A novel method for parameter identification combining analytical method and optimization algorithm

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Abstract: Single-diode model is widely used in photovoltaic system modelling and output estimation because of its simplicity and accuracy. This paper proposed a novel method for parameter identification and performance estimation by using measured data. The proposed method combines the analytical method and optimization algorithm to extract the model parameters and considers the deviations of different operating conditions between the measured and estimated data in calculation procedure, which reduces the dimensions of the search space and save computational cost for parameter optimization. The accuracy and effectiveness of the proposed method are validated by large number of experimental data under wide range environmental conditions.

1. Introduction

Solar energy has become an indispensable part of the energy system and is viewed as one of the most potential energies due to its clean, efficient and renewable. Most solar power comes from photovoltaics (PV) modules that turn sunlight directly into electricity. Therefore, the accurate modeling of PV modules is essential to understand and predict how PV devices operate under varying operating conditions [1].

Single-diode model (SDM) has been widely used to rebuilt the current-voltage (I-V) characteristics of PV module due to its simplify and good accuracy, which contains five parameters, photo-generated current $I_{ph}$, ideality factor $n$, reverse saturation current $I_0$, series resistance $R_s$ and shunt resistance $R_{sh}$. Normally, for a given temperature and irradiance condition, their values can be obtained through a set of transformation equations which are functions as reference values and environmental conditions [2, 3]. However, the five parameters cannot be directly measured from the PV module and the temperature and irradiance dependence of SDM’s parameters are uncertain. Instead, the characteristic parameters short circuit (SC) current $I_{sc}$, open circuit (OC) voltage $V_{oc}$, maximum power point (MPP) current $I_m$ and voltage $V_m$ have been studied thoroughly in literatures due to the ease of direct measurement [2, 4]. Thus, the temperature and irradiance dependence of the characteristic parameters are clearer than that of SDM’s parameters and the performance of the PV module is mainly represented by these parameters which can be used in parameters identification. Moreover, the SDM’s parameters can be extracted from an I-V curves accurately taking advantages of the optimization algorithms under a specific operating condition. However, few works studied the parameters identification using the optimization algorithms under varying operating conditions.

In this study, a novel method based on SDM was proposed for the parameters identification and performance estimation from measured I-V data under varying operating conditions. The analytical and
optimization algorithm are combined in parameter extraction. By using analytical derivation from I-V equations at SC, OC and MPP, it reduces the dimensions of the search space and save computational cost for parameter optimization. In addition, the deviation of massive experimental data under a wide range of environmental conditions between estimated and measured data are used for parameter identification, which improves the accuracy. The accuracy and effectiveness of the proposed method are validated by large number of experimental data under varying operating conditions.

2. Proposed method
The equivalent circuit of SDM is shown in Figure. 1, which I-V equations can be expressed as:

\[ I = I_{ph} - \frac{V + IR_s}{R_{sh}} - I_0 \left[ \frac{V + IR_s}{e^{\frac{N_{th}}{kT}} - 1} \right] \]  

(1)

\[ V_{th} = \frac{kT}{q} \]  

(2)

Where \( k \) and \( q \) are the Boltzmann constant and the charge of a single electron, which is given by \( k=1.381 \times 10^{-23} \text{J/K} \), and \( q=1.602 \times 10^{-19} \text{C} \).

As shown in Eq. (1), the output characteristic is determined by the five unknown parameters \( I_{ph}, I_0, R_s, R_{sh}, n \). With the aim to identify these parameters, amount of works are carried out considering the particular points corresponding to SC, OC, MPP of the I-V characteristic [2, 3, 5]. At SC points, Eq. (1) can be expressed as:

\[ I_{sc} = I_{ph} - I_0 \left[ \frac{I_{sc}R_s}{e^{\frac{N_{th}}{kT}} - 1} \right] - \frac{I_{sc}R_s}{R_{sh}} \]  

(3)

At OC points, Eq. (1) can be expressed as:

\[ 0 = I_{ph} - I_0 \left[ \frac{V_{oc}}{e^{\frac{N_{th}}{kT}} - 1} \right] - \frac{V_{oc}}{R_{sh}} \]  

(4)

At MPP points, Eq. (1) can be expressed as:

\[ I_m = I_{ph} - I_0 \left[ \frac{V_m + l_m R_s}{e^{\frac{N_{th}}{kT}} - 1} \right] - \frac{V_m + I_m R_s}{R_{sh}} \]  

(5)

With these three independent equations, the number of unknown parameters can be reduced from five to two. Following the study in [3], \( I_{ph}, I_0 \) and \( R_{sh} \) can be expressed as:

\[ I_{ph} = \frac{I_{sc} V_{oc}(\exp_{mpp} - 1) + V_m I_{sc}(1 - \exp_{oc})}{A_1 \exp_{sc} + A_2 \exp_{mpp} + A_3 \exp_{oc}} \]  

(6)

\[ I_0 = \frac{A_1 \exp_{sc} + A_2 \exp_{mpp} + A_3 \exp_{oc}}{V_{oc}(I_{sc} - I_{m}) - V_m I_{sc}} \]  

(7)

\[ R_{sh} = \frac{A_1 \exp_{sc} + A_2 \exp_{mpp} + A_3 \exp_{oc}}{\exp_{oc}(I_m - I_{sc}) + \exp_{mpp} I_{sc} - \exp_{sc} I_m} \]  

(8)

Where \( \exp_{sc}, \exp_{mpp}, \exp_{oc} \) and \( A_1, A_2, A_3 \) are represented as:
\[
\exp_s \frac{I_{sc}R_s}{V_{oc}} = e^{\frac{V_{oc}}{N_{th}V_{th}}} \exp_{oc} = e^{\frac{V_{m}+I_{m}R_s}{N_{th}V_{th}}} \exp_{mp} = e^{\frac{V_{m}+I_{m}R_s}{N_{th}V_{th}}}
\]
\[
A_1 = V_m + I_mR_s - V_{oc}A_2 = V_{oc} - I_{sc}R_s, A_3 = I_{sc}R_s - V_m + I_mR_s - V_m
\]

As shown in Eqs. (3)-(5), \( I_{oc} \), \( I_{m} \), and \( R_{sh} \) are functions of \( n \), \( R_s \), \( I_{sc} \), \( V_{oc} \), \( I_m \) and \( V_m \). It has been reported that \( n \), \( R_s \) are insensitive to irradiance and temperature [6], thus, which values are considered as constant for varying operating conditions. The transformation equations of \( I_{sc} \), \( V_{oc} \), \( I_m \) and \( V_m \) are reported in [2, 6], which are given as:

\[
I_{sc} = I_{sc,ref}(E_e)x_{isc}[1 + \alpha_{isc}(T - T_{ref})]
\]
\[
V_{oc} = V_{oc,ref} + \beta_{voc}(T - T_{ref}) + k_{voc}N_sV_{th} \log E_e
\]
\[
I_m = I_{m,ref}[C_0 E_e + C_1 E_e^2][1 + \alpha_{im}(T - T_{ref})]
\]
\[
V_m = V_{m,ref} + C_2 N_sV_{th} \ln E_e + C_3 N_s[V_{th} \ln E_e]^2 + \beta_{vm}E_e(T - T_{ref})
\]

Where \( x_{isc} \) is the optimal index of \( \frac{g}{s_{ref}} \); \( \beta_{voc} \) and \( k_{voc} \) are the temperature and irradiance coefficients of \( V_{oc} \), respectively; \( C_{0-3} \) represent the irradiance coefficients of \( I_m \) and \( V_m \), \( \alpha_{im} \) and \( \beta_{vm} \) are the temperature coefficients of \( I_m \) and \( V_m \), respectively and \( E_e = \frac{g}{s_{ref}} \). In the following study, \( n \), \( R_s \) and all the temperature and irradiance coefficients can be extracted by fitting a large number of measured data.

3. Simulation process

In order to obtain \( n \), \( R_s \) and the coefficients of \( I_{sc} \), \( V_{oc} \), \( I_m \) and \( V_m \), the measured I-V data under different environmental conditions are used. The operating data should cover a wide range of environmental conditions as far as possible to obtain accurate results.

In the first step, the coefficients of \( I_{sc} \), \( V_{oc} \), \( I_m \) and \( V_m \) are obtained by fitting the measured data at SC, OC and MPP. Some functions of MATLAB such as “lsqnonlin” can be used. In the second step, \( n \) and \( R_s \) can be extracted by fitting a large number of I-V curves through some optimization algorithms. Thus, a powerful optimization algorithm named guaranteed convergence particle swarm optimization (GCPSO) [7] is applied in this study. \( n \) and \( R_s \) are optimized by minimizing the deviations between the measured and estimated I-V curves under varying operating conditions. The average root mean square error (RMSE) of optimizing I-V curves is adopted as follows.

\[
\text{RMSE} = \frac{\sum_{j=1}^{N_j} \left( \frac{\sum_{i=1}^{N_{ij}} (I_{(j,i)} - I(V_{(j,i)},I_{(j,i)}))^2}{N_{ij}} \right)^{\frac{1}{2}}}{N_j}
\]

Where \( I_{(j,i)} \) and \( I(V_{(j,i)},I_{(j,i)}) \) are the measured and estimated current of \( i \)th point on \( j \)th I-V curve, respectively; \( N_{ij} \) denotes the number of empirical points on \( j \)th I-V curve; \( N_j \) denotes the number of measured I-V curves.

4. Results and discussion

With the aim to validate the accuracy of proposed method, a large number of measured I-V data for the multi-crystalline (mSi) PV module provided by the National Renewable Energy Laboratory (NREL) are used in this study, which incorporate a wide range of environmental condition. The specification for mSi0166 are listed in Table 1 and the values of \( I_{sc} \), \( V_{oc} \), \( I_m \) and \( V_m \) are measured at Stand Test Condition (STC), 1000 W/m², 25 ℃, AM1.5, provided by manufacturer.

| PV modules | Series cells | Location | #Curves | \( I_{sc} \) (A) | \( V_{oc} \) (V) | \( I_m \) (A) | \( V_m \) (V) |
|-----------|-------------|----------|---------|----------------|--------------|-------------|-------------|
| mSi0166   | 36          | Cocoa    | 36765   | 2.65994        | 22.0341      | 2.44501     | 17.9879     |

4.1. Parameters extraction of proposed method

100 I-V curves are used to extract the parameters in this study and the results are shown in Table 2. In
addition, the estimated results of $I_0$, $V_0$, $I_m$ and $V_m$ using Eqs. (11)-(14) versus the measured data are depicted in Figure. 2. The solid line represents the proportional function. All the blue dots have great agreement with the solid line, which indicates the good accuracy of the estimated results.

**TABLE 2 THE OPTIMAL PARAMETERS OF PROPOSED METHOD**

| Parameters | Value          | Parameters | Value          |
|------------|---------------|------------|---------------|
| $a_{I_{EC}}$ (A/K) | 3.182e-3     | $a_{I_{EC}}$ (A/K) | 3.932e-4     |
| $x_{I_{EC}}$ | 1.006         | $C_2$      | 0.3664        |
| $\beta_{V_{EC}}$ (V/K) | -0.0715     | $C_3$      | -11.18        |
| $k_{I_{EC}}$ | 1.176         | $\beta_{V_{IN}}$ (V/K) | -0.0699    |
| $C_0$      | 0.9597        | $n$        | 1.3171        |
| $C_1$      | 0.0539        | $R_s$ (Ω) | 0.1976        |

Figure. 2 Estimated (a) $I_{EC}$, (b) $V_{EC}$, (c) $I_m$, (d) $V_m$ vs measured data for mSi0166

4.2. Performance estimation under different operating conditions

In order to test the performance estimation of I-V characteristic under different operating conditions, five different irradiance and temperature conditions are selected, which are shown in Table 3. For comparison, the estimated results of Laudani et al. [3]’s and Batzelis et al. [5]’ method are adopted in this study. The measured and estimated I-V and P-V curves are depicted in Figure. 3. The estimated results of both I-V and P-V curves for proposed method show great agreement with the measured data. However, the methods of Laudani and Batzelis have a big deviation in the range where the current drops sharply, especially in the low irradiance ranges. The results indicates the good performance in the estimation of I-V characteristic for proposed method.

Moreover, the RMSE of 36765 I-V curves for three methods are calculated and listed in Table 4. The RMSE of proposed method is 0.0327 A which is reduced by 34.9% and 35.1% in comparison with that of Laudani’s method (0.0502 A) and Batzelis’ method (0.0504 A), respectively. The results demonstrates the great improvement of proposed method in the estimation of I-V characteristic under varying operating conditions.

**TABLE 3 IRRADIANCE AND TEMPERATURE OF DIFFERENT OPERATING CONDITIONS**

| Condition | C1 | C2 | C3 | C4 | C5 |
|-----------|----|----|----|----|----|
| Irradiance (W/m²) | 202.5 | 392.3 | 617.3 | 818.1 | 996.7 |
| Temperature (℃) | 24.1 | 24.2 | 30.4 | 42.3 | 42.3 |

Figure. 3. Comparison of (a) I-V, (b) P-V characteristic of three methods under five operating conditions.
TABLE 4 RMSE FOR THREE METHODS

| Method        | Laudani’s | Batzelis’ | Proposed |
|---------------|-----------|-----------|----------|
| RMSE (A)      | 0.0502    | 0.0504    | 0.0327   |

Figure. 4. The estimated and measured output power of proposed method during the week.

4.3. Output power estimation under a week
With the aim to validate the performance of proposed method in the estimation of output power, the proposed method is applied to output power in a week. The measured data was recorded from 6:00 in the morning to 18:00 in the afternoon during the week, which incorporates a wide range of temperature and irradiance conditions. The estimated and measured output power during the week are depicted in Figure. 4. The estimated data have great agreement with the measured data, which indicates the great performance of the proposed method in terms of the estimation of output power.

5. Conclusion
In this work, a novel method based on SDM was proposed for the parameters identification and performance estimation from measured I-V data under varying operating conditions. The proposed method shows great accuracy in terms of the estimation of I-V characteristic and output power under varying operating conditions, comparing with the results estimated by Laudani’s and Batzelis’ methods. The great accuracy and ease of implement of proposed method make it useful to calculate the real performance of PV module and track its maximum power under changing conditions.

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