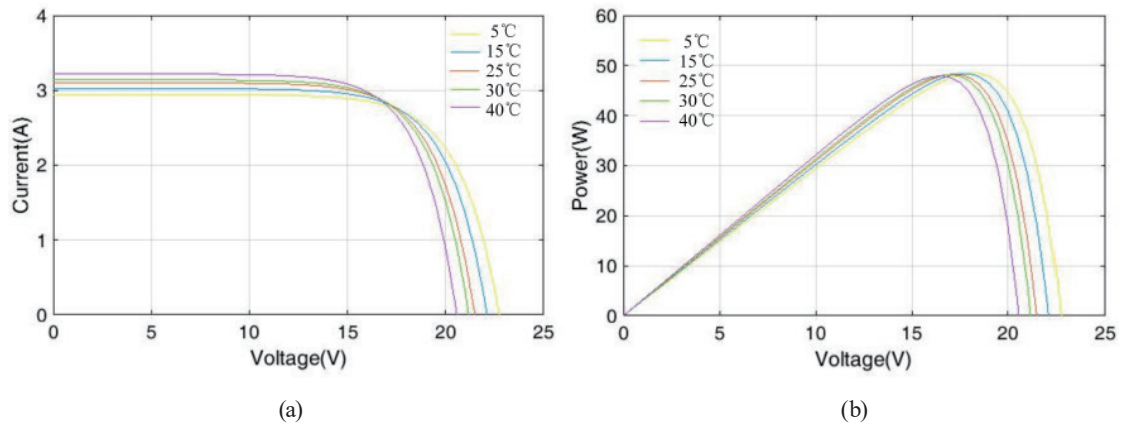


Fig. 6. $V-I$ and $P-V$ curves of simulated PV power regulation system at $G = 1000$ W/m² and different temperatures.

found that the maximum power and optimal working voltage of the system gradually increased with decreasing temperature. Also, with the ambient temperature (T) fixed at 25 °C, the solar radiation intensity was reduced from 1000 to 200 W/m².

The optimal working voltage remained unchanged, but the maximum power gradually decreased. As the PV array is highly susceptible to external factors, the operating voltage and that of the system have a nonlinear relationship. Therefore, it is important to make the system have one MPP with varying light intensity or temperature, which maximizes the efficiency of the PV power generation system.

3.2.2 Simulation results

The simulation model of the disturbance observation method was established by MATLAB/Simulink by using the parameters in Table 2. In addition to the parameters, a sampling time of 5×10^{-5} s, a switching frequency of 2×10^3 , a disturbance compensation length of 0.001 mm, and an initial duty cycle of 0.5 were input to the simulation model. The simulated results are shown in Figs. 7 and 8.

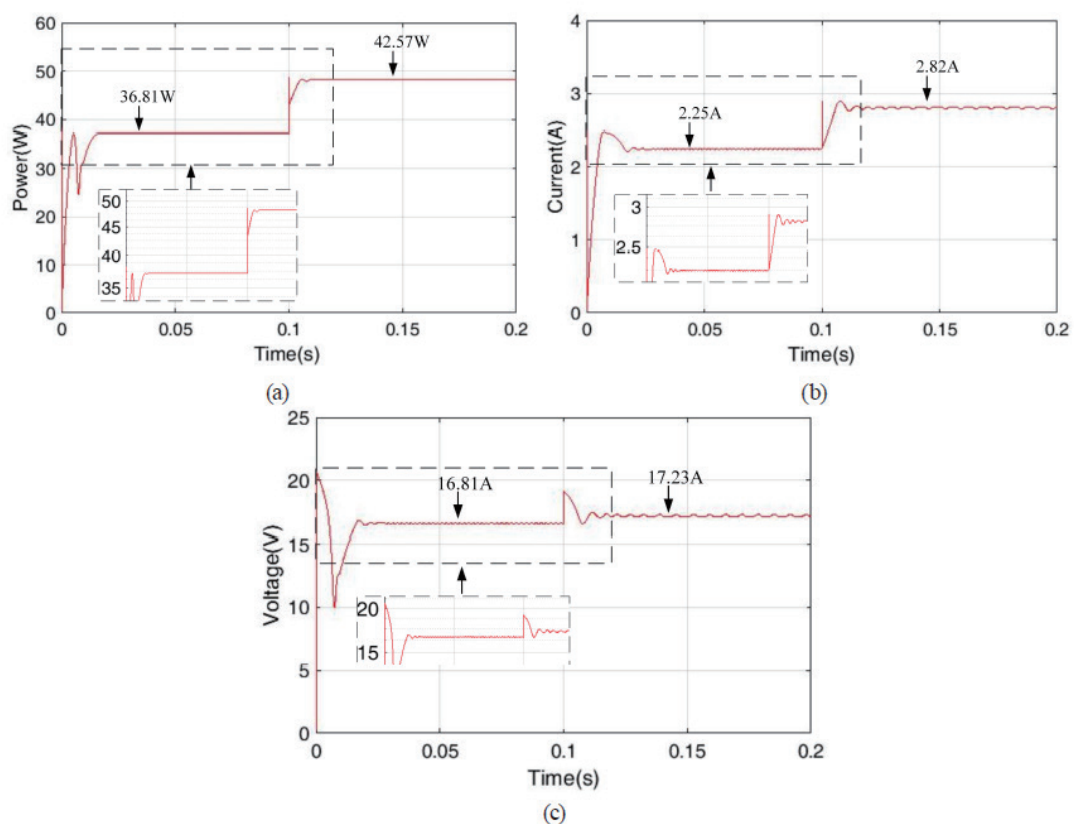


Fig. 7. (Color online) P - V curve when $G = 1000$ W/m² and $T = 25$ °C. (a) MPP, (b) I_m , and (c) V_m tracking diagrams.

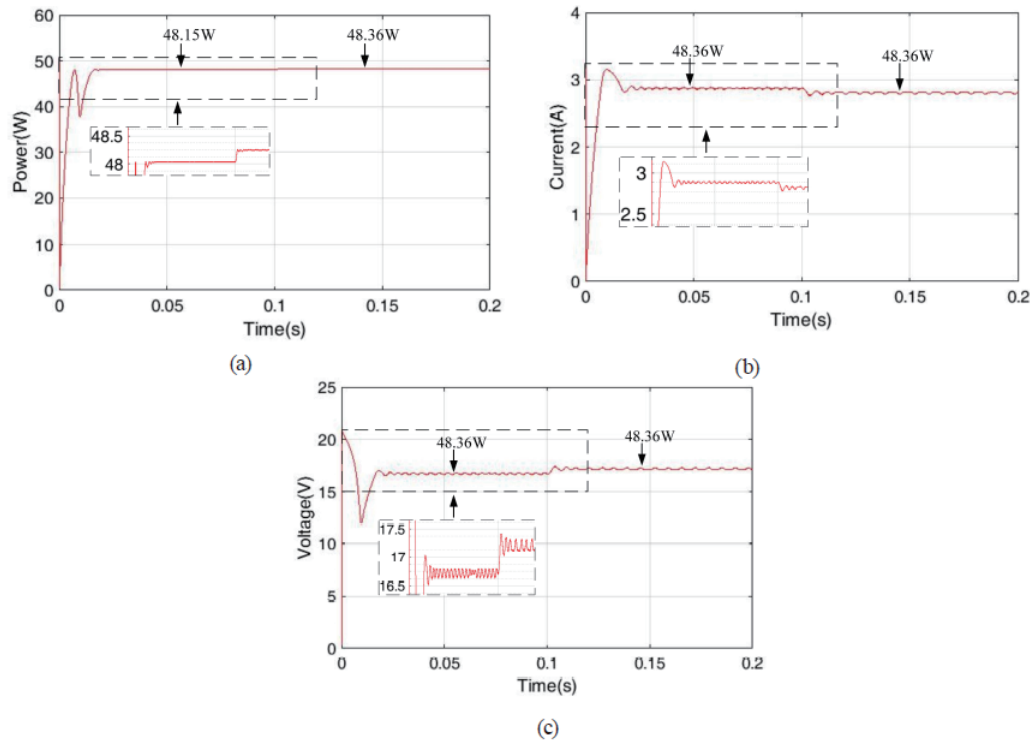


Fig. 8. (Color online) P - V curve when $G = 800 \text{ W/m}^2$ and $T = 15 \text{ }^\circ\text{C}$ (until 0.1 s), and $G = 1000 \text{ W/m}^2$ and $T = 25 \text{ }^\circ\text{C}$ (up to 0.2 s). (a) MPP, (b) I_m , and (c) V_m tracking diagrams.

Figure 7 shows that the system reached the MPP in less than 0.01 s for $G = 1000 \text{ W/m}^2$ and $T = 25 \text{ }^\circ\text{C}$. The maximum power achieved by the disturbance observation method was 55.1 W with a fluctuation of 1.8 W, which we regard as ideal for the MPP tracking system. The power first reached a peak and fluctuated until a stable MPP value of 55 W was maintained after 4 ms.

For $G = 800 \text{ W/m}^2$ and $T = 15 \text{ }^\circ\text{C}$, the power fluctuated considerably and reached a stable value of 42 W. Then, G and T were changed to 1000 W/m^2 and $25 \text{ }^\circ\text{C}$, respectively, which contributed to the sudden increase in power to 55 W from 0.1 s (Fig. 8).

Figure 9 shows that the power fluctuated and reached a stable value of 30 W at 0.1 s for $G = 600 \text{ W/m}^2$ and $T = 30 \text{ }^\circ\text{C}$. The power suddenly dropped to less than 10 W, then increased to 20 W when G and T were changed to 600 W/m^2 and $30 \text{ }^\circ\text{C}$, respectively.

Both step-change modes can track the MPP and the output voltage and current of the PV battery within about 0.01 s. The parameters (light intensity G and temperature T) of the system change at 0.1 s, which occurs in about 1 ms. Once again, by tracking the MPP and reaching a steady state, the dynamic characteristics and stability of the system can reflect changes in light intensity in a timely and smooth manner, and the system can quickly trace the maximum power output of the PV battery.⁽¹⁶⁾

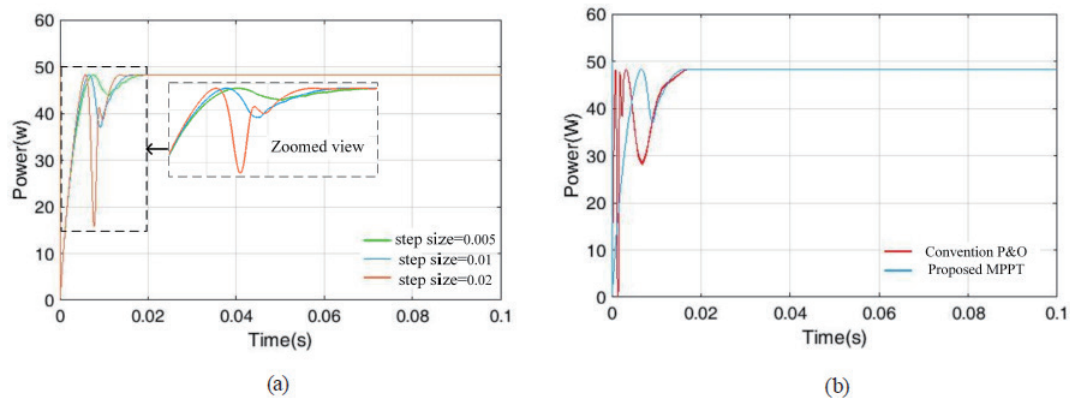


Fig. 9. (Color online) (a) Simulation comparison of the MPPT in different step sizes. (b) Simulation comparison of the Convention P&O and Proposed MPPT.

4. Conclusions

To determine the characteristics of the MPP of a PV power generation system, we established and simulated a model using MATLAB/Simulink. The MPPT of a PV battery was obtained by an improved disturbance observation method. Simulation results revealed that the system model found the MPP efficiently, which effectively improved the output efficiency of the PV system. This method requires only a small part of the PV cell body to be used as the PV sensor to monitor its electrical and temperature characteristics and to ensure the maximum efficiency of power generation. The simulation results of the $I-V$ and $P-V$ characteristic curves of the PV cells show the linear characteristics of the cells' operation, which reduces the instability and complexity of the PV system. Once the working point of the circuit is adjusted to the MPP, the PV cell always operates at the MPP owing to the strict linear relationship between the PV cell and the PV sensor. Similarly to other tracking algorithms, it realizes the automatic tracking of the PV cells to obtain the MPP for enhancing the efficiency of PV cells.

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