A hybrid intelligent algorithm for parameter identification of double diode model of PV

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ABSTRACT

Differential evolution (DE) and fireworks algorithm (FWA) are two good optimization algorithms. Each of them has many advantages and has been widely used. Yet it is also inadequate. DE is easy to fall into local optimization and its parameters are difficult to set. FWA is not enough to exploit the local space. In this paper, a hybrid algorithm which combines DE and FWA (FWADE) is presented. By mixing and randomly redistributing the population of DE and FWA in the process of evolution, FWADE has the virtues of DE and FWA. The algorithm has fast solution speed to find global solution. The paper describes the algorithm process of FWADE in detail. The presented algorithm is used to identify the parameters of double diode model of PV cell and the result is compared with that of DE and FWA. The result shows that the hybrid algorithm can get a better solution in parameters identification of double diode model of PV.

Keywords: Differential evolution, fireworks algorithm, double diode model of PV, parameters identification

1. INTRODUCTION

With the increase of energy consumption, renewable energy has been widely valued. Among them, solar energy has received additional attention because of its economic performance, infinity, cleanliness and accessibility[1]. Photovoltaic (PV) cell is the basic component in a photovoltaic power generation system which converts solar energy into electrical energy. In the study of photovoltaic power generation system, it is important to establish the accurate mathematical model of PV[2, 3]. The accurate model of PV is helpful to simulate and predict the power output accurately[4, 5].

Usually, two equivalent circuit models of PV are used to simulate PV cell, namely single diode model and double diode model. The former has five components to be identified. It can accurately simulate the I-V output of PV at high irradiance. However, its accuracy is not enough at low irradiance. Compared with single diode model, double diode model adds a diode to compensate the loss in the depletion region. Double diode model of PV can accurately simulate the I-V curve of PV cell[6, 7]. The main problem is that double diode model has more components and requires more computation.

In order to identify the parameters of double diode model, actual measurement output voltages and currents (I-V curve) are need. Because of the nonlinearity of the I-V curve, it is difficult to determine the parameters of double diode model. The traditional curve fitting technique is applied to estimate the double diode model parameters, but there are significant errors in parameters identification because of the greatly nonlinear of the I-V curve[8, 9]. Different from traditional mathematics, intelligent optimization algorithm is suitable for solving nonlinear problems, such as solving the parameters identification of PV. Many researchers have studies parameter identification of PV model using evolution algorithm. Literature[10] used differential evolution (DE) algorithm to extract the parameters of single diode model. A differential evolution algorithm was improved named adaptive differential evolution algorithm to extract the parameters of solar cell models and the results showed its effectiveness[11]. Single and double diode parameters of solar cell models were compared using firefly algorithm[12].

In this paper, a hybrid intelligent algorithm which combines the advantages of differential evolution and fireworks algorithm named FWADE is proposed. The idea of FWADE is to mix the population of DE and FWA at the end of every iteration and randomly redistributes the population of DE and FWA at the beginning of every iteration. The paper describes the implementation of FWADE in detail. Finally FWADE is used to identify the parameters of double diode model. Simulation results verify the effectiveness of the algorithm.

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2. EQUIVALENT CIRCUIT MODEL AND OPTIMIZATION PROBLEM OF PV PARAMETERS IDENTIFICATION

2.1. Double diode model of PV

In double diode model circuit of PV, there are a current source, two diodes and two resistances. The current source represents the photocurrent. One diode represents the diffusion phenomena, and the other diode represents the recombination loss in the depletion region. This model can give more accurate output characteristic of PV cell than single diode model in low irradiance and ambient temperature. Figure 1 shows the double diode circuit model of PV.

From the circuit, the current equation can be obtained as:

$$I_t = I_{pv} - I_{d1} - I_{d2} - I_{sh} \tag{1}$$

In equation (1), I_{d1} and I_{d2} are currents of diode D1 and D2 respectively in Figure 1, they can be descried by diode current. So equation (1) can be written as:

$$I_t = I_{pv} - I_{sd1}\left[\exp\left(\frac{V_t+I_tR_s}{m_1V_T}\right)-1\right] - I_{sd2}\left[\exp\left(\frac{V_t+I_tR_s}{m_2V_T}\right)-1\right] - \frac{V_t+R_sI_t}{R_p} \tag{2}$$

where I_{sd1} and I_{sd2} are reverse saturation currents of two diodes respectively. m_1 and m_2 represent ideal factors of diodes. V_T is thermal voltage which can be described by electron charge q, Boltzmann constant k and cell temperature T as:

$$V_T = \frac{kT}{q} \tag{3}$$

Equation (2) describes the output characteristic I-V of PV cell. If equation (2) is used to describe the characteristics output of PV, there are seven parameters to be determined. They are photocurrent I_{pv}, saturation currents I_{sd1} and I_{sd2} of diode D1 and D2, ideality factors m_1 and m_2 of diode D1 and D2, series resistance R_s and parallel resistance R_p.

2.2. Double diode model parameters identification problem

From the description above, there are seven parameters to be identified which can be listed as vector:

$$U = [I_{pv}, I_{sd1}, I_{sd2}, m_1, m_2, R_s, R_p]$$

Actual measurement voltage and current output of PV cell are used to determine the vector U. Figure 2 shows a set of voltage and current data of PV cell.

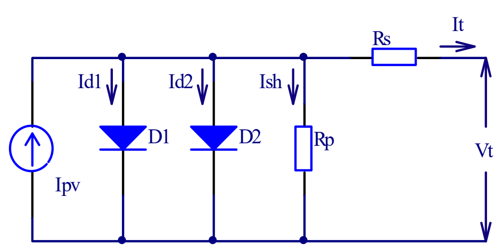

Figure 1. Double diode model of PV.

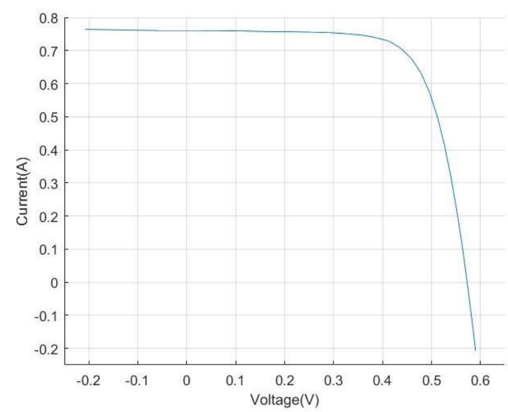

Figure 2. Output characteristic of PV cell.

In order to determine seven parameters using intelligent algorithm, the initial values of seven parameters are estimated at first, and based on equation (2), the error between actual and estimated can be calculated. The objective is to minimize the error between the actual data and estimated data. Based on equation (2), the objective function can be constructed as equation (4).

$$\min z(U_t, I_t) = I_t - I_{pv} + I_{sd1}\left[\exp\left(\frac{V_t+I_tR_s}{m_1V_T}\right) - 1\right] + I_{sd2}\left[\exp\left(\frac{V_t+I_tR_s}{m_2V_T}\right) - 1\right] + \frac{V_t+R_sI_t}{R_p} \tag{4}$$

In the evolution of intelligent optimization, every actual measurement I-V output and estimated vector U are substituted into equation (4) and the error will be calculated and evaluated. In order to obtain the optimal solution of parameters, the sum of square root error is selected as follows:

$$\text{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n} z^2(U_t, I_t)} \tag{5}$$

where n is the number of measurement pair of voltage and current. According to equations (4) and (5), it will guide the evolution to better solution.

3. HYBRID ALGORITHM DESCRIPTION

3.1. Overview of DE algorithm

Differential Evolution was proposed in 1997. It is a heuristic and parallel search algorithm which belongs to a swarm intelligence search algorithm[13, 14].

DE randomly generates the initial value and finds the optimal solution through difference calculation and iteration. For the problem of population *NP* and dimension D, it randomly generates initial population:

$$X_i = \{x_{i1}, x_{i2}, \dots, x_{ij}, \dots x_{iD}\} \tag{6}$$

where $i = 1,2, \dots NP$ represents the *i*th individual, $j = 1,2, \dots D$ represents the *j*th dimension.

In each iteration of the algorithm, mutation, crossover and selection are performed.

In DE algorithm, there are five mutation strategies to generate mutation vector $V_{i,G+1}$. Among them, the DE/best/1 strategy is described as:

$$V_{i,G+1} = X_{best,G} + F * (X_{r1,G} - X_{r2,G}) \tag{7}$$

where *F* is the difference vector scale factor. $X_{best,G}$ represents the best individual in generation *G*. $X_{r1,G}$ and $X_{r2,G}$ are two different vectors which are chosen from the population.

In DE algorithm, there are two crossover methods. Binomial crossover is described as:

$$u_{ij,G+1} = \begin{cases} v_{ij,G+1} & rand(0,1) \le CR \text{ or } j = rand(i) \\ x_{ij,G} & otherwise \end{cases} \tag{8}$$

where $\text{rand}(0,1)$ is a random number between 0 and 1. It is independently generated for each *i* and *j*.

According to the fitness values, the better vector between $X_{i,G}$ and trial vector $U_{i,G+1}$ will be selected. The selection operation is defined by:

$$X_{i,G+1} = \begin{cases} U_{i,G+1} & if\ f(U_{i,G+1}) \le f(X_{i,G}) \\ X_{i,G} & otherwise \end{cases} \tag{9}$$

At the end of each iteration, the evolution stop condition will be checked. If the condition is not satisfied, the next iteration will be carried out.

3.2. Overview of fireworks algorithm

Fireworks algorithm was first published in 2010 which simulated the explosion of fireworks. By introducing random strategy and selection strategy, FWA controls the direction of fireworks explosion and achieves global optimization[15, 16].

FWA randomly generates *NP* fireworks as an initial population and calculates their fitness value. It includes three steps in each iteration: explosion, mutation and selection.

Every individual in population explodes and generates new fireworks. The number of fireworks that the *i*th individual generates is S_i and the explosion amplitude is A_i. S_i and A_i can be described as equations (10) and (11) respectively.

$$S_i = S_{total} \frac{Y_{max} - f(x_i) + \varepsilon}{\sum_{i=1}^{n}(Y_{max} - f(x_i)) + \varepsilon} \quad (10)$$

$$A_i = A_{max} \frac{f(x_i) - Y_{min} + \varepsilon}{\sum_{i=1}^{N}(f(x_i) - Y_{min}) + \varepsilon} \quad (11)$$

In equations (10) and (11), S_{total} is the largest amount of fireworks produced. $f(x_i)$ is the fitness value of the *i*th individual. A_{max} indicates the maximum explosion amplitude. Y_{max} and Y_{min} are the best fitness and the worst fitness respectively. ε is a minimum to avoid zero numerator or zero denominator.

FWA uses Gaussian mutation to produce new fireworks. It randomly selects an individual fireworks and makes Gaussian mutation. Gaussian mutation can be described as:

$$x_i^k = x_i^k g \quad (12)$$

where *g* is a Gaussian random number which has mean 1 and variance 1.

NP fireworks will be selected from new fireworks which are produced through explosion and mutation. The individual with the best fitness value will be preserved and the remain *NP*-1 individuals will be selected with probability $p(x_i)$:

$$p(x_i) = \frac{R(x_i)}{\sum_{j \in K} R(x_j)} \quad (13)$$

After the three steps mentioned above, the population of generation *G*+1 is determined.

3.3. FWADE algorithm realization

DE is an effective algorithm in search space and has better global search ability. But the parameters of DE are difficult to set and the algorithm is easy to achieve local optimum. FWA is an algorithm with excellent performance and wide adaptability. But it is not enough to exploit the local space. In this paper, the two algorithms are combined to make full use of their advantages. FWADE is described as follow:

Step 1: Initial population

Produce initial population of the hybrid algorithm and the number is *NP*. Divide the initial population into two parts. One part is the initial population of DE which number is *NP1*. The other part is the initial population of FWA which number is *NP2*.

Step 2: Evolution

The evolution consists of DE evolution and FWA evolution.

(1) DE evolution.

Firstly, for the *NP1* individuals of DE population, the mutation operation is carried out. The mutation strategy is equation (7) and the corresponding mutation vectors $V_{i,G+1}$ are generated. Then, the crossover operation is carried out to produce *NP1* trial vectors $U_{i,G+1}$. The crossover strategy adopts binomial crossover which is described in equation (8). Finally, the better vector between the original population $X_{i,G}$ and the trial vectors $U_{i,G+1}$ is selected through equation (9). Through the three operations, the individual $X_{i,G}$ of population is renewed to $X_{i,G+1}$ and the population is renewed which has better fitness. So the *NP1* individuals of the next generation are determined.

(2) FWA evolution.

Firstly, *NP2* individuals of FWA population explode to generate new fireworks. The number of the *i*th individual and the explosion amplitude are shown in equations (10) and (11) respectively. Then the new fireworks are generated based on equation (12). Finally, in all new fireworks, the individual with best fitness is kept and the other *NP2*-1 individuals are selected with probability (13). So the *NP2* fireworks of the next generation are determined.

Step 3: Mixing and distribution

Randomly mix *NP1* individuals of DE and *NP2* individuals of FWA that produce through step2 above to obtain the new *NP* population of hybrid algorithm. Then the population is randomly divided into DE population with *NP1* individuals and FWA population with *NP2* individuals. Finally, in each iteration, the stop condition of evolution will be check. If the stop condition is not satisfied, the step 2 will be carried on until the stop condition is satisfied.

The flow chat of FWADE is shown as Figure 3.

4. IDENTIFIED PARAMETERS USING FWADE

In this section, the parameters of double diode model of PV will be identify using the presented hybrid algorithm. In the method, the measure voltage and current output data shown in Figure 1 are utilized. And the result is compared with DE and FWA algorithm.

The parameters of double diode model of PV are set to 7-dimensional individual of the hybrid algorithm. The real voltage and current of PV shown in Figure 2 are used to assess the error between the real and estimated.

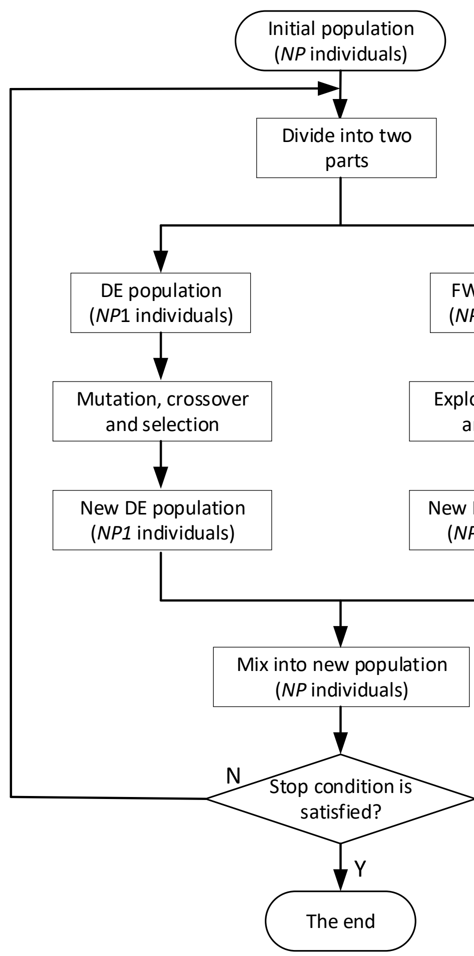

Figure 3. Hybrid algorithm flow chat.

The pseudo code of FWADE algorithm is listed below:

Algorithm: FWADE algorithm	
1	Initialize parameters of algorithm: *NP*, *D, ……, G*=0
2	initialize the population X_i randomly at generation =0
3	**While** stopping condition is not satisfied **do**
4	Randomly divide population (*NP*) into *NP1* and *NP2*
5	Calculate the fitness value and mean square error based on equations (4) and (5)
6	DE evolution according to (7) to (9)
7	FWA evolution according to (10) to (13)
8	Mix DE population (*NP1*) and FWA population (*NP2*)
9	Update population *NP*
10	Add a generation *G* = *G*+1
11	**End While**

In order to test the performance of FWADE, standard DE algorithm and FWA algorithm are also implemented using the same algorithm parameters. The convergence curves of three algorithms are shown in Figure 4.

From Figure 4, all the three algorithms can identify the parameters of PV. The convergence rate of FWADE algorithm is the fastest and it has the lowest error.

The real curve and fitting curves of three algorithms are shown in Figure 5.

Figure 5 shows the real curve of PV output and three fitting curves using DE, FWA and FWADE. The figure shows that the hybrid algorithm can fit real curve very well and it is the best fitting curve.

The identification parameters by three algorithms are also listed in Table 1.

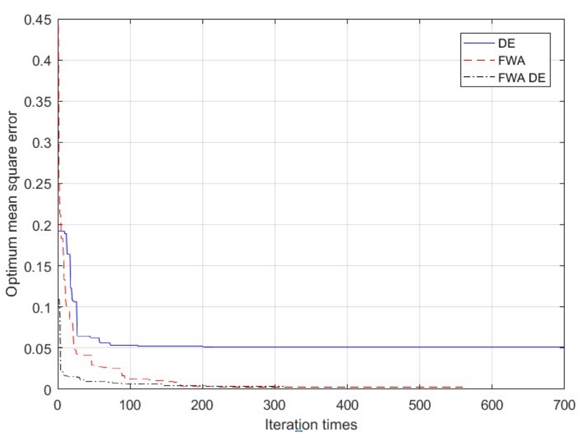

Figure 4. Convergence curves.

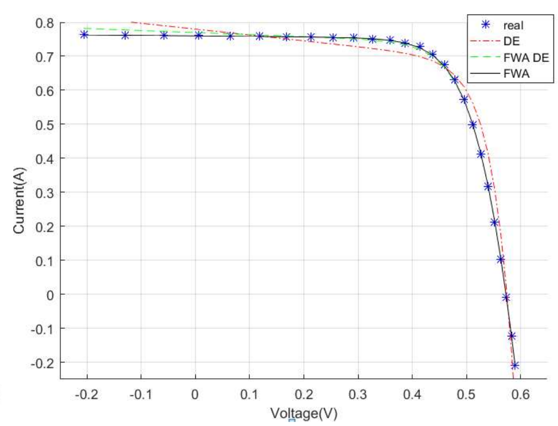

Figure 5. Fitting curves.

Table 1. Identification results of three algorithms

	DE	FWA	FWA_DE
I_{pv}(A)	0.780	0.760	0.771
I_{sd1}(A)	1.486-07	8.773e-07	2.483e-07
I_{sd2}(A)	2.146e-13	5.257e-07	4.072e-07
m_1	1.420	1.929	1.475
m_2	1.533	1.542	1.724
$R_s(\Omega)$	0.0014	0.0320	0.0329
$R_p(\Omega)$	5.815	71.764	16.775

5. CONCLUSION

Differential evolution and fireworks algorithm are widely used. A hybrid intelligent algorithm which combines the advantages of differential evolution and fireworks algorithm is proposed in this paper. By mixing the population and randomly redistributing the population of DE and FWA, FWADE algorithm is fully combines the advantages of two algorithms.

The implementation method of FWADE is described and the algorithm is used to identify the seven parameters of double diode model of PV. The result shows that it can efficiently identify the parameters of double diode model. Compared with standard DE and FWA algorithm, FWADE algorithm has faster convergence speed and can find better solution.

REFERENCES

[1] Yan, Y. F., "Solar energy utilization technology and its application," Journal of Solar Energy, 33, 47-56 (2012).

[2] Ishaque, K., Salam, Z. and Taheri, H., "Simple fast and accurate two-diode model for photovoltaic modules," Solar Energy Materials & Solar Cells, 586 (2011).

[3] Yao, Y. Q. and Wang Y. B., "An improved double-diode model based simulation method for PV modules," Conf. Record of the IEEE Photovoltaic Specialists Conf., 224 (2020).

[4] Elgohary, R., Abu Elela, A. A. and Elkholy, A., "Electrical characteristics modeling for photovoltaic modules based on single and two diode models," Twentieth Inter. Middle East Power Systems Conf., 685 (2018).

[5] Liu, Y., Lu, Z. and Yang, F., "The investigation of solar PV models," Power & Energy Society Innovative Smart Grid Technologies Conf., 1 (2018).

[6] Tutkun, N., Gegin, K. and Sarma, N., "Comparison of typical PV module performances based on the circuit models," Asia-Pacific Power and Energy Engineering Conf., 206 (2018).

[7] Hoarcă, I. C., "Mathematical modeling and simulation of PV systems part I: mathematical modeling and Simulink implementation," Inter. Conf. on Applied and Theoretical Electricity, (2021).

[8] De Soto, W., Klein, S. A. and Beckman, W. A., "Improvement and validation of a model for photovoltaic array performance," Sol. Energy, 80(1), 78-88 (2006).

[9] Meng, X., Gao, F. and Xu, T., "A hybrid model parameter extraction method for single-diode model of PV module" Energy Conversion Cong. and Expo., 3649 (2020).

[10] Chin, V. J., Salam, Z. and Ishaque, K., "An improved method to estimate the parameters of the single diode model of photovoltaic module using differential evolution," 4th Inter. Conf. on Electric Power and Energy Conversion Systems, (2015).

[11] Chellaswamy, C. and Ramesh, R., "Parameter extraction of solar cell models based on adaptive differential evolution algorithm," Renewable Energy, 97, 823-837 (2016).

[12] Louzazni, M., Khouya, A. and Amechnoue, K., "Comparative prediction of single and double diode parameters for solar cell models with firefly algorithm," 10th Inter. Symp. on Advanced Topics in Electrical Engineering, 860 (2017).

[13] Storn, R. and Price, K., "Differential evolution—A simple and efficient heuristic for global optimization over continuous spaces," Global Optimization, 11, 341 (1997).
[14] Chiou, J. P., "A variable scaling hybrid differential evolution for solving large-scale power dispatch problems," IET Generation, Transmission and Distribution, 3, 154 (2009).
[15] Tan, Y. and Zhu, Y., "Fireworks algorithm for optimization," Advances in Swarm Intelligence, 355, (2010).
[16] Cao, J., Li, T. and Jia, H., "Fireworks explosion optimization algorithm with genetic operators," Computer Engineering, 12, 149 (2010).