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Cuckoo Search Algorithm for Extraction Ten Parameters of Photovoltaic Models

خوارزمية بحث الوقواق لاستخراج عشرة متغيرات لنماذج الخلايا الكهروضوئية

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KEYWORDS:
Photovoltaic, extraction, cuckoo search, three-diode model, modified three-diode model.

الملخص العربي:- **العنصر الهام في استخراج المتغيرات المجهولة في النموذج الكهروضوئي هي النماذج الرياضية. لذلك ، يتم تحليل خمسة دوائر مكافئة في هذه الورقة البحثية. المتغيرات المجهولة هي خمسة لنموذج مفرد من الصمام الثنائي ، وسبعة لنموذج مزدوج من الصمام الثنائي ، وثمانية لنموذج مزدوج معدل من الصمام الثنائى ، وتسعة لنموذج ثلاثى من الصمام الثنائي وعشرة لنموذج ثلاثى معدل من الصمام الثنائي. تتم مقارنة أداء نموذج ثلاثى من الصمام الثنائي نموذج ثلاثى معدل من الصمام الثنائي بعد تقدير جميع المتغيرات المجهولة دون افتراض لاي متغير بأداء كل من نموذج مفرد من الصمام الثنائي ، و لنموذج مزدوج من الصمام الثنائي ، و لنموذج مزدوج معدل من الصمام الثنائى لنفس الخلية الشمسية. تم اقتراح خوارزمية تحسين بحث الوقواق (CSOA) لتقدير المتغيرات المجهول للدوائر الخمسة المكافئة للخلايا الشمسية. يتم تحليل خطأ الجذر التربيعي المتوسط ، والخطأ المطلق للتيار والطاقة ، والخطأ المطلق لنقطة الطاقة القصوى إلى أداء نماذج الخلايا الشمسية الخمسة.**

Abstract—**the important issue in the extraction of the unknown parameters in the photovoltaic model is the mathematical models. Therefore, a five equivalent circuit is analyzed in this work. The unknown parameters are five for single diode model, seven for double-diode model, eight for modified double-diode, and nine for three-diode model and ten for modified three-diode parameters. The performance of the modified three-diode model and three-diode model after estimate all parameters without assumption for any variable are compared with the performance of the both single diode model, double-diode model and also the modified double-diode of the same solar cell. Cuckoo search optimization algorithm (CSOA) is proposed for the estimation of the unknown parameters for the five solar cell equivalent models. The root mean square error, the absolute error for current and power, and the maximum power point absolute error are analyzed to the performance of the five solar cell models.**

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I. INTRODUCTION

THE resources of renewable energy are several resources, the most important resource is the energy produced from solar cells due to its wide availability and its cleanliness. The behavior of the solar cell is analyzed by the I-V and P-V characteristic curves. These characteristic curves are dependent on the cell temperature, the solar radiation and the equivalent circuit of the solar cell. Based on the equivalent circuit their unknown's parameters must be identified.

For single diode model, there are five unknown's parameters. Abdel-Halim [1] built his model on a simple equivalent circuit and didn't consider the ideality factor of diode and the shunt resistance. Chatterjee [2] approximated the PV module characteristics by neglecting the term (-1) in the reverse saturation current equation, then form five equations and solve it simultaneously, which is tedious effort. Carlos de Manuel [3], represented estimation of the parameters based on the lambert W-function. Mokhtar et al. [4] estimated the five parameters based on iteration method.

Kunjie et al. [5] developed extraction of unknown's parameter using multiple learning backtracking search algorithm.

For double-diode model, there are seven unknown's parameters. Kunjie et al. [5] developed extraction of unknown's parameter for the two-diode model using multiple learning backtracking search algorithm. Kurobe et al. [6] developed new two-diode model for detailed analysis. Dalia et al. [7] estimated the eight parameters based moth-flame optimization algorithm. Ismail et al. [8] used genetic algorithm to estimate these parameters. For modified double-diode model, there are eight unknown's parameters. Kassis et al. [9] modified double-diode model of multi-crystalline silicon solar cell. For three-diode model, there are seven unknown's parameters. Dalia et al. [7] estimated the seven parameters based moth-flame optimization algorithm. Nishioka et al. [10] analyzed the effect of three-diode model on multi-crystalline silicon solar cell.

The analysis of three-diode model in Dalia et al. [7] was developed with assumption of the ideality factor value of the first and second diode. Table 1 shows the comparison between this several optimization techniques for estimating parameters of photovoltaic and the objective of this paper.

TABLE 1
COMPARISON OF SEVERAL TECHNIQUES

ref	model	objective	algorithm
4	Single diode model	Estimate five parameters	Mathematical solution
5	Single diode model	Estimate five parameters	Multiple learning backtracking search
5	Double-diode model	Estimate seven parameters	Multiple learning backtracking search
7	Double-diode model	Estimate seven parameters	Moth-flame optimization
7	Modified double-diode model	Estimate eight parameters	Moth-flame optimization
7	Double-diode model	Estimate seven parameters	Moth-flame optimization
This paper	Single diode model	Estimate five parameters	Cuckoo- search algorithm
	Double-diode model	Estimate seven parameters	
	Modified double-diode model	Estimate eight parameters	
	Three-diode model	Estimate nine parameters	
	Modified three-diode model	Estimate ten parameters	

In this paper, two points are contributed. Firstly; the parameters in the three-diode model is estimated without any assumption for any parameter. Secondly; a new complicated modified for three-diode model is analyzed. CSOA is used for estimating the unknown's parameter for the five equivalent circuits of solar cell models. Evaluation of each model is based on the root mean square error for the current and the absolute error for the current and power and the absolute error at maximum power point.

The manuscript organization is as follows: section 2 discusses mathematical formulation of photovoltaic model. Section 3 explains the problem formulation. Section 4 explains the cuckoo search optimization algorithm details. Section 5 the simulation and results will be discussed. The conclusion of this paper is in section 6.

II. MATHEMATICAL FORMULATION OF PHOTOVOLTAIC MODELING.

The physical characteristics and the operation performance of photovoltaic are described with several equivalent circuit of photovoltaic models. Due to several factors such as leakage current and grain limits, the equivalent circuit of photovoltaic model must be modified to explain more details [7]. Therefore, the modified three-diode model as well as, three-diode model, modified double-diode, double-diode model and single diode model are studied.

A. *Single diode model*

The single diode model is represented by current source in parallel to a diode, a shunt resistor and a series resistor as in fig1. Hence, the basic equation of the output current is given by this formula:

$$I = I_{ph} - I_{d1} - I_{sh} \quad (1)$$

$$I = I_{ph} - I_{s1}\left[e^{\frac{q(V+IR_s)}{a_1 K T_c}} - 1\right] - \frac{V + IR_s}{R_{sh}} \quad (2)$$

Where, I is current output from solar cell, I_{ph} is the light generated current, I_{sh} is the leakage current, I_{d1} is the dark saturation current of the first diode, R_{sh} is the shunt resistance, R_s is the series resistance, a_1 is the diode ideality factor, K is Boltzmann's constant, q is the charge of electron, T_c is the cell temperature. The five parameters should be estimated according to Equation (2), are$(I_{ph}, I_{s1}, a_1, R_s, R_{sh})$. The cuckoo search optimization technique is used for extracting these parameters. R_s was introduced as to consider the voltage drops and internal losses in due to flow of current. R_{sh} takes into account the leakage current to the ground when diode is in reverse biased [7].

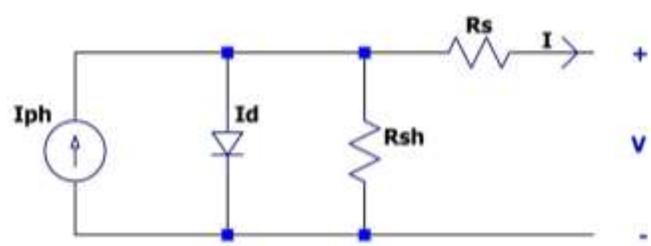

Fig1. Equivalent circuit of single diode model

B. *Double-diode model*

The double-diode model is represented by current source in parallel to a two-diode in two parallel branches, a shunt resistor and a series resistor as in fig2. Hence, the basic equation of the output current is given by this formula:

$$I = I_{ph} - I_{d1} - I_{d2} - I_{sh} \quad (3)$$

$$I = I_{ph} - I_{s1}\left[e^{\frac{q(V+IR_s)}{a_1KT_c}} - 1\right] - I_{s2}\left[e^{\frac{q(V+IR_s)}{a_2KT_c}} - 1\right] - \frac{V + IR_s}{R_{sh}} \quad (4)$$

Where, I_{d2} is the dark saturation current of the second diode, a_2 is the ideality factor of the second diode. The seven parameters should be estimated according to Equation (4), are$\left(I_{ph}, I_{s1},\ a_1, R_s, R_{sh},, I_{s2},\ a_2\right)$. The cuckoo search optimization technique is used for extracting these parameters. The second diode current represent due to recombination in the space charge region [7].

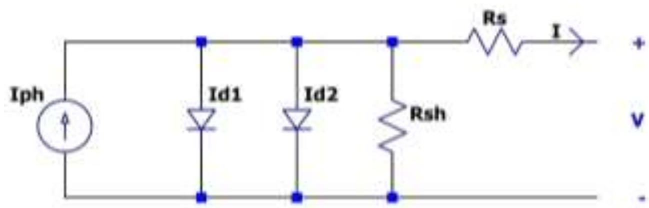

Fig2. Equivalent circuit of double-diode model

C. *Modified double-diode model*

The modified double-diode model is represented as double-diode in addition to series resistance in series with the second diode an on fgi3.

Hence, the basic equation of the output current is given by this formula:

$$I = I_{ph} - I_{s1}\left[e^{\frac{q(V+IR_s)}{a_1KT_c}} - 1\right] - I_{s2}\left[e^{\frac{q(V+IR_s-I_{d2}R_{s1})}{a_2KT_c}} - 1\right] - \frac{V + IR_s}{R_{sh}} \quad (5)$$

Where, R_{s1} is the additional series resistance.The eight parameters should be estimated according to Equation (5), are$\left(I_{ph}, I_{s1},\ a_1, R_s, R_{sh},, I_{s2},\ a_2, R_{s1}\right)$. The cuckoo search optimization technique is used for extracting these parameters. The effect of grain boundary region is taken into consideration by adding additional resistance in the second diode [7].

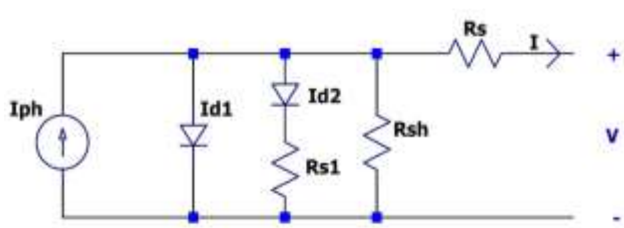

Fig3. Equivalent circuit of modified double-diode model

D. *Three-diode model*

The three-diode model is represented by current source in parallel to a three-diode in three parallel branches, a shunt resistor and a series resistor as in fig4. Hence, the basic equation of the output current is given by this formula:

$$I = I_{ph} - I_{d1} - I_{d2} - I_{d3} - I_{sh} \quad (6)$$

$$I = I_{ph} - I_{s1}\left[e^{\frac{q(V+IR_s)}{a_1KT_c}} - 1\right] - I_{s2}\left[e^{\frac{q(V+IR_s)}{a_2KT_c}} - 1\right] - I_{s3}\left[e^{\frac{q(V+IR_s)}{a_3KT_c}} - 1\right] - \frac{V + IR_s}{R_{sh}} \quad (7)$$

Where, I_{d3} is the dark saturation current of the third diode, a_3 is the ideality factor of the third diode. The nine parameters should be estimated according to Equation (7), are$\left(I_{ph}, I_{s1},\ a_1, R_s, R_{sh},, I_{s2},\ a_2, I_{s3},\ a_3\right)$. The cuckoo search optimization technique is used for extracting these parameters. The influence of grain boundary and leakage current is taken into consideration by adding the third diode [7].

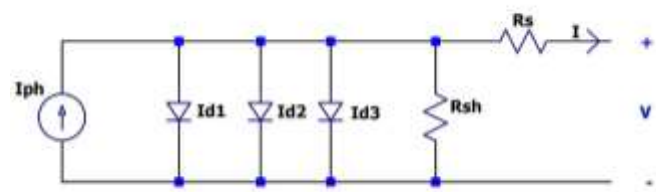

Fig4. Equivalent circuit of three-diode model

E. *Modified three-diode model*

The modified three-diode model is represented as the three-diode model in addition to series resistance in series with the third diode as in fgi5.

Hence, the basic equation of the output current is given by this formula:

$$I = I_{ph} - I_{s1}\left[e^{\frac{q(V+IR_s)}{a_1KT_c}} - 1\right] - I_{s2}\left[e^{\frac{q(V+IR_s)}{a_2KT_c}} - 1\right] - I_{s3}\left[e^{\frac{q(V+IR_s-I_{d2}R_{s2})}{a_3KT_c}} - 1\right] - \frac{V + IR_s}{R_{sh}} \quad (8)$$

Where, R_{s2} is the additional series resistance. The ten parameters should be estimated according to Equation (8), are$\left(I_{ph}, I_{s1},\ a_1, R_s, R_{sh},, I_{s2},\ a_2, I_{s3},\ a_3, R_{s2}\right)$. The cuckoo search optimization technique is used for extracting these parameters. The effect of grain boundary region is taken into consideration by adding additional resistance in the third diode.

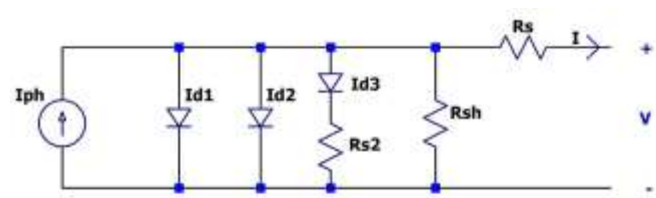

Fig5. Equivalent circuit of modified three-diode model

III. PROBLEM FORMULATION

The problem of extraction unknown's parameter for several photovoltaic models are dependent on minimizing the difference between the experimental data and the calculated current data.

The guideline requirements to apply any optimization technique are developed by the confirmation of the vector of variables (X), the boundary limits and the objective function.

The variables vectors are as follow; $X = (I_{ph}, I_{s1}, a_1, R_s, R_{sh})$ for single diode model, $X = (I_{ph}, I_{s1}, a_1, R_s, R_{sh}, , I_{s2}, a_2)$ for double-diode model, $X = (I_{ph}, I_{s1}, a_1, R_s, R_{sh}, , I_{s2}, a_2, R_{s1})$ for modified double-diode model, $X = (I_{ph}, I_{s1}, a_1, R_s, R_{sh}, , I_{s2}, a_2, I_{s3}, a_3)$ for three-diode model, $X = (I_{ph}, I_{s1}, a_1, R_s, R_{sh}, , I_{s2}, a_2, I_{s3}, a_3, R_{s2})$ for modified three-diode model.

The boundaries of the parameters are given in table 2.

TABLE 2
BOUNDARIES OF UNKNOWN PHOTOVOLTAIC PARAMETERS [5]

Parameters	Lower bound	Upper bound
I_{ph}	0	1
I_{s1}, I_{s2}, I_{s3} (μA)	0	1
R_s, R_{s1}, R_{s2}	0	0.5
R_{sh}	0	100
a_1, a_2, a_3	1	2

The root mean square between the experimental and calculated currents is the objective function for the optimizer technique. The equation of the root mean square is as follow:

$$J(V, I, X) = I - I_{exp} \quad (9)$$

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(J(V, I, X)\right)^2} \quad (10)$$

Where, I can be calculated from the equation described in section two according to type of equivalent circuit of photovoltaic model, I_{exp} , is the experimental current, N is the reading data number.

IV. THE OPTIMIZATION ALGORITHM ANALYSIS

The cuckoo optimization algorithm is based on the bird life called 'cuckoo'. Adult cuckoos lay eggs in other birds' habitats. If the host birds are not found and removed, they will hatch and become mature cuckoos[11]. The migration of cuckoo and ecological specialties groups is expected to inspire them to reach a better place for breeding and breeding. Objective function is in this best position.

Each egg in the nest represents a solution, and the cuckoo's egg represents a new occurrence. The aim is to employ the new and potentially better solutions (cuckoos) to replace not-so-good solutions in the nests [12].

The CS algorithm is based on three Rules:

1- Each cuckoo lays one egg at a time and sinks into a randomly selected nest.
2- The best nests with high quality of eggs are passed on to subsequent generations.
3- The number of available host nests is determined and the host probability can be found the alien egg with probability Pa ε [0,1]. then it can throw it out or make new nest in another location.

The initial population is generated on the desired limits. another habit that cuckoos lay eggs within a maximum distance from their habitat with maximum range called egg laying radius (ELR)which is depend on the total number of eggs in nest, number of current cuckoo’s eggs in additional to variable limits maximum and minimum value. ELR is defined as the following equation:

$$ELR = \delta \frac{cuckoo\_current\_eggs}{total\_number\_of\_eggs}(variable_{max} - variable_{min}) \quad (11)$$

Where, δ is integer number to handle ELR

Each cuckoo randomly starts laying eggs in the nests of some other host birds in its ELR. After all the cuckoo's eggs are placed in the host bird's nest, some of them are identical to the host bird's own egg, which the host bird recognizes and throws from the nest. Therefore, after the egg laying process, P% (usually 10%) of all eggs is killed, with lower profit margins [11:13]. These eggs are unlikely to move forward. The remaining eggs grow, hatch and are eaten by host birds by host nests. Another interesting thing about cuckoo eggs is that only one egg can grow in the nest.

As young cuckoos mature and mature, they stay in their territory and community for a while. But when it comes time to lay eggs, they migrate to new and better habitats, more equality of eggs to host birds, and more food for new young. Once cuckoo groups are formed in different areas, the best profit society is selected as the target point for migration of other cuckoos. When mature cuckoos live throughout the environment, it is difficult to understand which group of cuckoos belongs. To solve this problem, the cuckoo group K means using clustering method. Now when cuckoo groups are formed, the value of their profit is calculated. The maximum value of these average profits is then determined by the target group and, consequently, the group's best residence is the new destination home for migratory cuckoos. When heading towards the target position, the cuckoo does not fly all the way to the destination residence. They can only fly a certain portion of the route and cause a breach.

Lévy flights, named by the French mathematician Paul Lévy, represents a mathematical model for random walks characterized by their step lengths which follow a power law written in the following form:

$$y = l^{-\alpha} \quad (12)$$

Where, l presents the flight length and presents the variance. Since 1< α< 3. y has an infinite variance.

Finding a suitable host nest plays a key role in the success of cuckoo’s reproduction strategy. Generally, the nest’s search plan is similar to food search, given that, in nature, animals seek their food randomly or quasi-randomly. They choose trajectories or directions that can be described by certain mathematical equations.

In order to generate a new solution $eggs_i^{(t+1)}$for a cuckoo i, a Lévy flight is executed as dictated by this expression:

$$eggs_i^{(t+1)} = eggs_i^t + \beta \odot y \quad (13)$$

where t is the number of iterations, i is the sample number, and β >0 is the step size. It is important to tune this value in order to get the desired step size controlled by the problem’s constraints. The product ʘ means the entry-wise multiplication.

The flow chart at figure6 shows the methodology of operation of the cuckoo search optimization method. Starting from the variables is initialized then laying the eggs to hosting nest sand kick off the worst solution and some eggs. If stopping criteria is not satisfied when determining the fitness, the eggs grow and determine the best environment for next iteration by calculating the new ELR, the process is repeated until satisfy the stopping criteria.

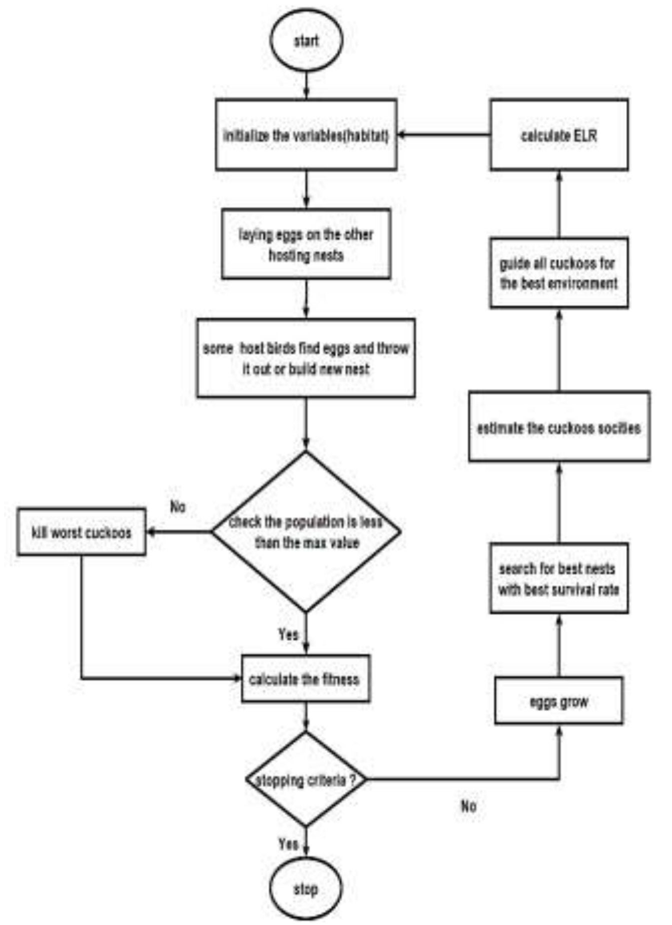

Fig6. Flow chart of optimization algorithm

V. SIMULATION AND RESULTS

The extraction of the parameters of the five suggested models is developed in this section. The proposed optimization algorithm is verified for estimation parameters of several equivalent circuit of photovoltaic, i.e., single diode, double-diode, modified double-diode, triple diode and modified triple diode. The solar cell used in this study is France silicon solar cell operating at 1000 W/m^2 solar radiation and 33 ℃ temperature [5]. The absolute error (AE) at maximum power point is carried out to evaluate the optimization algorithm.

$$AE_I = \left|I - I_{exp}\right| \quad (14)$$

A. Single diode model

The parameters extracted from the cuckoo Search algorithm is identified in table3. The results quality between the measured data and calculated data of the power and current are explained in table 4; also in this table the absolute error of the current

$AE_I\ (A)$ and the absolute error of the power $AE_P\ (w)$ are appeared. The values of current absolute error are ranged from 0.000015 to 0.010618682 and the values of power absolute error are ranged from 0.000001901 to 0.00619388. This result confirms the accuracy of the extracted parameters. Figure 7 shows the fitness function with respect to the iteration numbers of the optimization algorithm for single diode model.

TABLE 3
EXTRACTED PARAMETERS FOR SINGLE DIODE MODEL

Parameters	Value
$I_{ph}\ (A)$	0.760603
$I_{s1}\ (\mu A)$	1
a_1	1.656127
$R_s\ (\Omega)$	0.030277
$R_{sh}\ (\Omega)$	66.00847
$RMSE$	0.003277202
$AE\ at\ max\ power\ point$	0.00080963

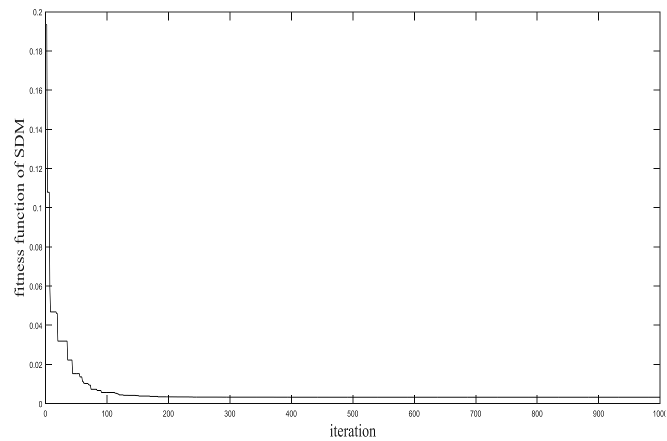

Fig7. The value of fitness function with respect to iteration for single diode model

B. Double-diode model

The parameters extracted from the cuckoo Search algorithm is identified in table5. The results quality between the measured data and calculated data of the power and current are explained in table 6; also in this table the absolute error of the current

$AE_I\ (A)$ and the absolute error of the power $AE_P\ (w)$ are appeared. The values of current absolute error are ranged from 0.0000101 to 0.01002602 and the values of power absolute error are ranged from 0.00000177442 to 0.005848182. This result confirms the accuracy of the extracted parameters. Figure 8 shows the fitness function with respect to the iteration numbers of the optimization algorithm for double-diode model.

TABLE 4
RESULTS DATA FOR SINGLE DIODE MODEL

Item	Experimental data [5]		Calculated current data		Calculated power data	
	V(V)	I_{exp} (A)	I_{sim} (A)	AE_I (A)	P_{sim} (w)	AE_P (w)
1	-0.2057	0.764	0.763985	0.0000150	-0.1571548	3.0855E-06
2	-0.1291	0.762	0.762209221	0.000209221	-0.0983742	2.701E-05
3	-0.0588	0.7605	0.761144679	0.000644679	-0.0447174	3.7907E-05
4	0.0057	0.7605	0.760166487	0.000333513	0.00433485	1.901E-06
5	0.0646	0.76	0.759268758	0.000731242	0.049096	4.7238E-05
6	0.1185	0.759	0.758432671	0.000567329	0.0899415	6.7228E-05
7	0.1678	0.757	0.757625581	0.000625581	0.1270246	0.00010497
8	0.2132	0.757	0.756769932	0.000230068	0.1613924	4.9051E-05
9	0.2545	0.7555	0.7557246	0.0002246	0.19227475	5.7161E-05
10	0.2924	0.754	0.754180454	0.000180454	0.2204696	5.2765E-05
11	0.3269	0.7505	0.751605305	0.001105305	0.24533845	0.00036132
12	0.3585	0.7465	0.747068326	0.000568326	0.26762025	0.00020374
13	0.3873	0.7385	0.73917844	0.00067844	0.28602105	0.00026276
14	0.4137	0.728	0.725865718	0.002134282	0.3011736	0.00088295
15	0.4373	0.7065	0.705131899	0.001368101	0.30895245	0.00059827
16	0.459	0.6755	0.673736108	0.001763892	0.3100545	0.00080963
17	0.4784	0.632	0.630276129	0.001723871	0.3023488	0.0008247
18	0.496	0.573	0.572814539	0.000185461	0.284208	9.1988E-05
19	0.5119	0.499	0.501564232	0.002564232	0.2554381	0.00131263
20	0.5265	0.413	0.416148432	0.003148432	0.2174445	0.00165765
21	0.5398	0.3165	0.319749826	0.003249826	0.1708467	0.00175426
22	0.5521	0.212	0.212971952	0.000971952	0.1170452	0.00053661
23	0.5633	0.1035	0.101884531	0.001615469	0.05830155	0.00090999
24	0.5736	-0.01	-0.01327825	0.00327825	-0.005736	0.0018804
25	0.5833	-0.123	-0.133618682	0.010618682	-0.0717459	0.00619388
26	0.59	-0.21	-0.19957741	0.01042259	-0.1239	0.00614933

TABLE 5
EXTRACTED PARAMETERS FOR DOUBLE-DIODE MODEL

Parameters	Value
I_{ph} (A)	0.760493
I_{s1} (μA)	008768
a_1	1.710285
R_s (Ω)	0.027994
R_{sh} (Ω)	89.11551
I_{s2} (μA)	0.6998
a_2	1.716644
$RMSE$	0.003126809
AE at max $power$ $point$	0.001584837

C. *Modified double-diode model*

The parameters extracted from the cuckoo Search algorithm is identified in table7. The results quality between the measured data and calculated data of the power and current are explained in table 8; also, in this table the absolute error of the current

AE_I (A) and the absolute error of the power AE_P (w) are appeared. The values of current absolute error are ranged from 0.00001002 to 0.010014348 and the values of power absolute error are ranged from 0.00000177442 to 0.005841369. This result confirms the accuracy of the extracted parameters. Figure 9 shows the fitness function with respect to the iteration numbers of the optimization algorithm for modified double-diode model.

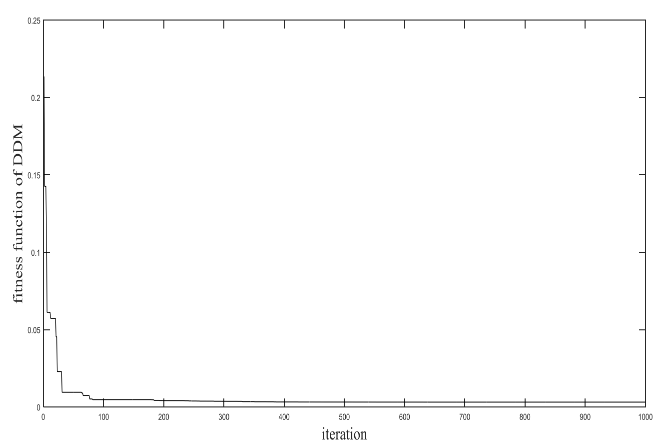

Fig8. The value of fitness function with respect to iteration for double-diode model

TABLE 6
RESULTS DATA FOR DOUBLE-DIODE MODEL

Item	Experimental data [5]		Calculated current data		Calculated power data	
	V(V)	$I_{exp}\ (A)$	$I_{sim}\ (A)$	$AE_I\ (A)$	$P_{sim}\ (w)$	$AE_P\ (w)$
1	-0.2057	0.764	0.7639899	1.01E-05	-0.15715272	2.07757E-06
2	-0.1291	0.762	0.761703147	0.000296853	-0.09833588	3.83237E-05
3	-0.0588	0.7605	0.760914468	0.000414468	-0.04474177	2.43707E-05
4	0.0057	0.7605	0.760188698	0.000311302	0.004333076	1.77442E-06
5	0.0646	0.76	0.75951981	0.00048019	0.04906498	3.10202E-05
6	0.1185	0.759	0.758888581	0.000111419	0.089928297	1.32032E-05
7	0.1678	0.757	0.758257816	0.001257816	0.127235662	0.000211062
8	0.2132	0.757	0.757540416	0.000540416	0.161507617	0.000115217
9	0.2545	0.7555	0.756574443	0.001074443	0.192548196	0.000273446
10	0.2924	0.754	0.755022698	0.001022698	0.220768637	0.000299037
11	0.3269	0.7505	0.752317539	0.001817539	0.245932603	0.000594153
12	0.3585	0.7465	0.747494906	0.000994906	0.267976924	0.000356674
13	0.3873	0.7385	0.739153573	0.000653573	0.286274179	0.000253129
14	0.4137	0.728	0.725254873	0.002745127	0.300037941	0.001135659
15	0.4373	0.7065	0.703917083	0.002582917	0.30782294	0.00112951
16	0.459	0.6755	0.672047196	0.003452804	0.308469663	0.001584837
17	0.4784	0.632	0.628432681	0.003567319	0.300642194	0.001706606
18	0.496	0.573	0.571251054	0.001748946	0.283340523	0.000867477
19	0.5119	0.499	0.500687634	0.001687634	0.256302	0.0008639
20	0.5265	0.413	0.416239164	0.003239164	0.21914992	0.00170542
21	0.5398	0.3165	0.320764928	0.004264928	0.173148908	0.002302208
22	0.5521	0.212	0.21469725	0.00269725	0.118534352	0.001489152
23	0.5633	0.1035	0.103708637	0.000208637	0.058419075	0.000117525
24	0.5736	-0.01	-0.011798773	0.001798773	-0.00676778	0.001031776
25	0.5833	-0.123	-0.133026028	0.010026028	-0.07759408	0.005848182
26	0.59	-0.21	-0.202235566	0.007764434	-0.11931898	0.004581016

TABLE 7
EXTRACTED PARAMETERS FOR MODIFIED DOUBLE-DIODE MODEL

Parameters	**Value**
$I_{ph}\ (A)$	0.761182
$I_{s1}\ (\mu A)$	0.933
a_1	1.840943
$R_s\ (\Omega)$	0.012441
$R_{sh}\ (\Omega)$	50.68641
$I_{s2}\ (\mu A)$	0.84
a_2	1.620654
$R_{s1}\ (\Omega)$	0.028892
$RMSE$	0.002705306
$AE\ at\ max\ power\ point$	0.001596508

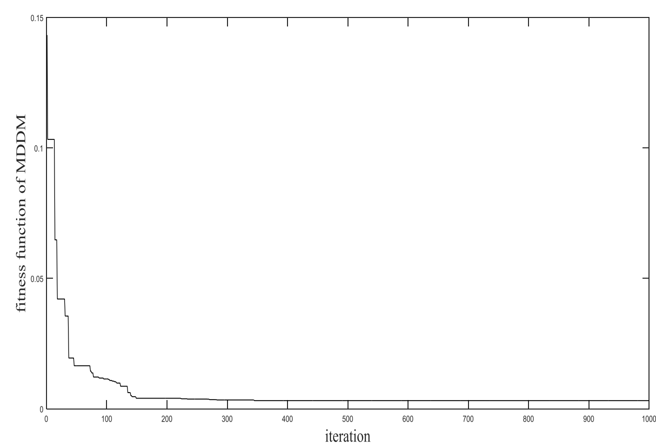

Fig9. The value of fitness function with respect to iteration for modified double-diode model

TABLE 8
RESULTS DATA FOR MODIFIED DOUBLE-DIODE MODEL

Item	Experimental data [5]		Calculated current data		Calculated power data	
	V(V)	I_{exp} (A)	I_{sim} (A)	AE_I (A)	P_{sim} (w)	AE_P (w)
1	-0.2057	0.764	0.76398998	1.002E-05	-0.15715274	2.06111E-06
2	-0.1291	0.762	0.763543401	0.001543401	-0.09857345	0.000199253
3	-0.0588	0.7605	0.762156089	0.001656089	-0.04481478	9.7378E-05
4	0.0057	0.7605	0.760881991	0.000381991	0.004337027	2.17735E-06
5	0.0646	0.76	0.75971332	0.00028668	0.04907748	1.85195E-05
6	0.1185	0.759	0.758627584	0.000372416	0.089897369	4.41313E-05
7	0.1678	0.757	0.757588615	0.000588615	0.12712337	9.87696E-05
8	0.2132	0.757	0.756512897	0.000487103	0.16128855	0.00010385
9	0.2545	0.7555	0.755256863	0.000243137	0.192212872	6.18783E-05
10	0.2924	0.754	0.753504446	0.000495554	0.2203247	0.0001449
11	0.3269	0.7505	0.750721589	0.000221589	0.245410887	7.24373E-05
12	0.3585	0.7465	0.745976109	0.000523891	0.267432435	0.000187815
13	0.3873	0.7385	0.737883093	0.000616907	0.285782122	0.000238928
14	0.4137	0.728	0.724383206	0.003616794	0.299677332	0.001496268
15	0.4373	0.7065	0.703501108	0.002998892	0.307641034	0.001311416
16	0.459	0.6755	0.67202177	0.00347823	0.308457992	0.001596508
17	0.4784	0.632	0.628590386	0.003409614	0.300717641	0.001631159
18	0.496	0.573	0.571332055	0.001667945	0.283380699	0.000827301
19	0.5119	0.499	0.500522774	0.001522774	0.256217608	0.000779508
20	0.5265	0.413	0.415810325	0.002810325	0.218924136	0.001479636
21	0.5398	0.3165	0.320294987	0.003794987	0.172895234	0.002048534
22	0.5521	0.212	0.214369632	0.002369632	0.118353474	0.001308274
23	0.5633	0.1035	0.10378341	0.00028341	0.058461195	0.000159645
24	0.5736	-0.01	-0.01159576	0.001595761	-0.00665133	0.000915329
25	0.5833	-0.123	-0.13301435	0.010014348	-0.07758727	0.005841369
26	0.59	-0.21	-0.20878607	0.001213926	-0.12318378	0.000716216

D. Three-diode model

The parameters extracted from the cuckoo Search algorithm is identified in table9. The results quality between the measured data and calculated data of the power and current are explained in table 10; also in this table the absolute error of the current $AE_I\ (A)$ and the absolute error of the power $AE_P\ (w)$ are appeared. The values of current absolute error are ranged from 0.00001002 to 0.010352854 and the values of power absolute error are ranged from 0.00000206111 to 0.00603882. This result confirms the accuracy of the extracted parameters. Figure 10 shows the fitness function with respect to the iteration numbers of the optimization algorithm for three-diode model.

TABLE 9
EXTRACTED PARAMETERS FOR THREE-DIODE MODEL

Parameters	Value
$I_{ph}\ (A)$	0.761182
$I_{s1}\ (\mu A)$	0.933
a_1	1.840943
$R_s\ (\Omega)$	0.012441
$R_{sh}\ (\Omega)$	50.68641
$I_{s2}\ (\mu A)$	0.84
a_2	1.620654
$I_{s3}\ (\mu A)$	0.84
a_3	1.620654
$RMSE$	0.002679151
AE at max power point	0.001488872

E. Modified three-diode model

The parameters extracted from the cuckoo Search algorithm is identified in table11. The results quality between the measured data and calculated data of the power and current are explained in table 12; also in this table the absolute error of the current $AE_I\ (A)$ and the absolute error of the power $AE_P\ (w)$ are appeared. The values of current absolute error are ranged from 0.0000877 to 0.007363115 and the values of power absolute error are ranged from 0.00000793162 to 0.004294905. This result confirms the accuracy of the extracted parameters. Figure 11 shows the fitness function with respect to the iteration numbers of the optimization algorithm for modified three-diode model.

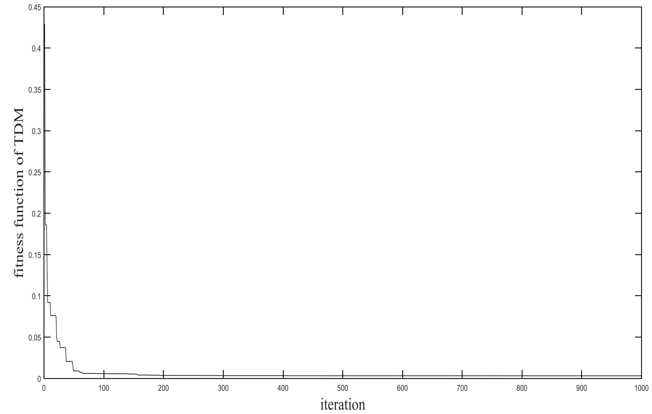

Fig10. The value of fitness function with respect to iteration for three-diode model

TABLE 10

RESULTS DATA FOR THREE-DIODE MODEL

Item	Experimental data [5]		Calculated current data		Calculated power data	
	V(V)	I_{exp} (A)	I_{sim} (A)	AE_I (A)	P_{sim} (w)	AE_P (w)
1	-0.2057	0.764	0.76398998	1.002E-05	-0.15715274	2.06111E-06
2	-0.1291	0.762	0.760769618	0.001230382	-0.09821536	0.000158842
3	-0.0588	0.7605	0.760065034	0.000434966	-0.04469182	2.5576E-05
4	0.0057	0.7605	0.759416262	0.001083738	0.004328673	6.1773E-06
5	0.0646	0.76	0.758817941	0.001182059	0.049019639	7.6361E-05
6	0.1185	0.759	0.758252017	0.000747983	0.089852864	8.8636E-05
7	0.1678	0.757	0.75768281	0.00068281	0.127139176	0.000114576
8	0.2132	0.757	0.757026168	2.61683E-05	0.161397979	5.57907E-06
9	0.2545	0.7555	0.756123356	0.000623356	0.192433394	0.000158644
10	0.2924	0.754	0.754643172	0.000643172	0.220657664	0.000188064
11	0.3269	0.7505	0.752023472	0.001523472	0.245836473	0.000498023
12	0.3585	0.7465	0.747305129	0.000805129	0.267908889	0.000288639
13	0.3873	0.7385	0.739085152	0.000585152	0.286247679	0.000226629
14	0.4137	0.728	0.725313573	0.002686427	0.300062225	0.001111375
15	0.4373	0.7065	0.704079806	0.002420194	0.307894099	0.001058351
16	0.459	0.6755	0.67225627	0.00324373	0.308565628	0.001488872
17	0.4784	0.632	0.628594704	0.003405296	0.300719706	0.001629094
18	0.496	0.573	0.571256011	0.001743989	0.283342982	0.000865018
19	0.5119	0.499	0.500448214	0.001448214	0.256179441	0.000741341
20	0.5265	0.413	0.415710275	0.002710275	0.21887146	0.00142696
21	0.5398	0.3165	0.319993444	0.003493444	0.172732461	0.001885761
22	0.5521	0.212	0.213775092	0.001775092	0.118025228	0.000980028
23	0.5633	0.1035	0.102830487	0.000669513	0.057924413	0.000377137
24	0.5736	-0.01	-0.0124861	0.002486099	-0.00716203	0.001426027
25	0.5833	-0.123	-0.13335285	0.010352854	-0.07778472	0.00603882
26	0.59	-0.21	-0.21060569	0.000605694	-0.12425736	0.000357359

TABLE 11
EXTRACTED PARAMETERS FOR MODIFIED THREE-DIODE MODEL

Parameters	Value
I_{ph} (A)	0.759207
I_{s1} (μA)	0.468
a_1	1.931475
R_s (Ω)	0.000132
R_{sh} (Ω)	59.17568
I_{s2} (μA)	0.948
a_2	1.698479
I_{s3} (μA)	0.568
a_3	1.597672
R_{s2} (Ω)	0.11459
RMSE	0.002391942
AE at max power point	0.001053656

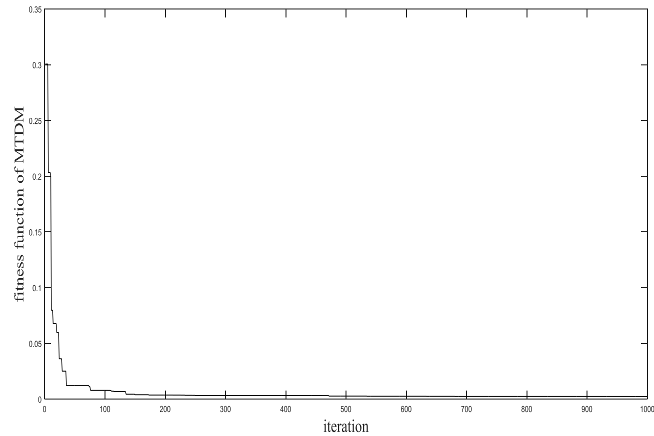

Fig11. The value of fitness function with respect to iteration for modified three-diode model

TABLE 12
RESULTS DATA FOR MODIFIED THREE-DIODE MODEL

Item	Experimental data [5]		Calculated current data		Calculated power data	
	V(V)	I_{exp} (A)	I_{sim} (A)	AE_I (A)	P_{sim} (w)	AE_P (w)
1	-0.2057	0.764	0.7640877	8.77E-05	-0.15717284	1.80399E-05
2	-0.1291	0.762	0.761388597	0.000611403	-0.09829527	7.89321E-05
3	-0.0588	0.7605	0.760200197	0.000299803	-0.04469977	1.76284E-05
4	0.0057	0.7605	0.759108488	0.001391512	0.004326918	7.93162E-06
5	0.0646	0.76	0.758106769	0.001893231	0.048973697	0.000122303
6	0.1185	0.759	0.757174912	0.001825088	0.089725227	0.000216273
7	0.1678	0.757	0.756279396	0.000720604	0.126903683	0.000120917
8	0.2132	0.757	0.755341895	0.001658105	0.161038892	0.000353508
9	0.2545	0.7555	0.754224011	0.001275989	0.191950011	0.000324739
10	0.2924	0.754	0.75262175	0.00137825	0.2200666	0.000403
11	0.3269	0.7505	0.75001583	0.00048417	0.245180175	0.000158275
12	0.3585	0.7465	0.745496732	0.001003268	0.267260578	0.000359672
13	0.3873	0.7385	0.737703296	0.000796704	0.285712486	0.000308564
14	0.4137	0.728	0.724598364	0.003401636	0.299766343	0.001407257
15	0.4373	0.7065	0.704186724	0.002313276	0.307940855	0.001011595
16	0.459	0.6755	0.673204453	0.002295547	0.309000844	0.001053656
17	0.4784	0.632	0.630109717	0.001890283	0.301444488	0.000904312
18	0.496	0.573	0.57280884	0.00019116	0.284113185	9.48154E-05
19	0.5119	0.499	0.501351691	0.002351691	0.256641931	0.001203831
20	0.5265	0.413	0.415458372	0.002458372	0.218738833	0.001294333
21	0.5398	0.3165	0.318622797	0.002122797	0.171992586	0.001145886
22	0.5521	0.212	0.212246456	0.000246456	0.117181268	0.000136068
23	0.5633	0.1035	0.102507616	0.000992384	0.05774254	0.00055901
24	0.5736	-0.01	-0.010331176	0.000331176	-0.00592596	0.000189963
25	0.5833	-0.123	-0.130363115	0.007363115	-0.07604081	0.004294905
26	0.59	-0.21	-0.204211355	0.005788645	-0.1204847	0.003415301

VI. Conclusion

This paper proposes a cuckoo search optimization algorithm to estimate the unknown's parameters for different models of photovoltaic. In case of single diode model the algorithm has been extracted five parameters and the root mean square error in this case is 0.003277202. In case of double-diode model the algorithm has been extracted seven parameters and the root mean square in this case is 0.003126809. In case of modified double-diode model the algorithm has been extracted seven parameters and the root mean square error in this case is 0.002705306. In case of three-diode model the algorithm has been extracted seven parameters and the root mean square error in this case is 0.002679151. In case of modified three-diode model the algorithm has been extracted seven parameters and the root mean square error in this case is 0.002391942. The parameters in the three-diode model has been estimated without any assumption for any parameter, the root mean square error for this case is better than single diode, double-diode and modified double-diode models. The root mean square error in case of modified three-diode model is better than the case of three-diode model.

In the future study, other optimization techniques such as genetic algorithm, grey wolf optimization algorithm, moth flame optimization algorithm and artificial intelligent are used in extraction of the nine parameters for three-diode model and ten parameters for modified three-diode model.

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