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AN IMPROVED VARIABLE STEP SIZE MPPT METHOD FOR PHOTOVOLTAIC ARRAY UNDER PARTIAL SHADING CONDITIONS

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Abstract: Photovoltaic (PV) systems are prone to partial shading effects, which cause multi-peak power points on the output curve, named local maximum power point (LMPP). The traditional perturbation and observation (P&O) algorithm will search into it when tracking maximum power. This paper proposes an improved variable step size (IVSS) perturbation tracking method to reduce the impact of perturbation step size choice on dynamic PV performance. MATLAB/Simulink software is used to develop and simulate the improved maximum power point tracking (MPPT) system. The IVSS tracking algorithm uses a program to achieve step perturbation. Finally, simulation results of the traditional P&O algorithm are compared with those achieved using the MPPT, verifying the superiority of proposed method in terms of tracking time, steady-state accuracy and maximum output power.

Keywords: Solar energy; Photovoltaic; Partial shading; Variable step size; Simulation.

1. Introduction

Traditional fossil fuels such as natural gas, oil and coal have long dominated global energy production. However, growing concern about climate change, coupled with the low and falling costs of renewable electricity generation, has made renewables the focus of world energy development. Currently, solar energy is the world's leading renewable energy source. Many technologies are involved in photovoltaic (PV) power generation, but the key to maximizing system efficiency is maximum power point tracking (MPPT) technology.

Solar photovoltaic power system uses PV modules to form PV array, which directly converts the received solar energy into electrical energy. Mismatch losses of PV generation system depends on several factors such as the availability of solar radiation, module operating temperature, shading, modules manufacturing tolerance, and PV power degradation. When a PV array is blocked or partially shaded by buildings, trees, dust or clouds, the power–voltage (P-U) curve will change from single-peak to multi-peak. In this situation, the traditional MPPT method may cause the PV array to operate at a local maximum power point, hence producing reduced output power (Li et al., 2018).

All of MPPT methods can be divided into two categories. The first category is traditional MPPT methods, including Constant Voltage (Goud et al., 2018), Perturbation and Observation (P&O) (Ahmed & Salam, 2015), and Increment Conductance (Loukriz et al., 2016) which often perform well under uniform irradiance. The second category consists of intelligent algorithms, including Particle Swarm Optimization algorithms (Dileep & Singh, 2017), Artificial Neural Network algorithms (Messalti et al., 2017), Fuzzy Logic Control (Tiwari & Tiwari, 2018) and so on. The algorithms from the second category have some advantages in global optimization, but the complicated calculations required hinder their use in practical engineering (Mao et al., 2020). Later, some authors proposed a method of combining P&O algorithm with fuzzy logic control (Tang et al., 2021), or combining P&O algorithm with PSO algorithm (Figueiredo & e Silva, 2021). By comparing the simulation results of these literatures, with the same input data, their simulation curves cannot be better than P&O in terms of model development, tracking stability and efficiency at the same time, Bollipo et al. (2020) and Hanzaei et al., (2020) also made a summary and comparison in their articles.

The P&O algorithm is a traditional tracking method; it is simple to develop, and easy to run. However, when performing PV multi-peak search under partial shading conditions, it will get stuck at a local peak point and cause more power loss (Chaieb & Sakly, 2018). Meanwhile, the tracking algorithm misjudgment will happen due to sudden change of irradiation when searching for the power point. The maximum power cannot be tracked in time. With the biggest reason for this situation by using P&O, is that it uses a fixed perturbation step size in tracking process. The choice of fixed step size also affects its tracking efficiency and tracking accuracy. To overcome the problems above, this paper aims to develop an improved variable step size (IVSS) tracking method based on the P&O algorithm, which perturbs the tracking system with varying steps. The improved method is compared with the P&O in respect to output power and tracking speed under the same input shading conditions. To show the advantages of this improved method.

2. Modeling of PV Cell

The topological structure of the PV system is presented in **Figure 1**. This system comprises of a PV array, control system (MPPT), pulse width modulation (PWM) generator, DC–DC converter and system load.

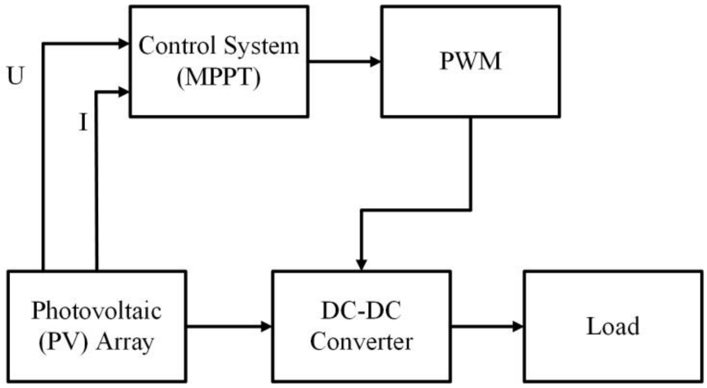

Figure 1. Topology of proposed photovoltaic system

A PV cell is an energy conversion device, which is influenced by environmental factors during operation, including irradiance (S) and temperature (T), and its output current (I) and voltage (U) will change accordingly. Therefore, I and U are usually used to characterize a PV cell. A simple PV cell model is implemented by a parallel connection of a current source and one diode. A single-diode model, commonly used equivalent circuit model **(Figure 2)**.

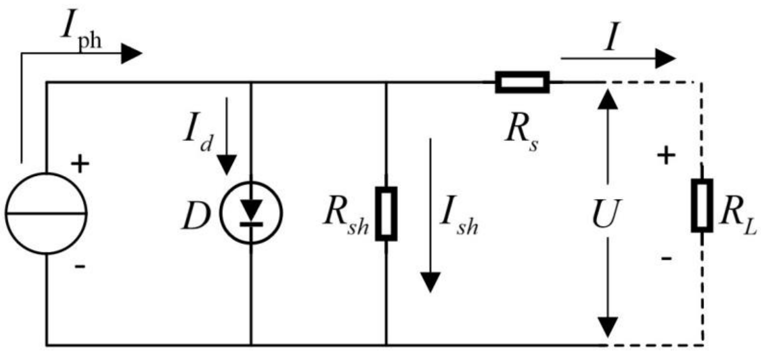

Figure 2. The equivalent circuit of a PV cell

The circuit in **Figure 2** is composed of components such as parallel resistance R_{Sh}, anti-parallel diode D, ideal current source I_{ph} and equivalent resistance R_S. Load operating current I is given in the following equation (Chennoufi et al., 2021):

$$I = I_{ph} - I_0 \left\{ exp\left[\frac{q(U + IR_S)}{AKT}\right] - 1 \right\} - \frac{U + IR_S}{R_{Sh}} \quad (1)$$

Where:

U	=	Terminal voltage
I_{ph}	=	Current produced by irradiation
I_0	=	Reverse saturation current of equivalent diode
K	=	Boltzmann constant= 1.3805×10^{-23}J/K
T	=	Operating temperature of environment (Kelvin)
A	=	Ideality factor of diode
q	=	Electron charge = 1.6×10^{-19}C.

The mathematical model of a PV cell is based on analysis of physical characteristics, which reflects the output characteristics. When the PV cell leaves the factory, the manufacturer will provide rated parameters, such as I_{sc}, U_{oc}, U_m, and I_m. The structure of a PV cell can be simplified based on equation (1). The equivalent parallel resistance R_{sh} is assumed to be very large, and assumed to be an open circuit, and I_{sh} is ignored. On the other hand, the equivalent series resistance R_s is very small, and is assumed to be a short-circuit. The ratio of R_s to R_{sh} is almost 0, and it can be seen from the circuit diagram in Figure 2 that $I_{sc} = I_{ph}$. When the PV cell is in open-circuit state, $U = U_{oc}$, $I = 0$ A. When the radiation and temperature of the environment are as per standard test conditions (STC), $U = U_m$, $I = I_m$ (Wu, 2019). Hence, the mathematical equation model of PV cell can be simplified as:

$$I = I_{sc}\left\{1 - C_1\left[exp\left(\frac{U}{C_2 U_{oc}}\right) - 1\right]\right\} \tag{2}$$

Meanwhile:

$$C_1 = \left(1 - \frac{I_m}{I_{sc}}\right)\left[exp\left(\frac{-U_m}{C_2 U_{oc}}\right)\right] \tag{3}$$

$$C_2 = \left(\frac{U_m}{U_{oc}} - 1\right)\left[ln\left(1 - \frac{I_m}{I_{sc}}\right)\right]^{-1} \tag{4}$$

Splitting equation (1) into three equations will give only four unknown input parameters in the formula. Parameters I_{sc}, U_{oc}, U_m and I_m are available **(Table 1)**, therefore C_1 and C_2 can be determined. Hence, the volt–ampere output curves of the PV cell under various irradiation levels can be plotted through simulation.

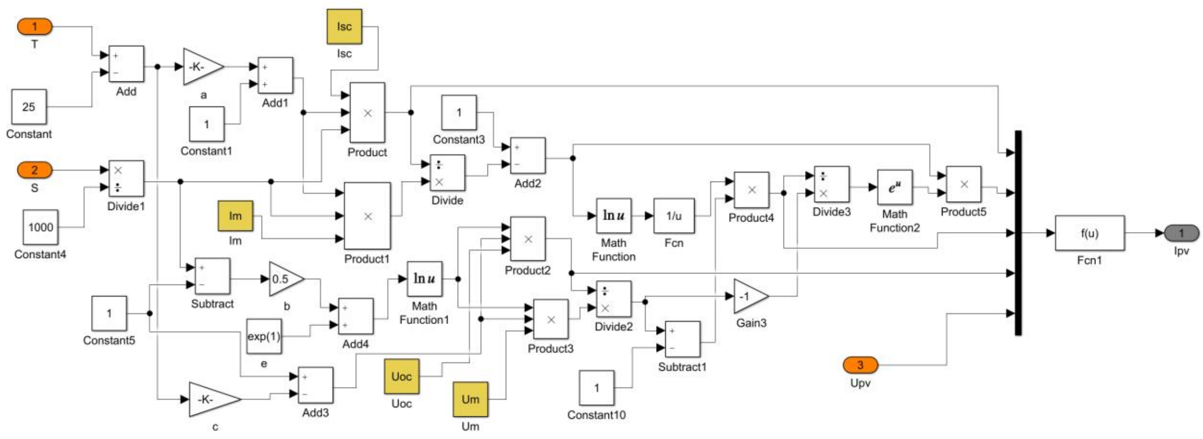

Figure 3. A mathematical model of a PV cell in Simulink

Using equations (2), (3) and (4), the simulation model is developed in MATLAB Simulink **(Figure 3)**. The PV module selected for this study is SUNTECH STP290-20/Wfw and its electrical parameters provided by manufacturer are presented in **Table 1**.

Table 1. Electrical parameters of SUNTECH STP290-20/Wfw

Maximum Power at STC (P_{max})	290W
Current at Maximum power (I_m)	9.09A
Voltage at Maximum power (U_m)	31.9V
Short circuit current (I_{sc})	9.56A
Open circuit voltage (U_{oc})	39.1V

Figures 4 and **5** show the output curves of one PV module. When a PV module is exposed under uniform irradiance with no shading, a single peak P–U curve is observed.

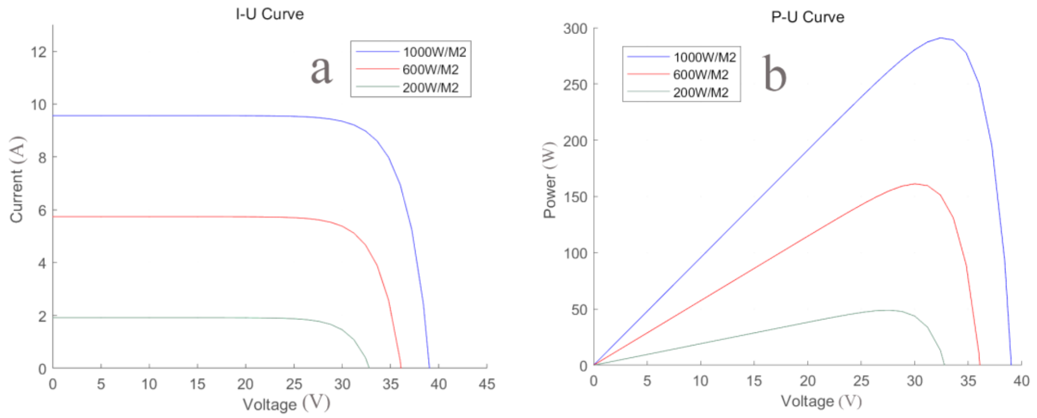

Figure 4. Output characteristic curve of PV module under different irradiation; T = 25℃; (a): I-U Curve, (b): P-U Curve

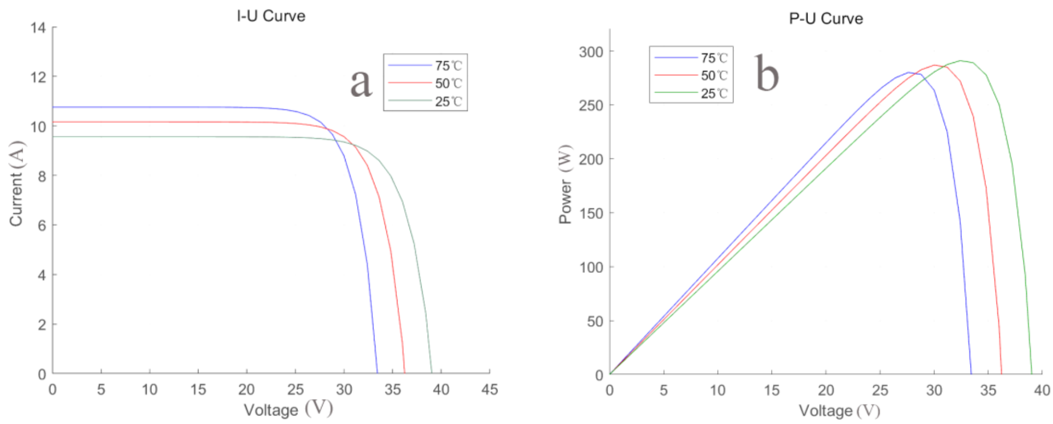

Figure 5. Output characteristic curve of PV module under different temperature; S = $1000W/m^2$; (a): I-U Curve, (b): P-U Curve

Next, four PV modules are connected in 4×1 to form a PV array. The four PV modules are shaded at various levels while being held at constant temperature (25℃). This means that the irradiance received by each module is different (1000 W/m^2, 800 W/m^2, 600 W/m^2, 400 W/m^2). The simulation curves are presented in **Figure 6**. The irradiance mismatch caused the bypass diode to turn on, and create a four-step ladder shape in the output curve.

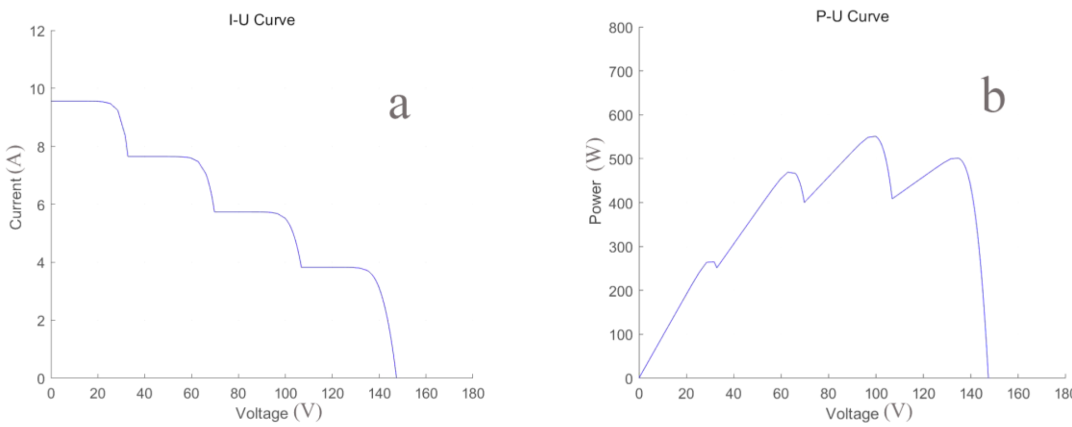

Figure 6. Output characteristic curve under partial shading condition; (a): I-U Curve, (b): P-U Curve

3. Proposed MPPT Method

3.1. Traditional Perturbation and Observation Algorithm

The purpose of P&O algorithm is to find a working point perturbation that can be set in the control process. The positional relationship between operating point and maximum power point is judged according to positive and negative difference between the power before and after perturbation (P_k and P_{k-1}). In addition, voltage changes at the two moments are compared to determine the direction of perturbation, to approach maximum output. This process will continue until the system stabilizes at the maximum power point.

In actual operation, it's difficult to find the perturbation that makes the operating point stabilize at the maximum power point. Therefore, a specific range " ε " will be set to determine maximum power point. When an operating point falls within this range of $P_k - P_{k-1} \leq |\varepsilon|$, it is regarded as the maximum power point. The simulation model of the MPPT using P&O is developed in MATLAB Simulink software **(Figure 7)**.

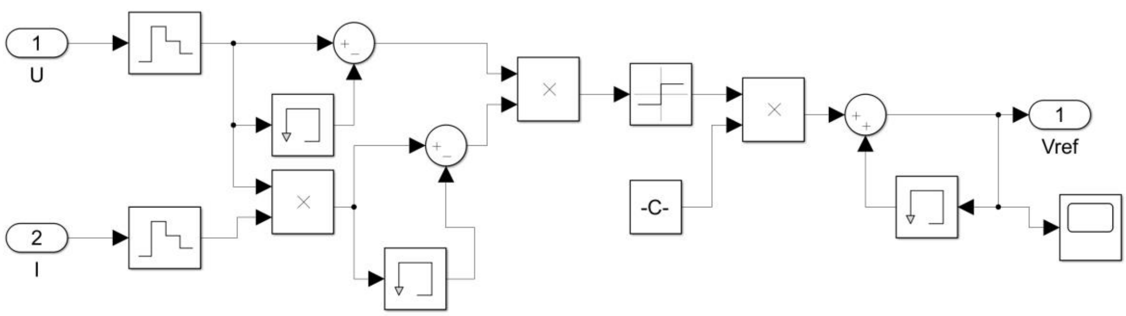

Figure 7. Subsystem of P&O algorithm in Simulink

This P&O block is a module used to realize perturbation tracking using the P&O algorithm. The 4×1 PV array subsystem, the P&O subsystem block, and the PWM control block are connected to the boost drive circuit to form a complete MPPT simulation circuit using the P&O algorithm.

3.2. Improved Variable Step Size Tracking Method

The perturbation step of the P&O algorithm is usually a fixed constant (Sharma & Katti, 2017). In order to reduce the influence of step size selection on steady-state accuracy and tracking speed, and make full use of the P&O algorithm advantages, this research sought to develop an IVSS perturbation tracking method.

Unlike the fixed-step method, this study uses a variable step voltage for segmented tracking. In the early stage of tracking, in the interval farthest from the maximum power point, a more significant step tracking is employed to improve the tracking speed of the system. As the simulation reaches near the maximum point, perturbation tracking with a smaller step size is employed to reduce the output power ripple and improve the steady-state accuracy. This not only improves the rapidity of tracking but ensures the stability of oscillation at maximum power point. **Figure 8** is a flowchart that details the algorithm developed for the improved tracking method.

The PV array adopts a 4×1 configuration, and the parameters of the PV module model are assigned to electrical values supplied on the manufacturer's datasheet. Under STC ($S_{ref} = 1000W/m^2$, $T_{ref} = 25°C$), the maximum power voltage U_m is 31.9V, maximum power currentI_m is 9.09A, open circuit voltage U_{oc} is 39.1V, and short circuit current I_{sc} is 9.56A. **Figure 9** shows the complete simulation circuit of the MPPT system using an improved tracking method. The PV system is tracked through the Boost drive conversion circuit.

The tracking simulation module (MPPT control) of variable step size perturbation is realized using MATLAB Simulink. The duty cycle input data involved in tracking is placed in the MPPT parameters block. The initial disturbance step size is set to 0.0001. When the system tracks near the maximum power, the perturbation amount is gradually reduced to 0.1 times the original perturbation step size through the MATLAB program setting.

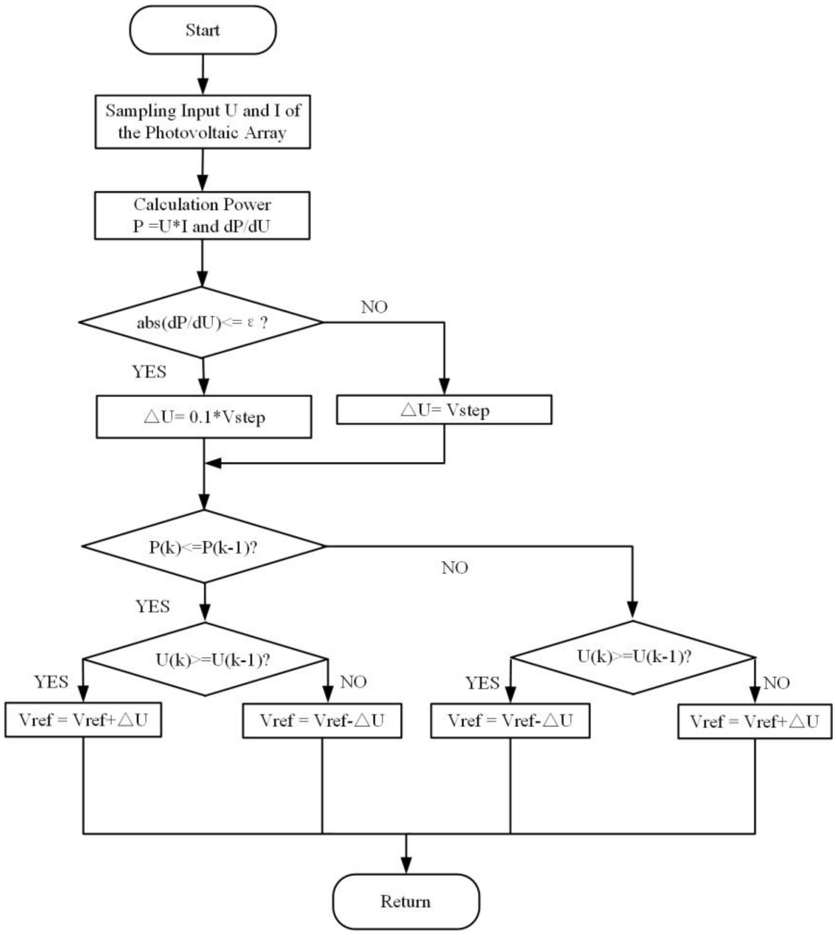

Figure 8. Flowchart of improved variable step size tracking algorithm

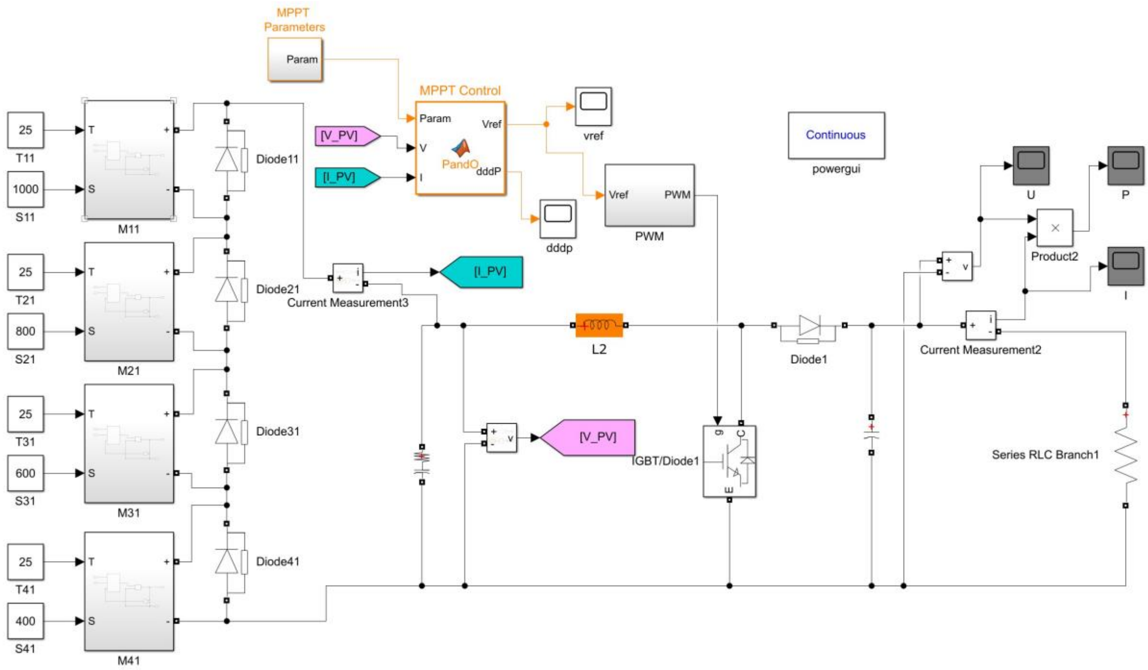

Figure 9. Complete simulation assembly of the improved MPPT system

4. Simulation Results and Discussion

The maximum rated output power of one PV module is 290W, there are four PV modules are connected here to form the PV array. Therefore, the total output power under STC is 1160W. The perturbation step of traditional P&O algorithm is fixed; a different step size changes tracking speed and stability. Therefore, this research refers to the published literature simulation data (Zhang, 2019), using two different step sizes of 0.001 and 0.01 for simulation. The result curves are shown in **Figure 10 (a)** and **(b)**. In addition, the simulation results of the IVSS tracking method are shown in **Figure 10 (c)**.

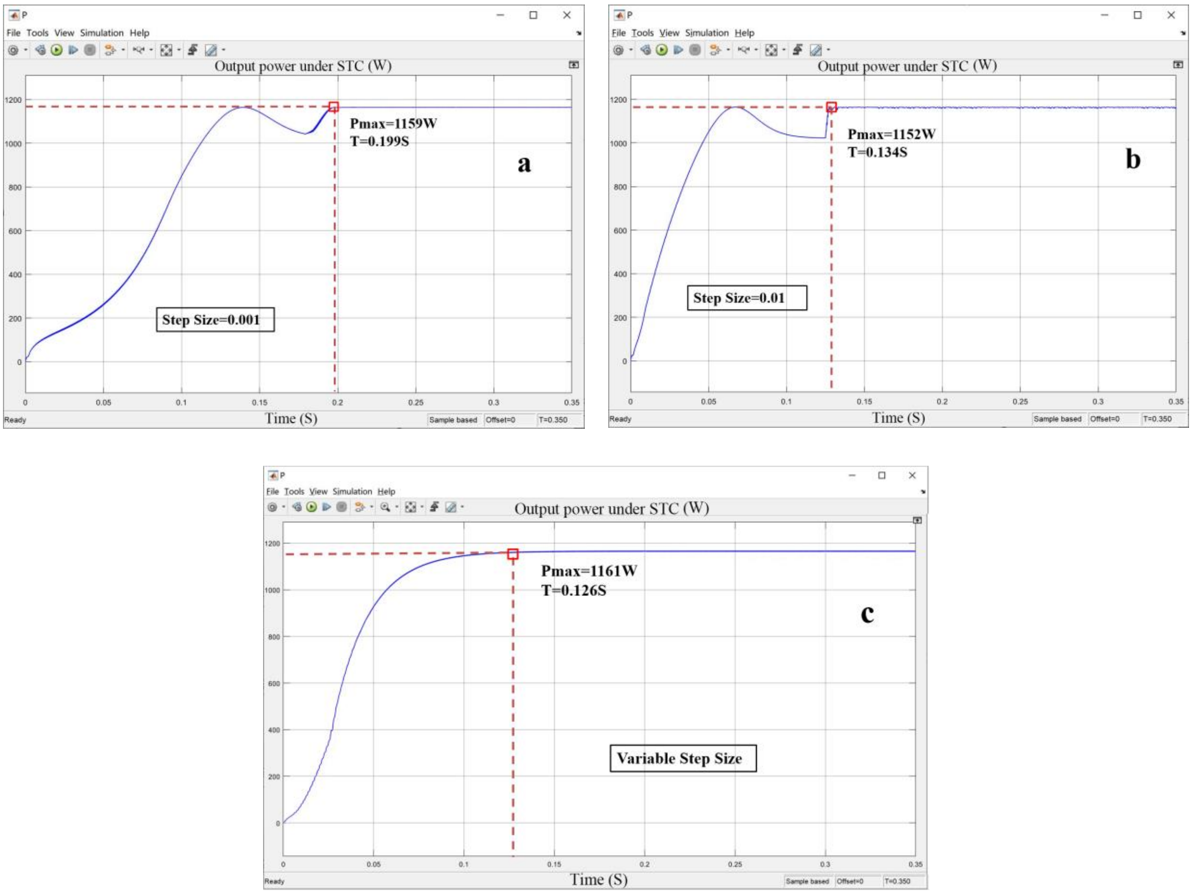

Figure 10. Tracking simulation curve of output power under STC; (a): P&O algorithm with 0.001 step size, (b): P&O algorithm with 0.01 step size, (c): IVSS method

These results obtained using the P&O algorithm when the array is under STC, suggest that the step size has little effect on maximum power value; it only affects the tracking time. The smaller step size influences tracking speed whereby a longer time is required to track the maximum power point. However, the steady-state oscillation is smaller. On the other hand, when step size is larger, the PV array will have a faster tracking speed. In this case, the steady state oscillation will be larger. The IVSS tracking method increases the tracking speed when power is far from the maximum point, and reduces the time taken for the system to track near peak point. Compared with the traditional P&O algorithm, this proposed system has good stability after reaching the maximum power point.

The PV modules in the PV array are set to different irradiation levels. The irradiation of M11 is set at $1000 W/m^2$, M21 at $600 W/m^2$, M31 at $400 W/m^2$, and M41 at $200 W/m^2$. When the four PV modules are at four different irradiances in a vertical direction, the output power curve will produce four peaks, creating a need to use the MPPT algorithm for maximum power tracking. Further simulations confirm that the maximum output power of the 4×1 PV array in this shading mode is 364.1W. The tracking results obtained using the traditional P&O algorithm and IVSS tracking method are shown in **Figure 11 (a)** and **(b)**. The maximum output power that the PV array can produce under uneven partial shading condition is 364.1W. The maximum power that can be tracked by the traditional P&O algorithm is only 269.2W, and the tracking time is 0.081s. The tracking efficiency of the system is (269.2/364.1) *100%=73.9%. The MPPT system fell into a local peak during tracking and failed to track the maximum power value; subsequently, the maximum output obtained using the improved tracking method is 347.4W, and the tracking time is 0.129s. The tracking efficiency of the system is (347.4/364.1) *100%=95.4%. Thus, the improved variable step tracking method increases the tracking efficiency to more than 95% and tracks a maximum power point under uneven shading conditions. Moreover, this IVSS tracking method tracks power of 338.6W when the traditional P&O algorithm tracks the maximum power of 269.2W at 0.081s and does so at 0.04s – halving the tracking time. The tracking speed of this scenario increased by 25%。

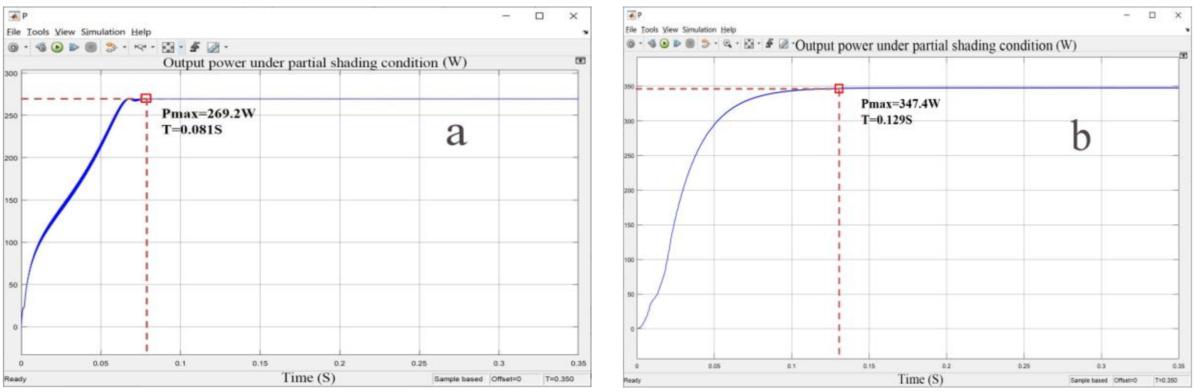

Figure 11. Tracking simulation curve of output power under partial shading condition; (a): P&O algorithm, (b): IVSS method

In addition, two sets of simulations with different irradiation levels were also carried out. The tracking time, maximum power and calculated tracking efficiency of all simulation results are shown in **Table 2**. After calculation with all scenarios in **Table 2**, a comparison for the P&O algorithm and IVSS method in case of different partial shading conditions is made, [(85.8-53.8) +(95.4-73.9) +(97-66.7)]/3*100%=28%. Under the same input radiation level, the tracking efficiency of IVSS method is always much higher than that of traditional P&O algorithm, the developed improved method has an average 28% higher tracking efficiency than the traditional PO algorithm.

Table 2. A comparison for the P&O algorithm and IVSS method in case of different partial shading conditions

M11 (W/m^2)	**M21** (W/m^2)	**M31** (W/m^2)	**M41** (W/m^2)	**Tracking method**	**Tracking time**	**Maximum power point**	**Tracking efficiency**
1000	1000	1000	1000	**P&O (0.01)**	0.134s	1152W	100%
				P&O (0.001)	0.199s	1159W	100%
				IVSS	0.126s	1161W	100%
1000	800	600	400	**P&O**	0.082s	296.7W	53.8%
				IVSS	0.121s	472.8W	85.8%
1000	600	400	200	**P&O**	0.081s	269.2W	73.9%
				IVSS	0.129s	347.4W	95.4%
600	400	200	200	**P&O**	0.112s	148.4W	66.7%
				IVSS	0.127s	216W	97%

In the situation shown in **Figures 10** and **11**, the MPPT system is always operating in partial shading. A simulation experiment is performed to verify the adaptability and accuracy of two MPPT tracking methods when the lighting environment sudden changes. The radiation level changes are shown in **Figure 12 (a)**. The system starts under STC, $S1 = 1000W/m^2$ (0~0.5s). After 0.5s, due to a change in the passing clouds or solar radiation angle, the PV array is evenly shaded, and the overall irradiance is uniformly reduced to $S2 = 400W/m^2$ (0.5s~1s). After another 0.5s, the shading of the array is weakened, and the overall irradiance is uniformly increased to $S3 = 800W/m^2$ (1s~1.5s); the output power of the system has rebounded. The purpose of this experiment is to verify the accuracy and adaptability of this MPPT system when the irradiation fluctuation occurs.

In simulation of a 4×1 PV array, when $S1 = 1000W/m^2$, the maximum power output is 1160W. When $S2 = 400W/m^2$, the maximum power is 411W. When $S3 = 800W/m^2$, the maximum power is 896.3W. The tracking results obtained using the P&O algorithm and IVSS tracking method are shown in **Figure 12 (b)** and **(c)**.

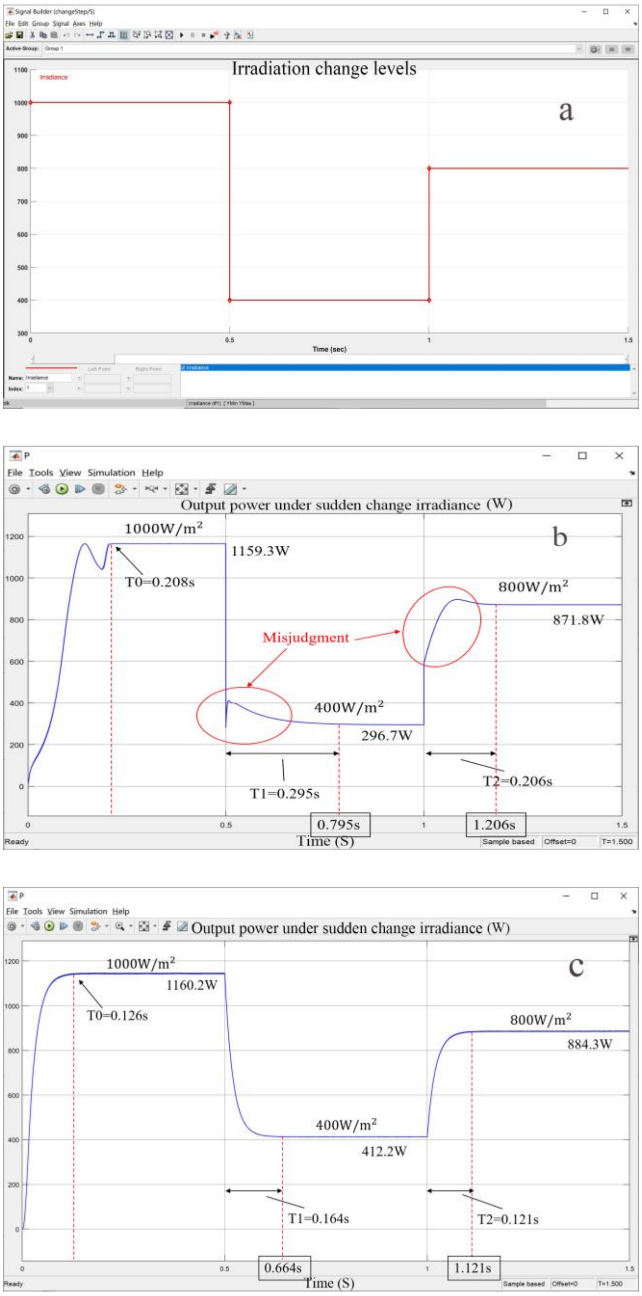

Figure 12. Tracking simulation curve of output power under uniform sudden change irradiance; (a): irradiation levels, (b): P&O algorithm, (c): IVSS method

At the start of this simulation process, the PV array is in an unshaded state, $S1 = 1000W/m^2$. Both P&O and IVSS methods track the maximum power point. The traditional P&O algorithm tracks the maximum power of 1159.3W after 0.208s. The IVSS method tracks the maximum power of 1160.2W after 0.126s, a significantly faster startup speed; moreover, compared to the traditional P&O algorithm, the IVSS startup curve is smoother. After 0.5s, the irradiance of the whole PV array changes uniformly to $S2 = 400W/m^2$; the P&O algorithm tracks maximum power of only 296.7W, far lower than the maximum power output of 411W, and stabilized at the maximum power point again at 0.295s. By contrast, when a fluctuation in irradiance occurs, the IVSS method requires only 0.164s to track the maximum output power of 412.2W, and no misjudgment occurred. After another 0.5s, the irradiance of the whole PV array rises to $S3 = 800W/m^2$. The traditional P&O algorithm tracked a maximum power point at 871.8W after 0.206s. And the same misjudgment occurs as before, the tracking process curve is more unstable. The IVSS method tracks the maximum output power to 884.3W at 0.121s, and reaches the maximum power point steadily. **Table 3** summarizes the data obtained for the simulation described in this section.

Table 3. A comparison of tracking time and maximum power in case of irradiation fluctuation for the P&O algorithm and IVSS method

Tracking method	**S1=1000W/m²**		**S2=400W/m²**		**S3=800W/m²**	
	Tracking time (T0)	**Maximum power**	**Tracking time (T1)**	**Maximum power**	**Tracking time (T2)**	**Maximum power**
P&O	0.208s	1159.3W	0.295s	296.7W	0.206s	871.8W
IVSS	0.129s	1160.2W	0.164s	412.2W	0.121s	884.3W

5. Conclusion

To address the multi-peak characteristics of the PV array under different partial shading conditions, an improved variable step size (IVSS) tracking method is proposed in this paper to track maximum output power point. The improved algorithm tracks maximum power point faster and with more stability than the traditional P&O algorithm. Moreover, this proposed improved method can efficiently find the new operating point of the system when irradiance fluctuates, hence displaying good dynamic characteristics. The proposed IVSS method overcomes the limitations of the traditional P&O algorithm in step size selection. It shortens the system startup time, reduces steady-state oscillation, and accelerates dynamic response. The tracking efficiency is increased by 28% on average.

Acknowledgement

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