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Unknown Parameters Extraction and Characteristics Simulation of Photovoltaic Module using 2D-scanning and Datasheet at the Standard Test Condition

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Abstract **Original Research Article**

Single-diode model is found to be more effective for photovoltaic module characterization in terms of computational time and accuracy compared to two-diode or three-diode models. To analyze the output characteristics of photovoltaic cell and module using single diode model, 5-unknown parameters including photo-current, reverse saturation current of diode, diode quality factor, series resistance and parallel resistance (or shunt resistance) have to be extracted. In this paper, we construct the two-dimensional search region with orthogonal basis of series resistance and diode quality factor, and present a mathematical modeling procedure and extraction algorithm for computing the photo current and the reverse saturation current corresponding to each point in the search region. The algorithm was implemented in MATLAB environment to extract the unknown parameters of R.T.C. France silicon photovoltaic cell and STP6-120/36 silicon photovoltaic module, and compare the results with previous extraction. The output characteristics of the mono-crystal silicon photovoltaic module JT100-12M are also presented.

Keywords: Photovoltaic module, Single-diode model, Unknown parameters extraction, 2D-scanning, I-V curve.

1. Introduction

Today, when the global demand for energy is increasing and fossil fuel resource depletion is in the forefront, the active use of renewable energy sources is an important strategic task. Statistics show that oil and natural gas are available for 50 years and coal for 150 years and that, in total, fossil fuels will remain almost unchanged in the 21st century. In addition, with the attempt to abolish coal use by 2040 to prevent global warming, climate change and environmental pollution due to the widespread use of coal, power generation using river-hydro energy, wind energy, solar energy, sea tidal and wave energy, biomass energy, nuclear fission and fusion energy is gaining momentum worldwide. Among them, solar energy utilization plays an important role in reducing greenhouse gas emissions, mitigating climate change, and protecting the ecological environment of humans, animals and plants. Solar energy is the richest source on Earth and the increasing use of solar energy is due to the ever-decreasing rate of conversion efficiency and development costs.

Solar cell characterization is of great significance in evaluating the performance of solar cell and modules and ensuring efficient utilization. The unknown parameters obtained through solar cell characterization and current-voltage curves under given operating conditions are significantly used in the design of solar PV systems, the enhancement of power generation capability, the diagnosis of power system faults, and the optimization of solar array design on satellite. To date, there have been many reports of extracting the unknown parameters of solar cell and modules using analytical, numerical and artificial intelligence techniques and predicting the current-voltage curves related to the operating temperature and solar radiation intensity. The methods for extracting unknown parameters based on analysis and numerical calculations include continuous discretization[1], nonlinear least-squares approximation[2], open-circuit voltage point, short-circuit current point, and algebraic search algorithm using three points of optimum power point[3], Gauss-Seidel algorithm and analytical method[4], and artificial intelligence techniques introduced in recent years. The goal of the updating of the method of unknown parameter extraction of solar cell and module is to reduce the computational burden while reducing the mismatch between the current-voltage simulation curve and the real curve under different conditions. The solar cell power can be modeled by a single diode model, a double diode model, a nd a triple diode model depending on the cell geometry. As the number of diodes in the model increases, the calculation accuracy increases, but long computation time is required. Previous studies have shown that the single diode model is superior to other models in terms of computational accuracy and computational complexity, and is well suited for unknown parameter extraction and current-voltage characteristic plot. We have reduced the fundamental dimension of the optimal solution to two by using the relationship between five unknown parameters, photocurrent and diode reverse saturation current, diode quality factor, series resistance and shunt resistance, for solar cell characterization based on the single-diode model. Generally, the diode quality factor of a solar cell is searched between 1 and 2, and the series resistance is found from 0 to the end of the user-defined value.

In this study, we set the range of search for series resistance from the characteristic parameters of the solar cell and module to the standard conditions, and set the range of search for the idealization coefficient of the diode to be the region of the region centered near the expected values according to the solar cell type. For each point of the square search region set above, the other three parameters were calculated and the current-voltage curve data of the solar cell were obtained from the five unknown parameters calculated as above. The best solution was chosen to find the parameter pair with the smallest error between the obtained current-voltage curve simulation data and the experimental data under the conditions. The algorithm of unknown parameter extraction and characterization described below, first extracts the unknown parameters under the given test conditions by using the initial data of electrical characteristics under certain test conditions (e.g., standard test conditions : 25 °C and AM1.5) of the solar cell, and then calculates the current-voltage simulation curve data under any operating conditions. The reliability of the algorithm was evaluated using the well-known R.T.C France cell and the STP6-120/36 module measurement data. The key point of our proposed method of unknown parameter extraction and characterization is, first, the reduction of the search space dimension from 5D to 2D. For this purpose, the photocurrent, reverse saturation current and shunt resistance are treated as dependent parameters that can be calculated by the series resistance and the diode quality factor. Second, it reduces the computational burden and reduces the computational time by narrowing the search space reasonably. For the sake of computational time reduction, the central value of the diode quality factor search interval was chosen according to the cell geometry, using the maximum value that the series resistance can have from the current-voltage curve and the minimum value of the parallel resistance.

2. Unknown parameters extraction method

Solar cells can be equivalently modeled using a single diode model, a two-diode model, and a three-diode model. As the number of diodes increases, the accuracy of the calculation of the unknown parameters increases, while the computational effort increases. Recent research results have shown that the single diode model is well suited for the uncertain parameter extraction and characterization of photovoltaic module [5-15].

The solar cell and module can be equivalent to the model shown in Fig. 1. The solar module is mainly composed of series connected solar cells for voltage expansion and there are few cases of parallel connection. Taking the diode quality factor of a solar cell module as the product of the number of series-connected cells, we can generally express the relationship between the output current and the output voltage for a solar cell and a module by Eq.(1).

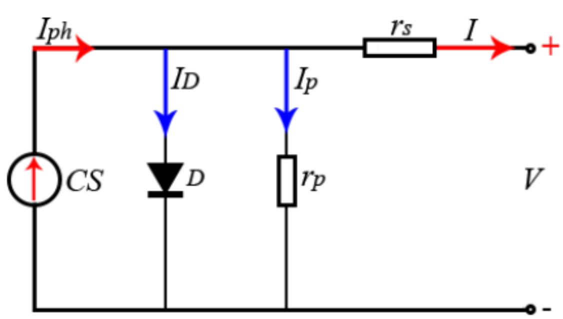

Fig. 1. Single-diode model of photovoltaic cell and module

$$I = I_{PH} - I_{SAT}\left(\exp\left(\frac{q(V+IR_S)}{AN_S kT}\right)-1\right)-\frac{V+IR_S}{R_p} \tag{1}$$

Where:

I : Output current of a solar cell or module (A)

V: Output voltage (V) of a solar cell or module

I_{PH}: Photocurrent of a solar cell or module (A)

I_{SAT}: The reverse saturation current of the diode (A)

A: The diode quality factor (no unit) of the solar cell that constitutes the module

Rs: The series resistance of the module (Ω)

Rp: Parallel resistance of the module (Ω)

Ns: Number of serially connected cells

q: The charge of the electron (C)

k: Boltzmann constant (1.38 e-23J/K)

2.1. Dimensionality Reduction of Unknown Parameters Matrix

Substituting the current and voltage corresponding to the two points A(0, Isc) and B(Voc, 0) of the current-voltage curve into Eq. (1), respectively, we obtain the following equations:

$$I_{SC} = I_{PH} - I_{SAT}\left(\exp\left(\frac{qI_{SC}R_S}{AN_SkT}\right) - 1\right) - \frac{I_{SC}R_S}{R_P} \tag{2}$$

$$0 = I_{PH} - I_{SAT}\left(\exp\left(\frac{qV_{OC}}{AN_SkT}\right) - 1\right) - \frac{V_{OC}}{R_P} \tag{3}$$

From Eqs. (2) and (3), the photocurrent can be expressed in two ways:

$$I_{PH} = I_{SC}\left(1 + \frac{R_S}{R_P}\right) + I_{SAT}\left(\exp\left(\frac{qI_{SC}R_S}{AN_SkT}\right) - 1\right) \tag{4}$$

$$I_{PH} = I_{SAT}\left(\exp\left(\frac{qV_{OC}}{AN_SkT}\right) - 1\right) + \frac{V_{OC}}{R_P} \tag{5}$$

From Eqs. (4) and (5), we have.

$$I_{SC}\left(1 + \frac{R_S}{R_P}\right) + I_{SAT}\left(\exp\left(\frac{qI_{SC}R_S}{AN_SkT}\right) - 1\right) = I_{SAT}\left(\exp\left(\frac{qV_{OC}}{AN_SkT}\right) - 1\right) + \frac{V_{OC}}{R_P} \tag{6}$$

By combining and aligning the reverse saturation current term of the diode in Eq. (6), the expression (7) in terms of open circuit voltage, short circuit current, series resistance and shunt resistance, and diode quality factor is obtained. Substituting Eq. (7) into Eq. (5), Eq. (8) is obtained which shows the relationship between photocurrent, open circuit voltage, short circuit current, diode quality factor, series resistance and shunt resistance.

$$I_{SAT} = \frac{V_{OC} - I_{SC}\left(R_P + R_S\right)}{R_P\left(\exp\left(\frac{qI_{SC}R_S}{AN_SkT}\right) - \exp\left(\frac{qV_{OC}}{AN_SkT}\right)\right)} \tag{7}$$

$$I_{PH}=\left(\exp\left(\frac{qV_{OC}}{AN_SkT}\right)-1\right)\frac{V_{OC}-I_{SC}(R_P+R_S)}{R_P\left(\exp\left(\frac{qI_{SC}R_S}{AN_SkT}\right)\right)}+\frac{V_{OC}}{R_P} \tag{8}$$

From Eqs. (7) and(8), it can be concluded that the photocur rent and the reverse saturation current of the diode among the f ive unknown parameters of the solar cell and module can be ca lculated from the other three parameters, open circuit voltage, s hort circuit current and operating temperature of the cell.

On the other hand, substituting the current and voltage of t he optimal operating point into Eq. (1), we obtain.

$$I_M=I_{PH}-I_{SAT}\left(\exp\left(\frac{q(V_M+I_MR_S)}{AN_SkT}\right)-1\right)-\frac{V_M+I_MR_S}{R_p} \tag{9}$$

Modification of Eq. (9) yields.

$$R_P=\frac{V_M+I_MR_S}{I_{PH}-I_M-I_{SAT}\left(\exp\left(\frac{q(V_M+I_MR_S)}{AN_SkT}\right)-1\right)} \tag{10}$$

Equation (10) shows the relationship between the series res istance and shunt resistance.

Using Eqs. (7), (8), and (10), the other three unknown para meters can be calculated from the series resistance of the solar cell and module and the idealization coefficient of the diode. R ewriting Eqs.(7), (8), and (10) under standard test conditions, t he following system of equations (11) is obtained:

$$\begin{cases} I_{SATN}=\dfrac{V_{OCN}-I_{SCN}(R_{PN}+R_{SN})}{R_{PN}\left(\exp\left(\frac{qI_{SCN}R_{SN}}{A_NN_SkT_N}\right)-\exp\left(\frac{qV_{OCN}}{A_NN_SkT_N}\right)\right)} : (11-A) \\ I_{PHN}=\left(\exp\left(\frac{qV_{OCN}}{A_NN_SkT_N}\right)-1\right)\dfrac{V_{OCN}-I_{SCN}(R_{PN}+R_{SN})}{R_{PN}\left(\exp\left(\frac{qI_{SCN}R_{SN}}{A_NN_SkT_N}\right)\right)}+\dfrac{V_{OCN}}{R_{PN}} : (11-B) \\ R_{PN}=\dfrac{V_{MN}+I_{MN}R_{SN}}{I_{PHN}-I_{MN}-I_{SATN}\left(\exp\left(\frac{q(V_{MN}+I_{MN}R_{SN})}{A_NN_SkT_N}\right)-1\right)} : (11-C) \end{cases} \tag{11}$$

The subscript N in the set of equations (11) means that the values are tested under standard test conditions. The manufactu rer's side delivers the electrical and mechanical parameters of t he solar cell and module measured under standard test conditio ns to the user side. The data measured under standard test cond itions include open circuit voltage, short circuit current, voltag e and current of the optimum operating point, maximum power and duty cycle, cell and module efficiency, temperature change coefficient of open circuit voltage, temperature change coefficient of short circuit current, and cell temperature calculation coefficient (*NOCT*).

$$\begin{cases} R_{PN\_MIN} = \dfrac{V_{MN}}{I_{SCN} - I_{MN}}, (12-A) \\ R_{SN\_MAX} = \dfrac{(V_{OCN} - V_{MN})}{I_{MN}}, (12-B) \end{cases} \quad (12)$$

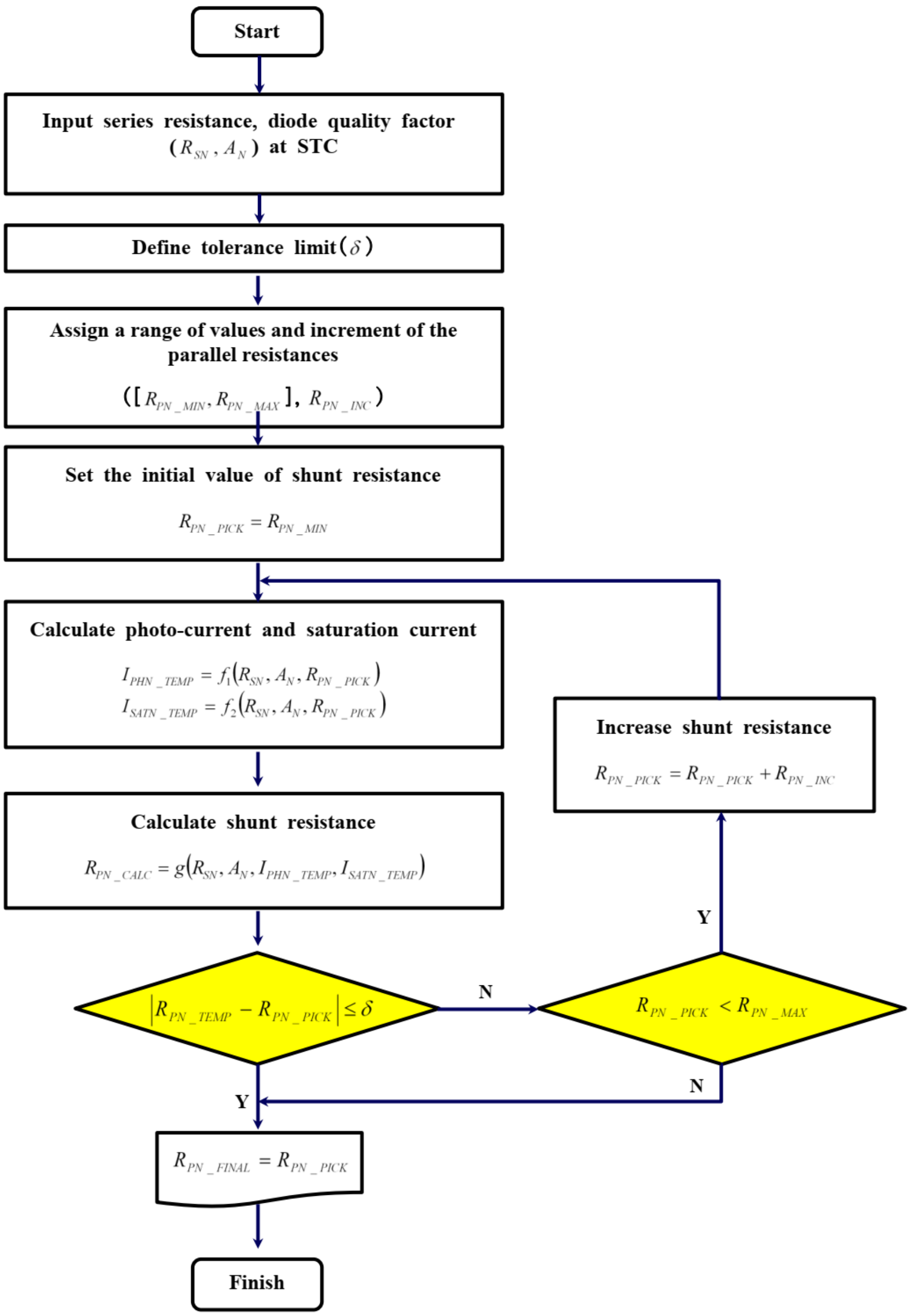

Fig. 2. Algorithm flow diagram for calculating shunt resistance from series resistance and diode quality factor.

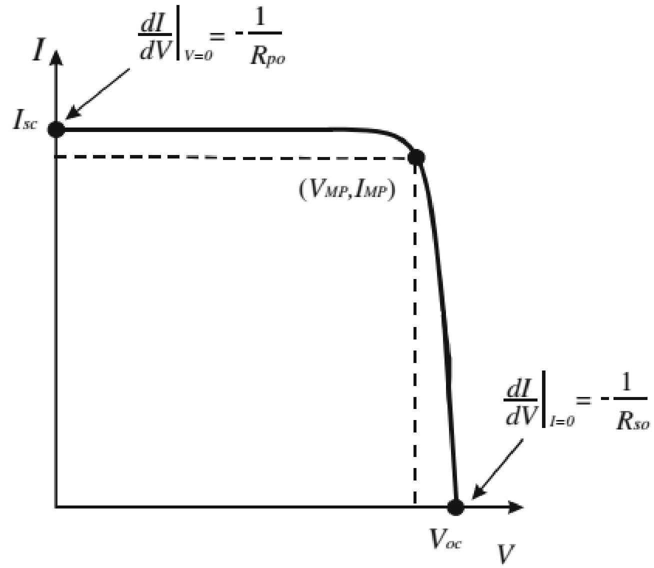

Fig. 3. Relationship between current-voltage curve and parasitic resistance value of solar cell.

Equations (11-A) and (11-B) are the expressions for calcul ating the reverse saturation current and photocurrent of the dio de from the series resistance and shunt resistance of the solar c ell or module and the idealization coefficient of the diode. On t he other hand, as shown in Eq. (11-C), shunt resistance is calcu lated by the photocurrent represented by the shunt resistor itsel f as well as the series resistance and diode quality factor, and t he reverse saturation current of the diode. This relationship sug gests that, given the series resistance and diode quality factor, t he shunt resistance, photocurrent and reverse saturation current calculations of the diode are not straight-line but ring-like. Giv en the series resistance of the solar cell or module and the ideal ization coefficient of the diode, the algorithm flow chart (F) fo r extracting the other three unknown parameters is shown in Fi g. 2. In the flowchart, f1, f2, and g represent Eqs. (11-A), (11-B), and (11-C), respectively. The factors determining the accur acy and time of shunt resistance calculation in the algorithm ar e the minimum, maximum and increment of shunt resistance. T he ideal value of shunt resistance is infinite, but in the simulati on calculations it is usually set to 10000ohms, and the increme nt is chosen according to the accuracy required by the compute r. Figure 3 shows the relationship between the current-voltage c urve of the solar cell and the series resistance and shunt resista nce values. As can be seen from the figure, the series resistanc e and shunt resistance are expressed as the inverse of the value of the derivative of the voltage versus the current at the open-c ircuit voltage point and the short-circuit current point, respecti vely, so that the maximum and minimum values of shunt resist ance can be selected using Eq. (12). In Eq. (12), V_{MN} and I_{MN} a re used as initial data in the calculation of unknown parameters as optimal operating point voltage and current values under no rmal conditions. Using the above algorithm, the diode quality f actor and shunt resistance corresponding to series resistance ar e determined.

2.2. Unknown parameters extraction of photovolta ic module under the standard test condition

Under standard test conditions, the operating temperature o f the solar cell is 25 °C and the atmospheric mass is 1.5 (solar r adiation intensity 1000 W/m^2). The measured electrical parame ters of the solar cell and module under standard conditions and the open-circuit voltage and short-circuit current variation coef ficients with temperature are provided by the manufacturer. Ho wever, the operating environment of solar cells varies with sea son and time, so the current-voltage curve changes. Accurate p rediction of the output characteristics of solar modules and arra ys is an indispensable priority step in the design and managem ent of PV systems. The calculation flow chart for the extractio n of unknown parameters of solar cell modules under normal c onditions is shown in Fig. 4. The green highlighted part in the f lowchart indicates the algorithm F mentioned above.

The maximum value of series resistance is calculated using Eq. (12-B), and the increment value is chosen according to the required calculation accuracy. The diode quality factor values a re generally chosen in the interval (1, 2), but we refer to Table 1. Table 1 gives a rough estimate of the diode quality factor val ues for the solar cell fabrication technique, but it cannot be sai d that the exact value is. Hence, we set up a diode quality facto r search interval centered on the values concluded by the autho rs according to the solar cell topology. The upper and lower bo unds that define the search range were chosen as values norma lly deviated from the central value to ±0.2.

Table 1. Diode quality factor for solar cell types

Fabrication techniques	Diode quality factor
Mono crystal silicon	1.2
Poly crystal silicon	1.3
Single-junction amorphous silicon	1.8
Double-junction amorphous silicon	3.3
Triple-junction amorphous silicon	5
CdTe	1.5
CIS	1.5
GaAs	1.3

In the step, indicated in red in the unknown parameter extr action flowchart shown in Fig. 4, the mean square error of the c alculated current-voltage curve points of a solar cell or module from a given parameter pair using Eq. (13) and the experiment ally measured values is calculated.

$$RMSE = \sqrt{\frac{\sum \left(I_{i\_CAL} - I_{i\_MEASURE}\right)^2}{n}} \tag{13}$$

In Eq. (13), n means the number of measurement points, an d I_{i_CALC} and $I_{i\_MEASURE}$ mean the calculated current and measured current intensities for the same operating voltage, res pectively. Given the unknown parameters of a solar cell or mo dule, one can use either the Newton-Raphson method or the La mbert W function to plot the current-voltage curve. Using Lam bert W function, the current-voltage relationship in the implicit form can be obtained by obtaining the explicit form of the func tion *I=f(V)* to calculate the current intensity at a given voltage. Only Lambert W functions are available in MATLAB environ ment, and in a general C++ environment, the user can override the computational module or implement it through interlocking with MATLAB. The Newton-Raphson method is an approxima te solution that can obtain with high accuracy the solution of e quations that are difficult to solve analytically, and can be appl ied to almost all equations. The point to consider in using the N ewton-Raphson method is that the solution obtained is valid on ly if the initial value of the calculation and the solution are in t he same monotone interval. As shown in Fig. 4, the main facto rs driving the search for unknown parameters are the series res istance and the diode quality factor, which implements the full search in a two-dimensional search space consisting of these t wo parameters.

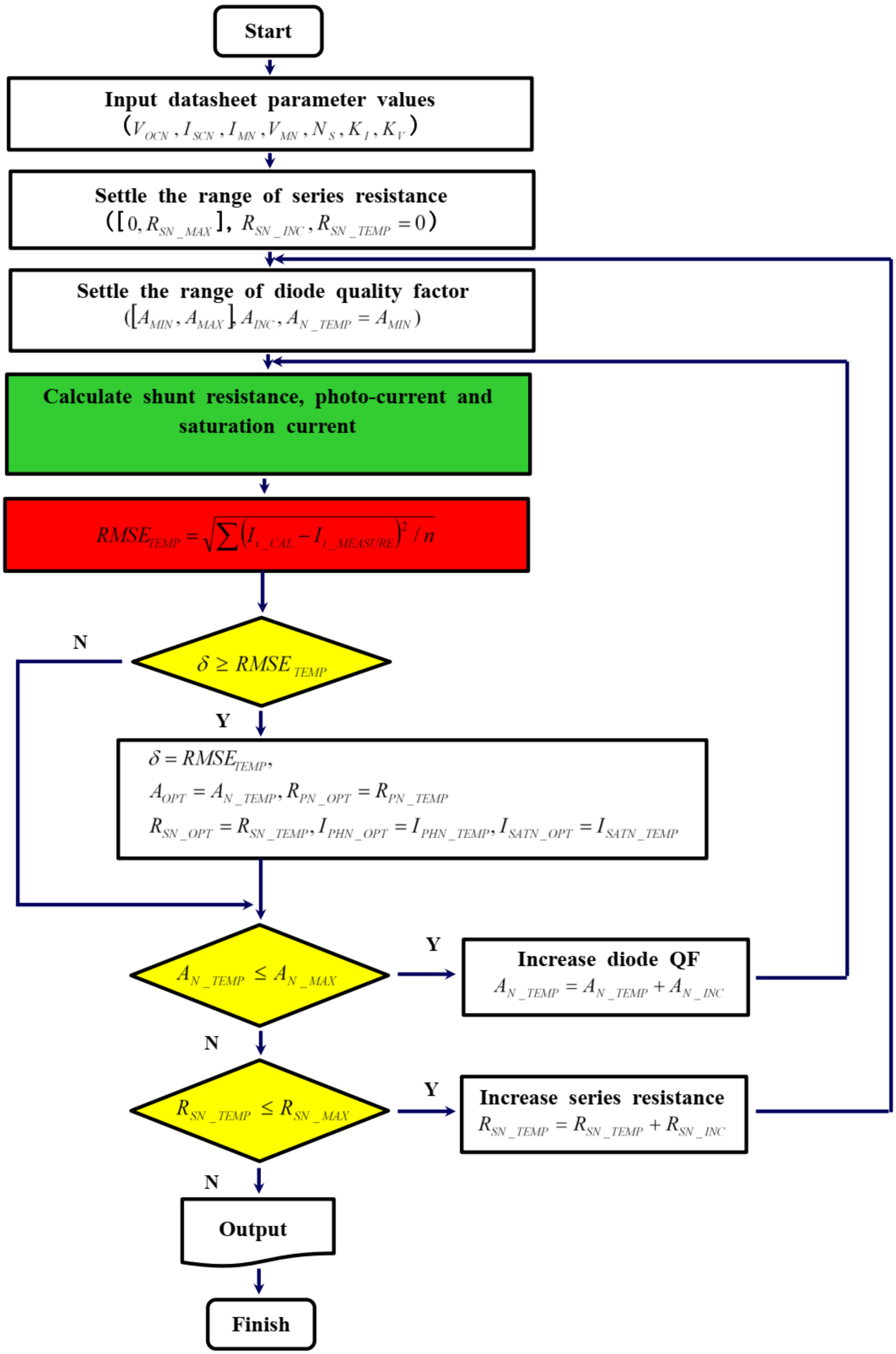

Fig. 4. Unknown parameter extraction flow diagram of solar cell and module at STC

3. Algorithm implementation and results analysis in Matlab environment

According to the calculation flow chart shown in Figs. 2 an d 4, the unknown parameters of the solar cell and module are e xtracted, and the code is written in MATLAB environment to c alculate the current-voltage curve points for any operating con ditions and the results are analyzed.

3.1. Mean square error comparison

To perform a comparative analysis with the previous calcul ation methods, we performed simulation calculations on the R TC France cell and STP6-120/36 module and measured the co mputation time.

The electrical parameters of the RTC France cell and STP6 -120/36 module are shown in Table 3.

Table 3. Electrical characteristics of the R.T.C. France cell and STP6-120/36 module (experimental measurements - 1000 W/m^2)[2]

	R.T.C France Cell(33℃)	STP6-120/36 Module(55℃)
I_{SC} (A)	0.7603	7.48
I_M (A)	0.6894	6.83
V_{OC} (V)	0.5728	19.21
V_M (V)	0.4507	14.93
N_S	1	36

The results of the unknown parameter calculations of the R. T.C. France cell and STP6-120/36 module are shown in Tables 4 and 5, respectively.

The unknown parameters of R.T.C.France cell and STP6-1 20/36 module correspond to the case of 33 °C and 55 °C cell te mperature and 1000 W/m^2 solar radiation, respectively. Fig. 5 s hows the distribution of the mean square error calculated from the current values calculated in the 2D search region and the m easured current values for the R.T.C.France cell.

Table 4. Results of the calculation of the unknown parameters of the R.T.C.France cell and comparison of mean square error

	I_{ph} (A)	I_{sat} (μ A)	A	R_s (Ω)	R_p (Ω)	*RMSE(A)*
2DSCAN	0.76080	0.36118	1.4940	0.0390	52.34974	7.5278e-4
SMA(2021)[17]	0.76079	0.31068	1.51770	0.03655	52.89000	7.7301e-4
SSA(2020)[18]	0.76116	0.8987	1.5900	0.031595	96.9350	2.8726e-3
SDO(2019)[20]	0.7608	0.3230	1.4812	0.03640	53.71850	9.8602e-4
FFO(2020)[16]	0.7608	0.3223	1.5215	0.0364	53.8989	7.75184e-4
LAPO(2020)[19]	0.76071	0.96105	1.5980	0.031142	99.1440	2.9350e-3

In the figure, there is an optimal search point in the region marked with deep blue.

Table 5. Unknown parameter estimation results and mean square error comparison of STP6-120/36 modules

	I_{ph} (A)	I_{sat} (μ A)	A	$R_s (\Omega)$	$R_p (\Omega)$	*RMSE(A)*
2DSCAN	7.4905	2.2016	47.0957	0.1638	1392.2985	1.5706e-2
SMA(2021)[17]	7.4648	2.1907	49.7412	0.1671	1500.000	1.3990e-2
SSA(2020)[18]	7.5035	32.3970	54.9396	0.1032	691.1640	5.6021e-2
SDO(2019)[20]	7.4725	2.3350	45.3636	0.1656	799.9164	1.6601e-2
HISA(2019)[7]	7.4753	1.9309	44.8004	0.1689	570.1977	1.4251e-2
LAPO(2020)[19]	7.5116	2.2000	53.2476	0.1170	1407.9000	4.1306e-2

The minimum value of the mean square error in the search interval is unique, and the corresponding diode quality factor a nd series resistance are 1.490 and 0.390 Ω, respectively.

In the figure, the horizontal axis is the axis of the diode qua lity factor and the vertical axis is the axis of series resistance.

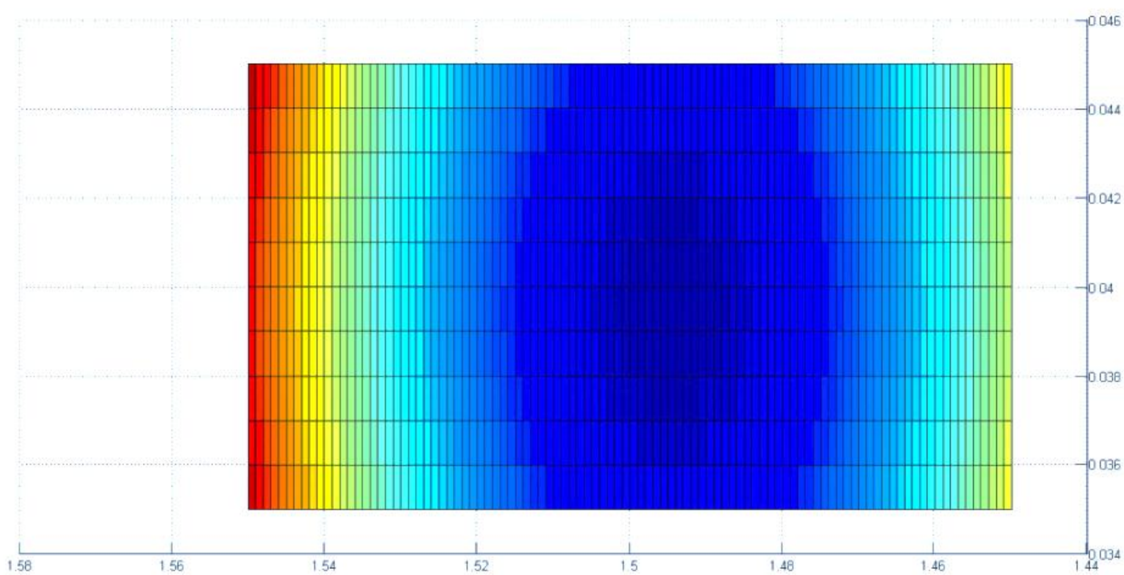

Fig. 5. Mean square error distribution in the 2D search region

3.2. Single-Crystal Silicon Solar Cell Module JT10 0-12M Unknown Parameter Extraction and Outpu t Characterization

The output characteristics change at different temperatures and solar radiation intensities were simulated from the measure d electrical and temperature change characteristics data under t he standard test conditions of the commercial solar cell module JT100-12M. The electrical and temperature variation character istics data given by the manufacturer are shown in Table 6.

To precisely simulate the changes of open circuit voltage a nd short circuit current, current-voltage curve and power-volta ge curve with variation of temperature and solar radiation inten sity, the above five unknown parameters must be extracted firs t. Since there are no current-voltage measurement points data o f the proposed solar cell module, the optimization objective fu nction of the unknown parameter extraction was taken as the m ean square error at the short-circuit current point, open-circuit voltage point, and maximum power point.

Through the simulation, the series resistance of the module is considered to be 0.06Ω, the parallel resistance is 8256.245Ω, and the idealization coefficient of the diode is considered to be 1.2010. Based on this, the current-voltage curve and power-voltage curve are obtained by varying the solar radiation intensity from 200 W/m2 to 1200 W/m2 at the reference temperature, as shown in Fig. 6.

Table 6. Electrical properties and temperature variation data (STC) of single-crystal silicon solar module JT100-12M

Electrical parameters	value
Open-circuit voltage (V_{OC})	22.44V
Short-circuit current (I_{SC})	5.69A
Optimum voltage (V_m)	18.05V
Optimum current (I_m)	5.54A
Number of eries connected cells (N_S)	36
Temperature variation coefficient of open circuit voltage (K_v)	-0.336%/K
Temperature variation coefficient of short circuit current (K_I)	0.042%/K

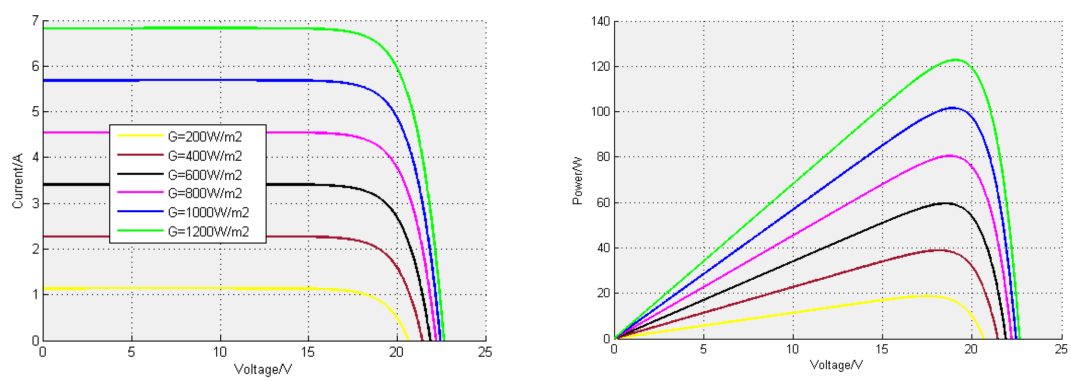

Fig. 6 Current-voltage curve and power-voltage curve of single crystal silicon solar cell model JT100-12M

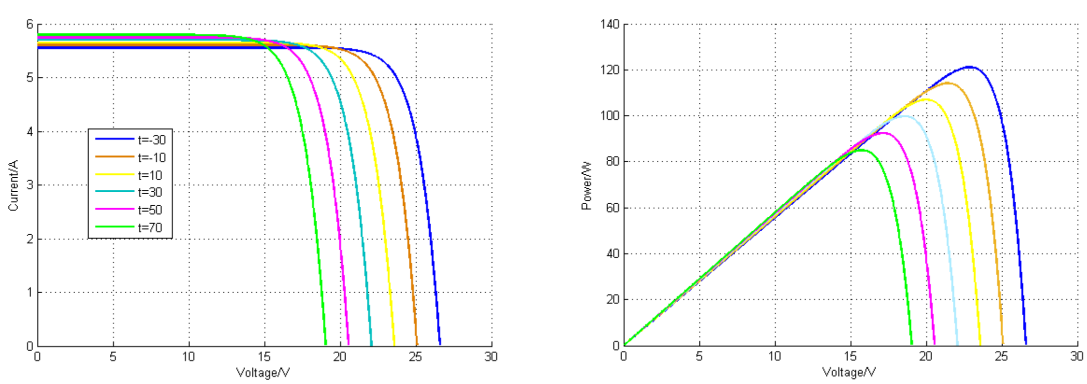

Fig 7. Variation of power curve with temperature variation

It can be seen that when the solar radiation intensity is 1000 W/m 2 and the temperature is changed from -30 to 50 °C, the current-voltage curve and the power-voltage curve change as shown in Fig. 7. As shown in the simulation results, the open circuit voltage of the solar cell increases with increasing solar radiation intensity, with lower temperature, and changes more sensitively with temperature. On the other hand, short-circuit current increases with increasing solar radiation intensity, with higher temperature, and changes sensitively to solar radiation intensity.

As above mentioned, we can extract the unknown parameters of the solar cell and module from the measured electrical characteristics of the solar cell or module under standard test conditions and obtain the current-voltage curve and power-voltage curve under any conditions.

4. Conclusions

In order to make the solar cell and module efficient in various fields such as power generation, temperature measurement and illumination measurement, it is essential to predetermine the unknown parameters such as parasitic resistances and diode quality factor. The number of unknown parameter extraction algorithms introduced to date has reached tens of times and the accuracy and speed of calculation are steadily increasing. The extraction algorithm presented in this paper can be said to have relatively high accuracy of the calculation results, but it has the disadvantage of long computation time. This is due to the fact that the dimensionality of the search space is reduced to two dimensions and the optimal point search is not efficient. However, in this study, we have confirmed the uniqueness of the optimal points in the search space. The goal of the next study is to design an algorithm that can lead to an optimal solution of a projectile starting at any point in the search space and to measure the computational accuracy and time.

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