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ACCURATE SOLUTION TO NONLINEAR PARAMETERS OF SOLAR CELLS BASED ON LIMIT CONSTRAINTS

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ABSTRACT

Accurate solution to the nonlinear parameters of solar energy mathematical model has a great influence on the accuracy of solar cell output power calculation, but it is difficult to obtain. Moreover, these parameters will also change as the environment or battery life changes. A method is proposed to accurately solve the nonlinear parameters of photovoltaic cells based on Newton-Raphson method with limit constraints. This method uses Newton-Raphson method to iteratively solve the exact solution of the nonlinear parameters. The limit constraints are used to effectively solve the problem that the stiffness of the Jacobian matrix is not converged due to the improper selection of the initial value, which makes convergence faster and can realize the real-time online exact calculation of the nonlinear parameters for the currently operating photovoltaic cell. A single-diode four-parameter mathematical model is built, and the fourth-order Jacobian matrix is deduced, and the limit constraint is given. Finally, the feasibility and validity of the proposed method are demonstrated by two example experiments.

Keywords: Nonlinear parameters, solar energy, Newton Raphson method, Jacobi matrix, limit constraints

1. INTRODUCTION

Nowadays, with the rapid development of science and technology, the demand for energy is increasing, and the main source of energy supply that mankind relies on, the fossil energy on the earth, is also facing exhaustion. Moreover, as the amount of energy provided by burning fossil energy is increasing, the pollution of the earth is becoming more and more serious, so clean and alternative energy sources are urgently needed to replace fossils energy. Solar energy, as a clean, non-geographical and inexhaustible alternative energy source, has attracted more and more attention from all countries. It is gradually becoming one of the main forms of access in the energy field.

Because the materials of photovoltaic cells are mostly semiconductor silicon, the parameters of photovoltaic cells are affected by illumination intensity and ambient temperature, showing a non-linear change, not constant. The parameters given by the factory photovoltaic cells are usually peak power, peak power voltage, peak power current, open circuit voltage, short circuit current and so on under the reference environment temperature and solar irradiance. However, some parameters are difficult to obtain by measurement, such as photo-generation current, diode current, shunt conductance and series resistance in the equivalent circuit model of single-diode photovoltaic cells as shown in Figure 1. At present, many documents have been researched and discussed. The estimation algorithm was used to determine maximum power point [1-2]. Genetic algorithm and pattern search optimization algorithm was used to obtain the parameters of photovoltaic cell model [3-4]. Parameters of PV model were extracted from experimental curve [5-6]. The linear least squares fitting technique was used in [7]. Parameters were obtained by five parameter equations [8]. Improved simplified swarm optimization was used to estimate exactly parameters of the solar cell models [9]. A practical implementation of photovoltaic I − V curves and maximum power point estimation algorithm were

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presented to solve the parameters of the solar array equivalent electrical model in real time [10]. Although many methods for solving nonlinear parameters of solor cell have been studied, these methods used estimation or simplification methods, and did not consider real-time accurate calculations with environmental changes or years of use.

The main purpose of this paper is to obtain photovoltaic power generation precise output power and eliminate the error caused by simplification. The precise equivalent model of photovoltaic power generation is adopted, and the precise solution of solar cell nonlinear parameter equation is obtained by Newton-Raphson method with limit constraints (NRLC). The work arrangement of this paper is as follows: Section II formulates the four unknown parameters mathematical model from photovoltaic cell single diode equivalent model, and deduces the fourth-order Jacobian matrix of the four non-linear parameters. The computational equations for solving jacobian matrix elements are derived. Section III formulates the specific limit constraints and the strategy method of calculating the parameters by the NRLC. And the implementation steps of this algorithm are described in detail by flow chart. The algorithm flow and calculation steps are given in Section IV. Section V carries out the two example experiments of the single-diode model using matlab/simulink. The validity of the method is compared with the actual test results. Section VI is conclusion and prospects for further research.

2. NR PRECISE MODEL ESTABLISHMENT

In the current commonly used models, the model established by equivalent circuit method has high accuracy. The single-diode equivalent circuit of photovoltaic cells is given in Fig. 1. The mathematical model in formula (1) shows that the model can accurately reflect the internal working principle of photovoltaic cells. However, because the parameters of the model are not easy to be measured, many literatures used a simplified method but to cause a certain error in the accuracy of the photovoltaic output characteristics. NR method has good convergence for accurately solving nonlinear equations.

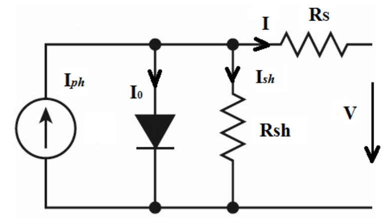

Figure.1 Single Diode Equivalent Circuit Model

The four unknown parameter mathematical model of photovoltaic cell output current based on Fig. 1 is shown in Formula (1).

$$I = I_{SC}[1 - C_1(\exp(\frac{U + I R_S}{C_2 U_{OC}}) - 1)] - G_{sh}(U + I R_S) \qquad (1)$$

Where, I_{SC}, U_{OC}, C_1, C_2 , Rs, Rsh ,U and I denote respectively short-circuit current, the open-circuit voltage, the reverse current influence factors, voltage influence factors, series resistance, parallel resistance, the output voltage and the output current. The values of C_1, C_2 and R_s are very small, while the values of R_{sh} are very large, which may cause the inverse matrix of Jacobian matrix to be rigid. Therefore, R_{sh} is treated by shunt conductance G_{sh}.

The photovoltaic panel provided by manufacturer are usually short circuit current I_{SC}, open circuit voltage U_{OC}, peak voltage Um and peak current I_m of photovoltaic cells under reference illumination intensity and reference temperature. C_1, C_2 , R_s and G_{sh} are generally not given. Because the materials of photovoltaic cells are mostly semiconductor silicon, the parameters of photovoltaic cells are affected by illumination intensity and ambient temperature, showing a non-linear change, not constant. With the increase of temperature, U_{OC} decreases, and I_{SC} increases slightly. When the voltage is low, the performance of photovoltaic array is similar to that of constant-voltage source, and U_{OC} is inversely proportional to temperature, and I_{SC} is approximately proportional to sunshine intensity. When the temperature remains unchanged, U_{OC} of photovoltaic array remains basically unchanged with the increase of illumination intensity, and the maximum power point voltage changes slightly within a certain range of illumination intensity. The models of U_{OC}, I_{SC}, U_m and I_m varying with temperature and solar irradiance are shown as follows:

$$\Delta T = T - T_{ref} \qquad (2)$$

$$\Delta S = S - S_{re} \qquad (3)$$

$$I'_{SC} = I_{SC} \times \frac{S}{S_{ref}} \times (1 + \alpha \Delta T) \qquad (4)$$

$$U'_{OC} = U_{OC} \times (1 - \mu \Delta T) \times \ln(e + \beta \Delta S) \qquad (5)$$

$$I'_m = I_m \times \frac{S}{S_{ref}} \times (1+\alpha\Delta T) \tag{6}$$

$$U'_m = U_m \times (1-\mu\Delta T) \times \ln(e+\beta\Delta S) \tag{7}$$

Where, *T, T_{ref}, S* and *S_{ref}* denote respectively battery current temperature, reference temperature, current illumination intensity and reference illumination intensity. *e* represents the natural logarithmic base. α, β and μ denote the compensation coefficients.

In order to obtain the parameters C_1, C_2, Rs and G_{sh} of photovoltaic cells at a certain temperature and illumination intensity, at least four equations are needed. These four equations are derived from the following four special operating situations.

1) When photovoltaic cell is open circuit, $I = 0$, $U = U'_{OC}$,the formula is shown as follows

$$f_1 = I'_{SC} \times \{1 + C_1[1-\exp(\frac{1}{C_2})]\} - G_{sh}U'_{OC} = 0 \tag{8}$$

2) When photovoltaic cells work at the maximum power point, $I = I'_m$, $U = U'_m$, the formula is shown as follows.

$$f_2 = I'_m - I'_{SC} \times \{1 + C_1[1-\exp(\frac{U'_m + I'_m \times R_S}{C_2 \times U'_{OC}})]\} + G_{sh}(U'_m + I'_m \times R_S) = 0 \tag{9}$$

3) When photovoltaic cells operate at the maximum power point, $I = I'_m$, $U = U'_m$, the voltage derivative is zero.

$$\frac{dP}{dV} = I + U \times \frac{dI}{dU} = 0$$

After the formula (1) is substituted into the above formula, the new formula is shown as follows.

$$f_3 = I'_m - \frac{U'_m \times I'_{SC} \times C_1}{C_2 U'_{OC}} \times \exp(\frac{U'_m + I'_m \times R_S}{C_2 \times U'_{OC}}) - U'_m \times G_{sh} = 0 \tag{10}$$

4) When photovoltaic cells operate at the maximum power point, $I = I'_m$, $U = U'_m$, the current derivative is zero. The formula of U is obtained from formula (1) as follows.

$$U = C_2 \times U_{OC} \times \ln \frac{I_{SC} \times (1+C_1) - I - G_{sh} \times (U_m + I_m R_S)}{I_{SC} \times C_1} - I\, R_S$$

And it is substituted into the following formula.

$$\frac{dP}{dI} = U + I \times \frac{dU}{dI} = 0$$

Then, the result is shown as follows:

$$f_4 = U'_m - \frac{U'_{OC} \times I'_m \times C_2 \times (1 + G_{sh} \times R_S)}{I'_{SC} \times (1+C_1) - I'_m - G_{sh} \times (U'_m + I'_m \times R_S)} - I'_m \times R_S = 0 \tag{11}$$

The formulas (8-11) are used to compose first-order non-linear equations for *C1, C_2, G_{sh}* and *R_s*. The value of four unknown parameters can be obtained by using Newton-Raphson method. Jacques matrix iterative equation is shown as follows

$$F(X) + J \times \Delta X = \begin{bmatrix} f_1 \\ f_2 \\ f_3 \\ f_4 \end{bmatrix} + \begin{bmatrix} \frac{\partial f_1}{\partial C_1} & \frac{\partial f_1}{\partial C_2} & \frac{\partial f_1}{\partial R_s} & \frac{\partial f_1}{\partial G_{sh}} \\ \frac{\partial f_2}{\partial C_1} & \frac{\partial f_2}{\partial C_2} & \frac{\partial f_2}{\partial R_s} & \frac{\partial f_2}{\partial G_{sh}} \\ \frac{\partial f_3}{\partial C_1} & \frac{\partial f_3}{\partial C_2} & \frac{\partial f_3}{\partial R_s} & \frac{\partial f_3}{\partial G_{sh}} \\ \frac{\partial f_4}{\partial C_1} & \frac{\partial f_4}{\partial C_2} & \frac{\partial f_4}{\partial R_s} & \frac{\partial f_4}{\partial G_{sh}} \end{bmatrix} \times \begin{bmatrix} \Delta C_1 \\ \Delta C_2 \\ \Delta R_s \\ \Delta G_{sh} \end{bmatrix} = 0 \tag{12}$$

Where, J is Jacques matrix. The elements of the Jacobian matrix are calculated by the following formulas.

1) The elements in the first row are obtained by the derivative of each parameter from equation (8) and shown in formula (13).

$$\begin{cases} \frac{\partial f_1}{\partial C_1} = I'_{sc}(1 - e^{1/C_2}) \\ \frac{\partial f_1}{\partial C_2} = \frac{I'_{sc}C_1}{C_2^2} e^{1/C_2} \\ \frac{\partial f_1}{\partial R_s} = 0 \\ \frac{\partial f_1}{\partial G_{sh}} = U'_{oc} \end{cases} \tag{13}$$

2) The elements in the second row are obtained by the derivative of each parameter from equation (9) and shown in formula (14).

$$\begin{cases} \frac{\partial f_2}{\partial C_1} = I'_{sc}(e^{\frac{U'_m + I'_m R_s}{C_2 U'_{oc}}} - 1) \\ \frac{\partial f_2}{\partial C_2} = \frac{I'_{sc}C_1(U'_m + I'_m R_s)}{C_2^2 U'_{oc}} e^{\frac{U'_m + I'_m R_s}{C_2 U'_{oc}}} \\ \frac{\partial f_2}{\partial R_s} = \frac{I'_{sc}C_1 I'_m}{C_2 U'_{oc}} e^{\frac{U'_m + I'_m R_s}{C_2 U'_{oc}}} + G_{sh} I'_m \\ \frac{\partial f_2}{\partial G_{sh}} = U'_{oc} + I'_m R_s \end{cases} \tag{14}$$

3) The elements in the third row are obtained by the derivative of each parameter from equation (10) and shown in formula (15).

$$\begin{cases} \frac{\partial f_3}{\partial C_1} = \frac{I'_{sc}U'_m}{C_2 U'_{oc}} e^{\frac{U'_m + I'_m R_s}{C_2 U'_{oc}}} \\ \frac{\partial f_3}{\partial C_2} = \frac{I'_{sc}U'_m C_1}{C_2^2 U'_{oc}} e^{\frac{U'_m + I'_m R_s}{C_2 U'_{oc}}} + \frac{I'_{sc}U'_m C_1(U'_m + I'_m R_s)}{C_2^3 U'_{oc}} e^{\frac{U'_m + I'_m R_s}{C_2 U'_{oc}}} \\ \frac{\partial f_3}{\partial R_s} = \frac{I'_{sc}U'_m C_1 I'_m}{C_2^2 U'^2_{oc}} e^{\frac{U'_m + I'_m R_s}{C_2 U'_{oc}}} \\ \frac{\partial f_3}{\partial G_{sh}} = -U'_m \end{cases} \tag{15}$$

4) The elements in the fourth row are obtained by the derivative of each parameter from equation (11) and shown in formula (16).

$$\begin{cases} \dfrac{\partial f_4}{\partial C_1} = I'_{sc} U'_m \\ \dfrac{\partial f_4}{\partial C_2} = I'_m U'_{oc} - I'_m U'_{oc} G_{sh} R_s \\ \dfrac{\partial f_4}{\partial R_s} = -I'_m U'_{oc} G_{sh} C_2 - I'_m U'_{oc} G_{sh} - I'_m \\ \dfrac{\partial f_4}{\partial G_{sh}} = -U'_{oc} I'_m R_s C_2 - U'^2_m - U'_m I'_m R_s \end{cases} \tag{16}$$

The parameter correction equation obtained by formula (12) is shown as follows:

$$\Delta X = -J^{-1} F(X) \tag{17}$$

Where, J^{-1} is Jacobian inverse matrix.

According to the above, as long as the selected initial values are suitable, the convergent solution of *C1, C2, G_{sh}* and *R_s* will be obtained. Then the four parameters are substituted into the formula (1), and the output current of the photovoltaic cell varies with illumination intensity and temperature is calculated.

However, due to the high requirement of the initial value of NR algorithm, the bad selection of the initial value will affect the non-singularity of Jacobian matrix that is easy to cause the non-convergence of the algorithm.

3. LIMIT CONSTRAINT NR ALGORITHM

Considering that the NR method belongs to the iterative solution method, once the conditions change, it may cause long iteration time, even non-convergence. Through a large number of experiments, it is found that the reason why the NR algorithm does not converge is mainly due to the improper selection of the initial value that may result in the rigidity of the Jacobian inverse matrix. If the parameters are set to the limit range, the Jacobian matrix will not be singular, and the solution convergence speed can be accelerated. Limit constraints are shown as follows:

$$\underline{x_i} \le x_i \le \overline{x_i} \tag{18}$$

Where, x_i represents the i_{th} unknown parameter; $\underline{x_i}$ represents the lower limit and $\overline{x_i}$ represents the upper limit.

When the value of a parameter exceeds the limit during the iteration, the limit is taken to prevent the singularity of the Jacobian matrix. In order to further speed up the convergence of the algorithm, the initial value chooses the median value, that is, the average value of the upper limit and the lower limit. The formula is shown as follows.

$$x_{i0} = (\underline{x_i} + \overline{x_i})/2 \tag{19}$$

During the NR method iteration, the parameter correction amount is obtained by using formula (17) and the parameters are corrected. When there are one or more parameters whose value exceeds the limit range, the limit is taken in order to ensure that each corrected Jacobian matrix and its inverse matrix can always Keep non-singular and ensure the convergence of the algorithm.

4. ALGORITHM IMPLEMENTATION PROCESS

The flow chart of the proposed algorithm is shown in Figure 2. The steps are as follows.

1) Firstly, the variables are calculated under current temperature and solar irradiance according to formula (2-7). Combined estimation method the upper and lower limits of the initial values of C1, C2, Rs, and Gsh are obtained according to the actual measured values of the voltage and current from the photovoltaic panel, and the initial values of the parameters are calculated according to formula (19).
2) Secondly, using the values of the variables in 1) , the elements values of the Jacobian matrix are calculated according to the formula (13-16), and then the Jacobian inverse matrix is calculated.
3) Then, the correction amounts of the parameters are calculated according to formula (17), and the parameters are corrected. If there is a parameter that is out of the constraint boundary of equation (18), let the parameter takes the boundary value.
4) Finally, the function values are calculated by the formula (8-11). If all the function values are less than the given minimum value, the results are exported, otherwise, it returns 2) and continues.

The flow chart of the NRLC method is shown in Figure 2.

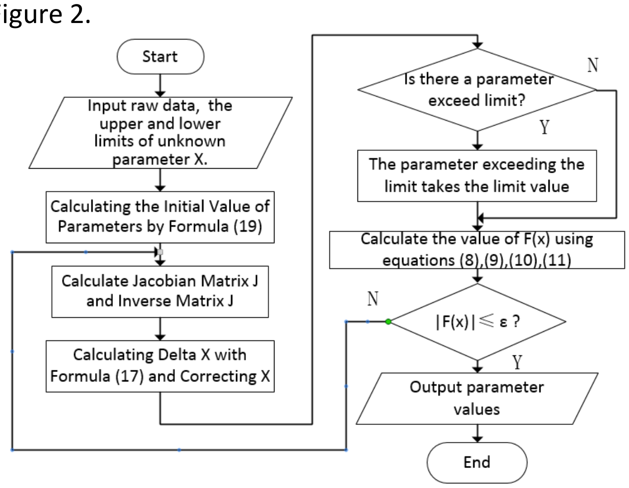

Figure.2 The algorithm flowchart

5. EXPERIMENTAL SIMULATION

In order to verify the correctness and validity of the proposed method, two photovoltaic panels are used as experiment examples.

5.1 *Experiment example 1*

In the first experiment example, the value of known parameters and the initial values of four unknown parameters are shown in Table 1. When ambient temperature is at 25°C, the curves of current versus voltage at different solar irradiances are shown in figure 3, and the curves of power versus voltage at different solar irradiances are shown in figure 4. When solar irradiance is at 1000W/m^2, the curves of current versus voltage at different temperatures are shown in figure 5, and the curves of power versus voltage at different temperatures are shown in figure 6.

Table 1 Parameters of photovoltaic panel 1

U_{oc} V	U_m V	I_{sc} A	I_m A	T_{ref}/°C	S_{ref} (W/m^2)	α (°C)$^{-1}$
22.8	17.6	7.6	6.85	25	1000	0.0025
β/ (W/m^2) $^{-1}$		μ/(°C)$^{-1}$	C_{10}	C_{20}	G_{sh0}	R_{s0}
0.0005		0.00288	0.000014	0.1	0.000125	1

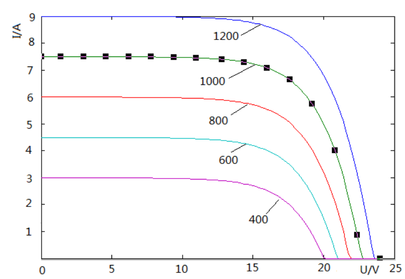

Figure 3 U-I curves under different solar irradiance

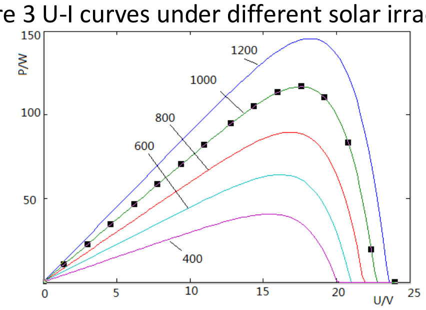

Figure 4 U-P curves under different solar irradiance

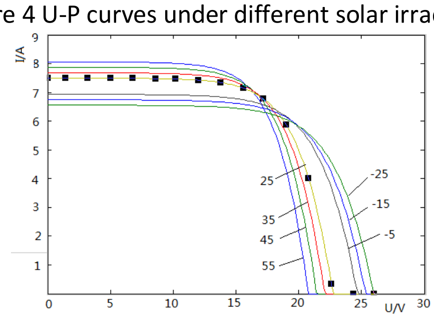

Figure 5 U-I curves under different temperatures

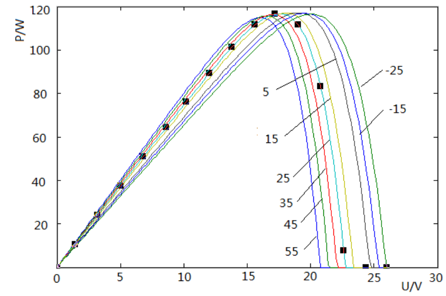

Figure 6 U-P curves under different temperatures

The values of nonlinear parameters under different temperatures and light intensities calculated by the proposed algorithm are partially listed in Table 2.

Table 2 Calculated parameter values of Pho-panel 1

T (°C)	S (W/m^2)	C$_1$	C$_2$	R$_s$	G$_{sh}$
25	1200	7.52E-06	0.08481	0.083713	0.0025
25	1000	6.72E-06	0.08402	0.096755	0.0025
25	800	5.91E-06	0.08313	0.126512	0.0025
25	600	5.4E-06	0.08252	0.154401	0.0025
25	400	4.93E-06	0.08194	0.208255	0.0025
35	1000	6.26E-06	0.08352	0.096169	0.0025
45	1000	7.6E-06	0.08489	0.082082	0.0025
55	1000	7.62E-06	0.08481	0.081956	0.0025

From the above experiment results, it can be seen that the error between the method and the actual measurement value is small, and the result of accurate solution is achieved.

5.2 *Experiment example 2*

In the second experiment example, the value of known parameters and the initial values of four unknown parameters are shown in Table 3. When ambient temperature is at 25°C, the curves of current versus voltage at different solar irradiances are shown in figure 7, and the curves of power versus voltage at different solar irradiances are shown in figure 8. When solar irradiance is at 1000W/m^2, the curves of current versus voltage at different temperatures are shown in figure 9, and the curves of power versus voltage at different temperatures are shown in figure 10.

Table 3 Parameters of photovoltaic panel 2

U_{oc}/V	U_m/V	I_{sc}/A	I_m/A	T_{ref}/°C	S_{ref}/(W/m^2)	α/(°C)$^{-1}$
21.24	18	3.05	2.77	25	1000	0.0025
β/ (W/m^2) $^{-1}$		μ/(°C)$^{-1}$	C_{10}	C_{20}	R_{s0}	G_{sh0}
0.005		0.00288	0.0000015	0.1	1	0.00125

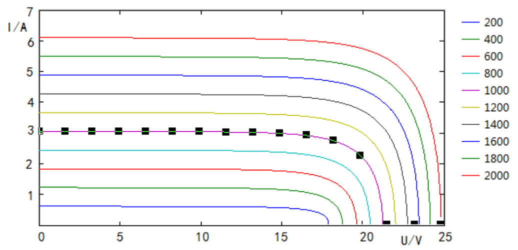

Figure 7 U-I curves under different solar irradiance

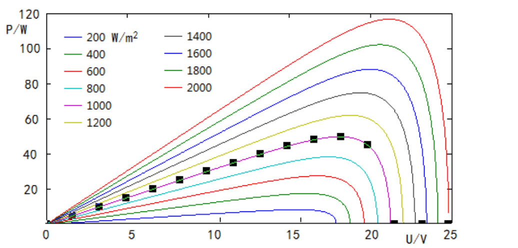

Figure 8 U-P curves under different solar irradiance

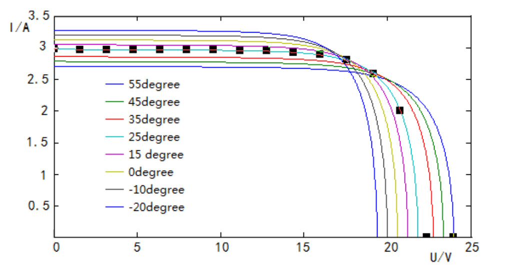

Figure 9 U-I curves under different temperatures

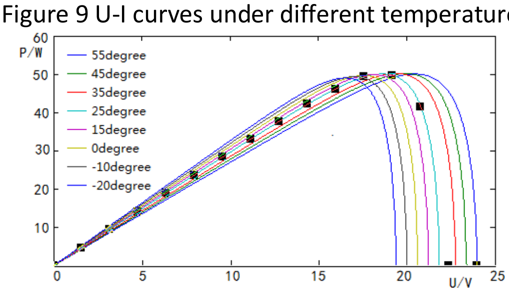

Figure 10 U-P curves under different temperatures

The values of nonlinear parameters calculated by the proposed algorithm are partially listed in Table 4 under different temperatures and light intensities.

Table 4 Calculated parameter values of Pho-panel 2

T (°C)	S (W/m²)	C_1	C_2	R_s	G_{sh}
25	1200	2.26E-05	0.09358	0.59764	0.0025
25	800	1.96E-05	0.09236	0.70528	0.0025
25	600	1.7E-05	0.0912	0.89777	0.0025
35	1000	2.32E-05	0.09377	0.56696	0.0025
45	1000	2.42E-05	0.09416	0.54106	0.0025

The experimental results of the second experimental example further prove the effectiveness of the proposed method.

6. CONCLUSION

In order to ensure the accuracy of photovoltaic cell output power, it is necessary not only to establish an accurate model, but also to obtain accurate model parameters. In this paper, the mathematical model of single-diode photovoltaic cells with four parameters is built, which the original five unknown equations are reduced to four, and the problem that the equation is not easy to obtain is solved. The proposed NRLC method effectively eliminates the disadvantage of NR that does not converge due to the improper selection of the initial value that results in the singularity of the Jacobian matrix. By using the constrained median as the initial value of NULA method, the convergence speed is greatly accelerated. Under the current conditions of photovoltaic panel usage and environment, the accurate solution of nonlinear unknown parameters of solar cell mathematical model can be calculated in real time and quickly. The validity of the method is proven by establishing an experimental model in Matlab / simulink. The experimental results are in accordance with the actual test results of photovoltaic panels. Subsequent research is focused on verifying the feasibility of the method in a multi-diode mathematical model. Secondly, it is necessary to combine the actual test results to conduct feasibility engineering application test on different photovoltaic panels.

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