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Differential Evolution Algorithm for Extracting Photovoltaic Parameters of Solar Cell Models

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ABSTRACT:The solarcell industry has grown rapidly with the ability to mass-produce photovoltaic panels at low prices for solar power generation. One of the essential information to evaluate the performance of the solar cell is the photovoltaic parameters, which consist of photocurrent current, saturation current, ideality factor, series resistance, and parallel resistance. In order to obtain accurate photovoltaic parameters, it is necessary to solve complex nonlinear mathematical equations. In this study, the differential evolution (DE) algorithm optimization method is used to extract the photovoltaic parameters of the RTC France solar cell. Furthermore, the Root Mean Square Error (RMSE) method is employed to determine the level of accuracy of the computation results. The results show that DE gives relatively low RMSE for both the single-diode model and the double-diode model. In addition, the current-voltage (I-V) curve and the power-voltage (P-V) curve also show very small differences between the calculated and experimental results

KEYWORDS: Differential Evolution, Optimization Algorithm, I-V Characteristics, Photovoltaic Parameters,Solar Power Generation.

I.INTRODUCTION

Solar energy is one of the best options for renewable energy resources to meet electricity demand in the future [1]. The construction of solar power generation is increasing every year because of the availability of solar energy, which is abundant in nature, environmentally friendly, and does not depend on fossil fuels. In addition, the advantages of solar power generation are they require an easy and fast installation process, long project lifetime, and does not require much maintenance during operation. Accurate photovoltaic parameters extraction of a solar cell is vital for the performance assessment of solar power systems. The photovoltaic parameters reproduce the current-voltage (I-V) curve of the solar cell.The photovoltaic parameters also affect to maximum power generated by a solar cell. However, the photovoltaic parameters should be obtained by solving the complex nonlinear mathematical equations, which is sensitive to the variations of solar irradiance and temperature [2], [3].

The mathematical model of I-V characteristics has a vast number of unknown variables. However, the single-diode model and the double-diode model can provide effective I-V results with a relatively high level of accuracy [4]. The single-diode model is the simplest I-V model and needs only five unknown parameters, while the double-diode model requires seven parameters. The accuracy of the single-diode model is decreased when the intensity of solar radiation conditions are low at open-circuit voltages because the single-diode model neglects recombination losses [5]. This problem can be solved by adding one diode to the double diode model because the additional diode brings back recombination losses previously neglected in the single-diode model. The photovoltaic parameters in the single-diode model and the double-diode model are the optimization problems that must be computed. There are generally two ways to solve these problems, i.e., the mathematical optimization method and the stochastic optimization method. Mathematical optimization methods usually use numerical techniques; for example, the Newton-Raphson algorithm [6]. However, mathematical methods are easily trapped in local optimums [7] and diverge more frequently when dealing with complicated nonlinear optimization equations. Therefore, to solve complex optimization problems, the stochastic optimization method is preferable. The stochastic optimization method can avoid local optimum points because it uses the mechanism of releasing agents randomly into the searching space [8].

In [9], [10], the authors used genetic algorithm (GA) to compute parameters of the solar cell. The single-diode and double-diode models were evaluated by using the manufacturer data sheet information. The downside of the reported results was a relatively high percentage of error related to the extracted parameters. In [11] particle swarm optimization (PSO) was applied to estimate the parameters of the solar cell from current-voltage characteristics. The performance of the PSO was compared with the GA for the single-diode and double-diode models. The results showed that photovoltaic parameters obtained by PSO were more accurate than GA method. In [12] authors used simulated annealing (SA) based approach to estimate solar cell model parameters. The SA algorithm has proved its effectiveness in the optimal estimation of solar cell model parameters. However, it is still challenging to investigate accurate and reliable solutions for parameters of the solar cell. In this study, a differential algorithm is proposed to extracted the photovoltaic parameters of single-diode and double-diode models. The experimental data of solar cell is adopted from [13], consisting of 26 pairs of voltage and current values of the RTC France cell under irradiance of 1000 W/m2 and temperature of 33˚C.

II.PHOTOVOLTAIC MODELS

The single-diode model consists of a current source, diode, series resistance, and parallel resistance, as shown in Fig. 1(a). The diffusion current can be calculated as follows:

$$I_d = I_o\left\{exp\left[\frac{(V+IR_S)}{AV_{th}}\right] - 1\right\} \quad (1)$$

Based on the equivalent circuit in Fig. 1, the photovoltaic output current can be calculated by using:

$$I = I_{PV} - I_o\left\{exp\left[\frac{(V+IR_S)}{AV_{th}}\right] - 1\right\} - \frac{V+IR_S}{R_p} \quad (2)$$

In eq. (2), I_{PV} is the photocurrent current, I_o is the reverse saturation current, A is the ideality factor, V is the photovoltaic output voltage, I is the photovoltaic output current, and V_{th} is the thermal voltage, which is defined as

$$V_{th} = N_s kT/q \quad (3)$$

The number of photovoltaic cells connected in series is denoted as N_s, while k is the Boltzmann constant ($k = 1.38\text{x}10^{-23}$ J /K), q is the electron charge ($q = 1.6\text{x}10^{-19}$ C), and T is solar cell junction temperature.

Different from the single-diode model, the double-diode model has two diodes in the equivalent circuit, as shown in Fig. 1(b). In the double-diode model, the recombination current is taken into account. Thus, in the double-diode model, there is a diffusion current due to the majority carrier (I_{d1}) and a recombination current due to the minority carrier (I_{d2}), each of which can be calculated as follows:

$$I_{d1} = I_{o1}\left\{exp\left[\frac{(V+IR_S)}{A_1V_{th}}\right] - 1\right\} \quad (4)$$

$$I_{d2} = I_{o2}\left\{exp\left[\frac{(V+IR_S)}{A_2V_{th}}\right] - 1\right\} \quad (5)$$

In eqs. (4) and (5), I_{o1} is the reverse saturation current due to the diffusion phenomenon, I_{02} is the reverse saturation current due to the recombination phenomenon, while A_1 is the diffusion ideality factor and A_2 is the recombination ideality factor. Thus the photovoltaic panel output current is

$$I = I_{PV} - I_{o1}\left\{exp\left[\frac{(V+IR_S)}{A_1V_{th}}\right] - 1\right\} - I_{o2}\left\{exp\left[\frac{(V+IR_S)}{A_2V_{th}}\right] - 1\right\} - \frac{V+IR_S}{R_p} \quad (6)$$

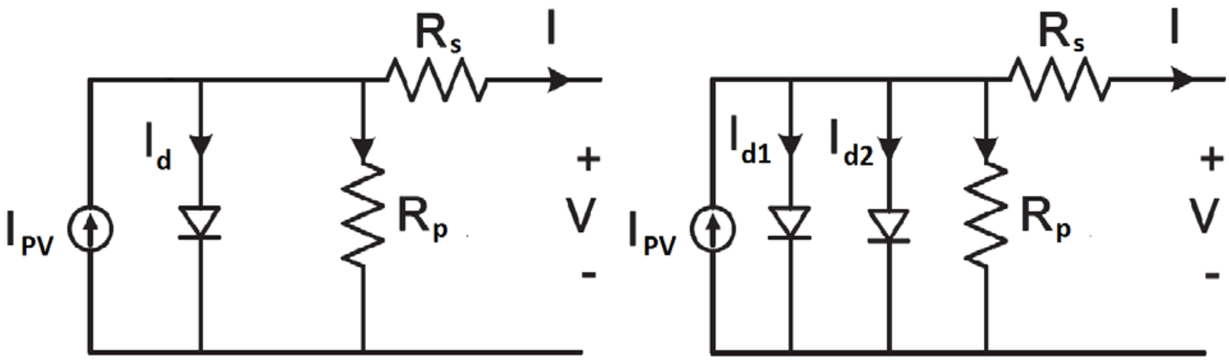

Fig. 1 (a) Single-diode model, (b) Double-diode model

In this study, the root mean square error (RMSE) method [14] is used to describe the objective function. The RMSE method is a method that compares the difference between experimental and estimated values. Thus, the objective function for the photovoltaic model problem is expressed as:

$$\mathcal{E} = \sqrt{\frac{1}{N}\sum_{k=1}^{N} f_k(V, I, \emptyset)} \quad (7)$$

where N is the number of sample experimental data, V and I are the photovoltaic output voltage and current, and $\emptyset$ is a vector containing the parameters to be calculated.

III. DIFFERENTIAL EVOLUTION ALGORITHM

The DE algorithm basically has two types of control parameters: mutation factor (F) and crossover rate (CR), which control perturbance and accelerate convergence in the optimization process. The values for these two parameters are in the range between 0 and 1. The DE algorithm applied to optimize the photovoltaic parameters for the single-diode model, and the double-diode model is shown in Algorithm 1. The first step of the algorithm is to create an initial generation of the population.

$$\phi_{i,j}^{(1)} = \phi_{minj} + rand_j\left(\phi_{maxj} - \phi_{minj}\right) \tag{8}$$

where ϕ_{minj} and ϕ_{maxj} are the lower and upper limits of ϕ, randj$\in$ [0, 1], j = 1, 2,…, N; i = 1, 2,…, NP, and NP are the population sizes.

Algorithm 1: Pseudocode DE

generate initial population
evaluate thepopulation
definea counter G = 1
while (criterianot met) **do**
perform mutation and recombination
perform selection
increase the counter G = G + 1
end **while** loop
yield a satisfactory ϕ

The next stage is to evaluate the population to determine which of the ϕ in the current generation are the best candidates to meet the predetermined criteria.

$$f_{bestj}^{(1)} = f(V, I, \phi_{bestj}^{(1)}),\ \phi_{bestj}^{(1)} \in \phi_{i,j}^{(1)} \tag{9}$$

New individuals are produced through mutation and recombination processes. Mutation and recombination operators are used to increase population diversity and to achieve faster convergence. Mutation operation is responsible for producing mutant individuals, while recombination operation is for creating individual trials.
The mutation and recombination processes are shown in Algorithm 2. In the mutation process, the indices *ra*, *rb*, *rc*, *rd*, and *re* are five mutually distinctive integers drawn randomly from {1, 2, 3,…,NP}. In addition, the integers *i*, *ra*, *rb*, *rc*, *rd*, and *re* must be unequal.

Algorithm 2: Mutation and Recombination Operations

for j = 1 to N
if ($rand_j^{(G)} \leq CR^{(G)}$) **or** ($j = j_{rand}$)
$t_{i,j}^{(G)} = \phi_{ra,j}^{(G)} + F(\phi_{rb,j}^{(G)} - \phi_{rc,j}^{(G)}) + F(\phi_{rd,j}^{(G)} - \phi_{re,j}^{(G)})$
else $t_{i,j}^{(G)} = \phi_{i,j}^{(G)}$
end **if**
end **for**

The selection process is performed by Algorithm 3. In the selection process, individual trials ($t_{i,j}$) are the best for the next generation if they provide the objective function value which is equal to or less than the objective function value produced by their parent.

Algorithm 3: Selection Process

for i = 1 to NP
if $f(t_{i,j}^{(G)}) \leq f(\phi_{i,j}^{(G)})$
$\phi_{i,j}^{(G+1)} = t_{i,j}^{(G)}$
else $\phi_{i,j}^{(G+1)} = \phi_{i,j}^{(G)}$
end **if**
$f_{best}^{(G+1)} = f(\phi_{i,j}^{(G+1)})$
end **for**

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IV. RESULT AND DISCUSSION

Voltage and current experimental data of the RTC France cell at a temperature of 33˚C and solar irradiance of 1000 W/m^2 are presented in Table 1. The single-diode model has five parameters to be extracted. To extract the photovoltaic parameters of the single-diode model, the DE algorithm used the typical design space:I_{PV} = {0, 1} A, I_o = {0, 1} µA, A = {1, 2}, R_S = {0, 0.5} Ω, and R_P = {0, 100} Ω.For the double-diode model, there are seven parameters that must be extracted. The more parameters indicate the higher the level of difficulty in calculating photovoltaic parameters. The DE algorithm used the typical design space for the double-diode model:I_{PV} = {0, 1} A, I_{o1} = {0, 1} µA, I_{o2} = {0, 1} µA, A_1 = {1, 2}, A_2 = {1, 2 }, R_S = {0, 0.5} Ω, and R_P = {0, 100} Ω.

Tabel 1. The RTC France Cell Data

Item	Experimental Data		
	V **(V)**	***I*** **(A)**	***P*** **(W)**
1	-0.2057	0.7640	-0.1572
2	-0.1291	0.7620	-0.0984
3	-0.0588	0.7605	-0.0447
4	0.0057	0.7605	0.0043
5	0.0646	0.7600	0.0491
6	0.1185	0.7590	0.0899
7	0.1678	0.7570	0.1270
8	0.2132	0.7570	0.1614
9	0.2545	0.7555	0.1923
10	0.2924	0.7540	0.2205
11	0.3269	0.7505	0.2453
12	0.3585	0.7465	0.2676
13	0.3873	0.7385	0.2860
14	0.4137	0.7280	0.3012
15	0.4373	0.7065	0.3090
16	0.4590	0.6755	0.3101
17	0.4784	0.6320	0.3023
18	0.4960	0.5730	0.2842
19	0.5119	0.4990	0.2554
20	0.5265	0.4130	0.2174
21	0.5398	0.3165	0.1708
22	0.5521	0.2120	0.1170
23	0.5633	0.1035	0.0583
24	0.5736	-0.0100	-0.0057
25	0.5833	-0.1230	-0.0717
26	0.5900	-0.2100	-0.1239

Table 2 presents the statistical *RMSE* value of the single-diode model and the double-diode model. The parameters of the RTC France cell were calculated using the DE algorithm with 30 trials. The statistical values evaluated consist of the minimum (min), maximum (max), average (mean), and standard deviation (sd) *RMSE* values.

Tabel 2. The Statistical Results

	Single-Diode Model	**Double-Diode Model**
I_{PV} (A)	0.7608	0.7608
I_{o1} (µA)	0.3230	0.3756
I_{o2} (µA)	-	0.2715
R_S (Ω)	0.0364	0.0366
R_P (Ω)	53.7185	54.5704
A_1	1.4812	1.9999
A_2	-	1.4664
RMSE MIN	9.8602E-04	9.8344E-04
RMSE MAX	1.5686E-03	1.4490E-03
RMSE MEAN	1.1224E-03	1.0150E-03
RMSE SD	1.3800E-04	7.8100E-05
Iteration	20000	30000

From the data in Table 2, the results on the double-diode model, regarding the min, max, mean, and standard deviation *RMSE* are better than the single-diode model. This shows that the double-diode model gives a better level of accuracy than the single-diode model, although the double-diode model requires a higher number of iterations than the single-diode model.Figure 2 shows that the convergence process of the DE algorithm in finding photovoltaic parameters for the single-diode model and the double-diode model. The DE algorithm obtains photovoltaic parameters of the single-diode model faster than of the double-diode model. The single-diode model converges more quickly than the double-diode model. The single-diode model achieves convergence in 20000 iterations, while the double-diode model requires 30000 iterations for convergence to find the photovoltaic parameters.

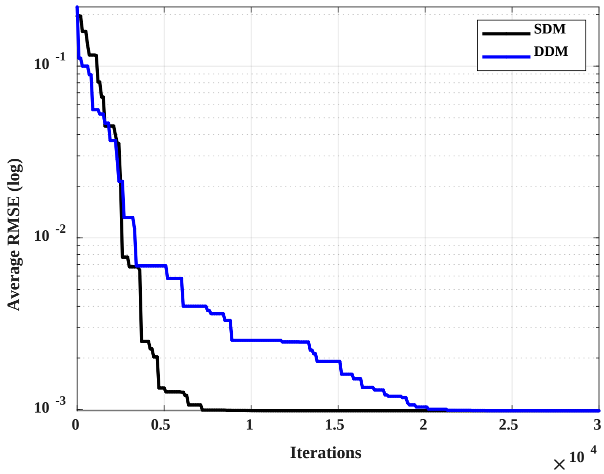

Fig. 2 Convergence curve of single-diode model and double-diode model

Next, to determine the level of accuracy of the DE algorithm in calculating photovoltaic parameters, we can assess the comparison of the I-V and P-V characteristics between the measurement data and the calculation results, as well as the individual absolute error (*IAE*) values yielded. The I-V and P-V characteristics for the single-diode model are shown in Figs. 3(a) and 3(b). From the curves of Figs. 3(a) and 3(b), it can be seen that the measurement data match very well with the calculations data

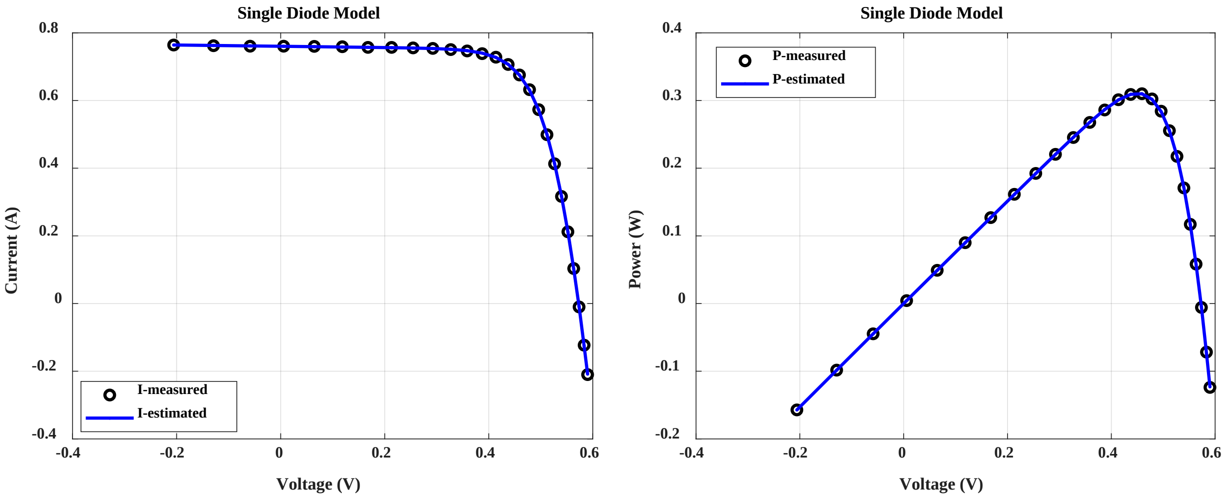

Fig. 3 (a) The I-V curve of single-diode model, (b) The P-V curve of single-diode model

The I-V and P-V characteristics for the double-diode model are shown in Figs. 4(a) and 4(b). For the double-diode model, the measured and calculated data also have very good fitness.

Subsequently, the *IAE* values are evaluated, as shown in Figs. 5(a) and 5(b). The calculated current *IAE* values for the single-diode model and the double-diode model are smaller than the 0.0025 A, while the power *IAE* is lower than 0.0015 W. This indicates a fairly good level of accuracy for both models.

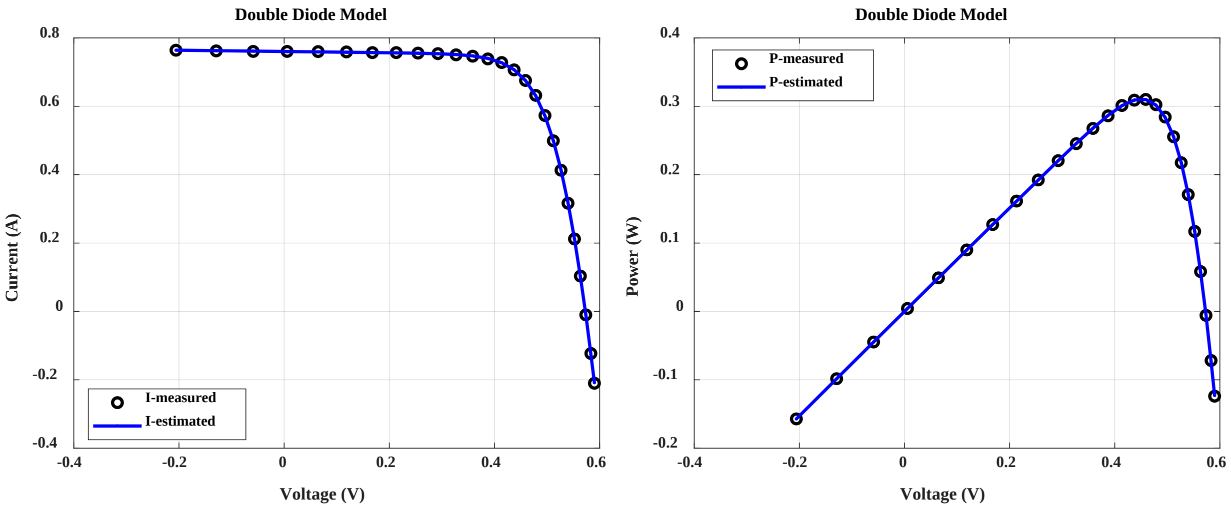

Fig. 4 (a) The I-V curve of double-diode model, (b) The P-V curve of double-diode model

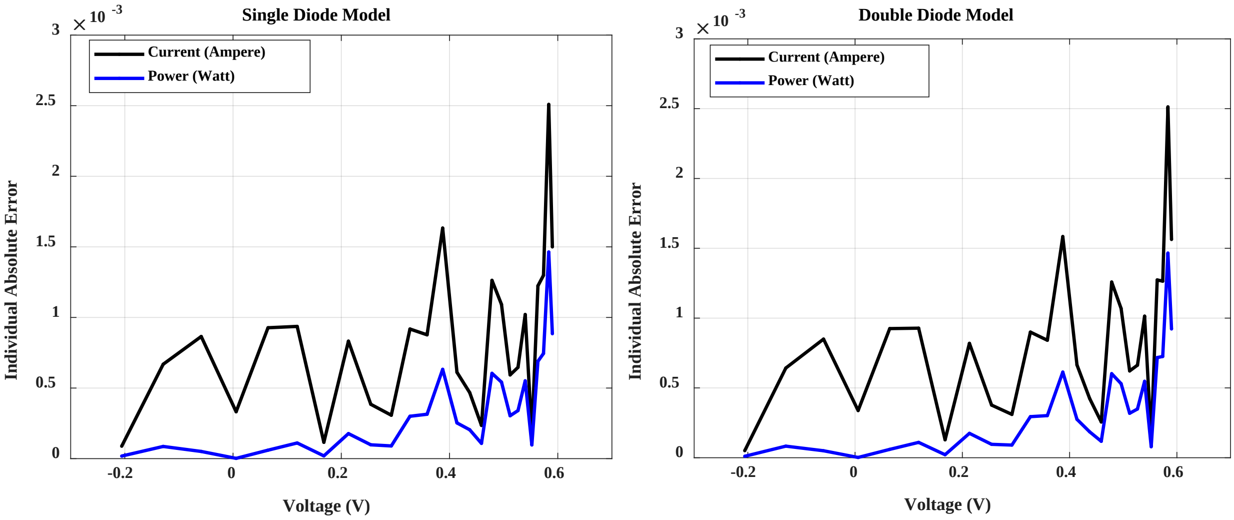

Fig. 5 (a) IAE values for the single-diode model, (b) IAE values for the double-diode model

V. CONCLUSION

In this study, the DE algorithm was used to extract photovoltaic parameters. The solar cell used wasthe RTC France cell. The voltage, current, and power data were obtained from measurements on the RTC France cell at a temperature of 33˚C and solar irradiance of 1000 W/m^2.From the calculation results, the RMSE of the single-diode model was 9.8602E-04,while the RMSE of the double-diode model was 9.8344E-04. Thus the double-diode model gave a better level of accuracy than the single-diode model. However, the single-diode model has a faster convergence rate than the double-diode model when extracting the photovoltaic parameters. Other results showed that I-V and P-V characteristic curves obtained by both the single-diode model and the double-diode model matched very well when compared to the measurement results.

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