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Unknown Parameter Estimation of a Detailed Solar PV Cell Model

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***Abstract*—This paper proposes a novel technique for unknown parameter estimation of a detailed solar photovoltaic (PV) cell model based on the artificial bee colony (ABC) algorithm and particle swarm optimization (PSO) algorithm. This combination allows to balance between the exploration and exploitation abilities of each algorithm for achieving a good optimization performance. The detailed solar PV cell model is the double-diode model with seven unknown parameters which are estimated by using the hybrid ABC-PSO algorithm. The numerical results of the parameter estimation using the hybrid ABC-PSO algorithm are compared with those using the PSO, advanced PSO and ABC algorithms showing that the convergence speed and value of the hybrid ABC-PSO algorithm are always better than the PSO, advanced PSO and ABC algorithms.**

Keywords—parameter estimation, solar PV cell model, artificial bee colony algorithm

I. INTRODUCTION

The exhaustion of fossil fuel sources and environmental pollution are the key factors of promoting the exploitation of renewable energy sources. Amongst renewable energy sources, the solar energy has received considerable attention due to its infinite potential, cleanness, exploitation and utilization easily. There are many various exploitation techniques of the solar energy. In particular, the power generation from the solar energy through photovoltaic (PV) power systems in general and solar cells in particular is increasingly popular [1]. It is realized that the solar PV power systems work in outdoor environments and are easily exposed by various weather conditions. This greatly affects the efficiency of the power generation, as well as safety issues of the solar PV power systems. Therefore, it is necessary to assess the actual situation of the solar PV cells. In order to describe the solar PV cells, there are many various solar PV cell models introduced. In particular, the single-diode solar PV cell model and double-diode solar PV cell model are the two utilized models widely. It is obvious that the double-diode model is used to obtain more accurate results than the single-diode model in the control and operation problems of the solar PV power system under various operating conditions. Then the unknown parameter estimation of the solar PV cell model are important requiring a reasonable and effective technique. There have been several parameter estimation techniques consisting of the analytical, numerical and meta-heuristic techniques. Amongst these techniques, the meta-heuristic techniques have been found more efficient than the numerical and analytical techniques in the parameter estimation, especially in case of the large numbers of unknown parameters. The meta-heuristic algorithms include genetic algorithm (GA) [2]-[3], particle swarm optimization algorithm (PSO) [4]-[6], the combination of the sine-cosine algorithm (SCA) and whale optimization algorithm (WOA) [7], Nelder-Mead optimization (NMO) [8], fireworks explosion optimization algorithm (FEO) [9], gravitational search algorithm (GSA) [10], coyote optimization algorithm (COA) [11], artificial bee colony optimization (ABC) [12], etc. In this paper, the hybrid ABC-PSO algorithm is proposed to estimate the seven unknown parameters of the double-diode solar PV cell model. The estimated parameters of the double-diode solar PV cell model using the hybrid ABC-PSO algorithm are compared with those using the PSO, advanced PSO and ABC algorithms. The remainder of this paper is organized as follows. The mathematical model of a detailed solar PV cell is described in Section II. A novel application of the hybrid ABC-PSO algorithm for parameter estimation of a detailed solar PV cell is presented in Section III. The numerical results follow to confirm the validity of the novel application of the hybrid ABC-PSO algorithm in Section IV. Finally, the advantages of the novel application of the hybrid ABC-PSO are summarized by comparing with other existing algorithms such as the PSO, advanced PSO and ABC algorithms.

II. MATHEMATICAL MODEL OF A DETAILED SOLAR PV CELL

Regarding the issues of controlling and operating solar PV power systems in general and parameter estimation of a solar PV cell in particular, a mathematical model describing the solar PV cell is really necessary. There are two popular solar PV cell models including the single-diode solar PV cell model and the double-diode solar PV cell model. Amongst these two models, the double-diode solar PV cell model is considered to be more detailed than the single-diode solar PV cell model.

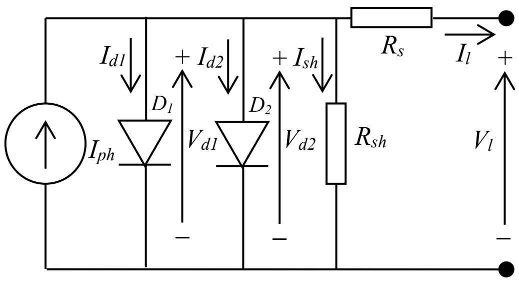

Fig. 1. Equivalent circuit of the double-diode solar PV cell model

It is realized that the more the solar PV cell model is detailed, the more the control and operation of the solar PV cell model is accurate and efficient. The double-diode solar

PV cell model is chosen for analysis and described through the equivalent circuit, Fig. 1.

From Fig. 1, it is applied the Kirchhoff's law of current and the Shockley equation, the current and voltage of the diode, D_1 are [13]:

$$I_{d1} = I_{01}\left[\exp\left(\frac{V_{d1}}{n_1 V_t}\right) - 1\right] \tag{1}$$

$$V_{d1} = V_l + R_s I_l \tag{2}$$

Similarly, the current and voltage of the diode, D_2 are:

$$I_{d2} = I_{02}\left[\exp\left(\frac{V_{d2}}{n_2 V_t}\right) - 1\right] \tag{3}$$

$$V_{d2} = V_l + R_s I_l \tag{4}$$

$$V_t = \frac{kT}{q} \tag{5}$$

$$V_{d1} = V_{d2} = V_d \tag{6}$$

$$I_{sh} = \frac{V_d}{R_{sh}} \tag{7}$$

The load current provided by a solar cell is:

$$I_l = I_{ph} - I_{d1} - I_{d2} - I_{sh} \tag{8}$$

From (1), (3) and (7), the equation (8) is re-written as follows:

$$\begin{aligned} I_l = I_{ph} - I_{01}\left[\exp\left(\frac{q(V_l + R_s I_l)}{n_1 kT}\right) - 1\right] - \\ - I_{02}\left[\exp\left(\frac{q(V_l + R_s I_l)}{n_2 kT}\right) - 1\right] - \frac{V_l + R_s I_l}{R_{sh}} \end{aligned} \tag{9}$$

Where

I_{d1} and I_{d2}: the current of the diode, D_1 and diode, D_2, respectively (A);

V_{d1} and V_{d2}: the voltage of the diode, D_1 and diode, D_2, respectively (V);

I_l: the load current provided by a solar cell (A);

V_l: the load voltage (V);

I_{01} and I_{02}: the reserve bias saturation current of the diode, D_1 and diode, D_2 (A);

q: the charge on the electron, $q = 1.602 \times 10^{-19}$ (C);

k: Boltzmann's constant, $k = 1.38 \times 10\text{-}23$ (m^2kg/s^2);

T: the absolute temperature of a solar PV cell in Kelvin (K);

R_{sh}: the shunt resistance (Ω);

R_s: the series resistance (Ω);

V_t: the panel's thermal voltage at 300^0K (V);

I_{ph}: the current source generated by a solar PV cell (A);

n_1 and n_2: the ideality coefficient of the diode, D_1 and diode, D_2.

It is realized that there are seven unknown parameters consisting of I_{ph}, I_{01}, I_{02}, R_s, R_{sh}, n_1 and n_2 in the double-diode model of a solar PV cell.

In this paper, the unknown parameter estimation problem is described through a root mean square error (RMSE) optimization problem which will be solve by using a hybrid algorithm of artificial bee colony (ABC) algorithm and the particle swarm optimization (PSO) algorithm. The hybrid ABC-PSO algorithm is described in the next section.

The root mean square error of the load current at various conditions is [11]:

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(I_{li}^{estimated} - I_{li}^{measured}\right)^2} \tag{10}$$

where

N: the number of measurements;

$I_{li}^{estimated}$: the i^{th} estimated load current provided by a solar cell (A);

$I_{li}^{measured}$: the i^{th} measured load current provided by a solar cell (A).

III. Hybrid ABC-PSO Algorithm Based Parameter Estimation

The ABC algorithm is inspired from the foraging behaviour of bees in nature [14]. It is assumed that the employed bee, the onlooker bee, and the scout bees are three artificial bee kinds in the colony utilized in the ABC algorithm. The ABC algorithm initializes the N sites of the random nectar source. Each site or each solution represents an employed bee.

The solution is:

$$x_{ij} = x_{ij}^{\min} + rand(0,1) \times \left(x_{ij}^{\max} - x_{ij}^{\min}\right) \tag{11}$$

Where

x_{ij}: the i^{th} solution of the j^{th} estimated parameters, $i = 1, 2, ..., N$, and $j = 1, 2, ..., M$;

x_{ij}^{max} and x_{ij}^{min}: the upper and lower bounds of estimated parameters;

N: the number of employed bees corresponding to the number of solutions;

M: the number of estimated parameters, $M = 7$.

Then each employed bee generates a modified nectar source depending on a neighbourhood of the present nectar source, and evaluates the quality of the nectar sources. When the employed bee group completes the search, it shares its information related to the nectar amounts and positions with the onlooker bee group on the dance area. An onlooker bee evaluates the nectar information taken from all employed bees and chooses a nectar source site with a probability related to its nectar amount. In this paper, the roulette wheel selection technique is applied to choose the nectar source site which has a higher probability of fitness function, p_i.

The probability of the fitness function is:

$$p_i = \frac{Fitness_i}{\sum_{i=1}^{N} Fitness_i} \quad (12)$$

An onlooker bee evaluates the nectar information taken from all the employed bees and selects a nectar source, X_i depending on its probability value, p_i. If a nectar source, X_i cannot be further improved through a predetermined number of trials, *Lim*, the nectar source is assumed to be abandoned. Then the corresponding employed bee becomes a scout bee. The scout bee randomly generates a nectar source as (11).

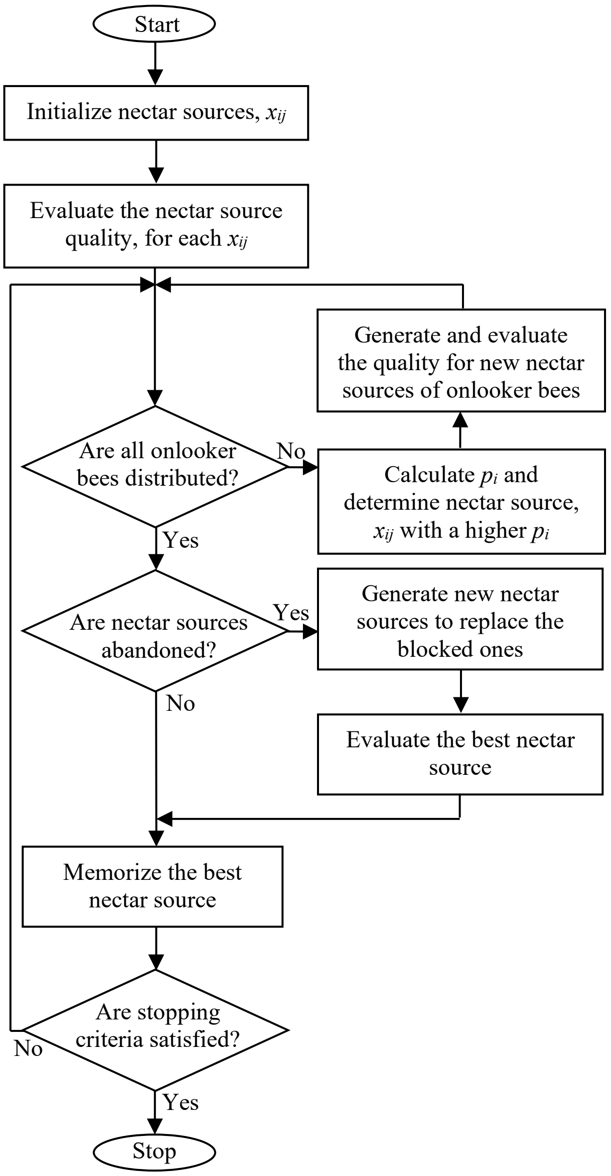

Fig. 2. Flowchart of the ABC algorithm

The predetermined trial number is:

$$Lim = N \times M \quad (13)$$

The flowchart of the ABC algorithm is shown in Fig. 2. It is realized that both the exploration and exploitation abilities are necessary for the population based algorithms. In order to achieve a good optimization performance, the balance approach of these two abilities is extremely important. In the ABC algorithm, the employed bees explore the new nectar source and send the information to the onlooker bees, whereas the onlooker bees exploit the nectar sources which are explored by the employed bees. It is obvious that the employed bee stage represents the exploration ability and the onlooker bee stage represents the exploitation ability. In the ABC algorithm, the search equation is good at the exploration but poor at exploitation. This certainly affects the convergence speed of the ABC algorithm. It is inspired by the particle swarm optimization (PSO) algorithm. The hybrid ABC-PSO algorithm is introduced for improving the exploitation of the ABC algorithm which is the combination between the ABC and PSO algorithms [15]. The hybrid ABC-PSO algorithm takes the advantages of the PSO's search process. Then the global best solution will be considered in the new search equation in the onlooker bee stage as follows.

$$v_{ij} = x_{ij} + \varphi_{ij}\left(x_{ij} - x_{kj}\right) + \sigma_{ij}\left(y_j - x_{ij}\right) \quad (14)$$

where

y_j: the j^{th} parameter of the global best solution;

σ_{ij}: the uniformly distributed random number, $\sigma_{ij} \in [0, 1.5]$.

The hybrid ABC-PSO algorithm is proposed to estimate seven unknown parameters consisting of I_{ph}, I_{01}, I_{02}, R_s, R_{sh}, n_1 and n_2 in the double-diode model of a solar PV cell.

IV. NUMERICAL RESULT

The numerical result is achieved on a commercial silicon solar PV cell. The data set of the solar PV cell's voltage and current is collected under the operating condition of the irradiation, G, 1000 W/m^2 and the temperature, T^0C, 33^{0}C [12]. The population size, N is 50. The predetermined trial number, *Lim* is 350. The stopping criterion is the maximum iteration number, $Iter^{max}$, 1000.

Table I shows the search space of estimated parameters in the double-diode solar PV cell model. Table II shows the parameters of the PSO, advanced PSO, ABC and hybrid ABC-PSO algorithms [15]. The parameters are estimated by using the PSO, advanced PSO, ABC and hybrid ABC-PSO algorithm shown in Table III respectively. It is based on the estimated parameters by using the hybrid ABC-PSO algorithm, the *V-I* and *V-P* experimental and estimated characteristics of the solar PV cell are shown in Figs. 3 - 4. Table IV gives information about the convergence value and speed of the PSO, advanced PSO, ABC and hybrid ABC-PSO algorithms. Furthermore, Table V shows that the error percentages of estimated load current provided by a solar cell which are always less than 0.1%. It is obvious that the achievement confirms the validation of the hybrid ABC-PSO algorithm in the parameter estimation application of the solar PV cell.

It is realized that the hybrid ABC-PSO algorithm's convergence speed and value are the best compared to those of the PSO, advanced PSO and ABC algorithms. The hybrid ABC-PSO algorithm converges at the 216th iteration and its convergence value is 0.000086 whereas the PSO, advanced PSO and ABC algorithms converge at 553th, 458th, 419th iteration respectively and their convergence values are 0.0088, 0.0065, 0.0036 in Table IV and Fig. 5 respectively.

It is obvious that the combination of the ABC and PSO algorithms has supported to enhanced the optimization performance through the balance between the exploration and exploitation abilities of the algorithm.

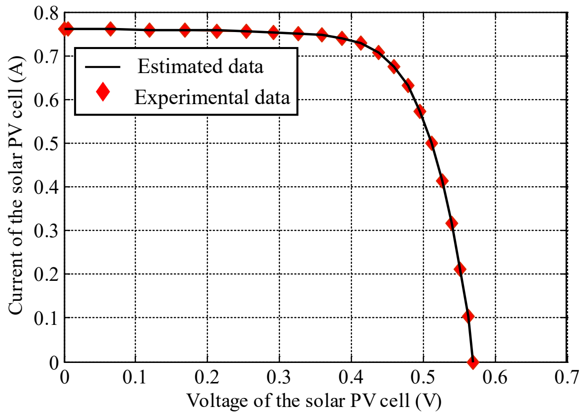

Fig. 3. *V-I* experimental and estimated characteristics of the double-diode solar PV cell using the hybrid ABC-PSO algorithm

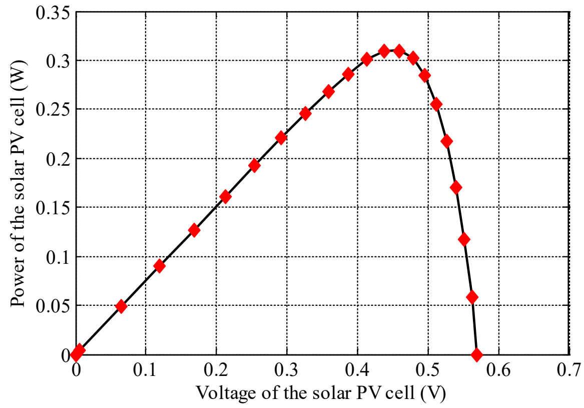

Fig. 4. *V-P* experimental and estimated characteristics of the double-diode solar PV cell using the hybrid ABC-PSO

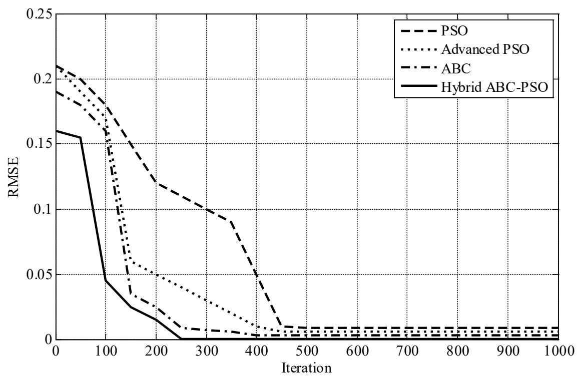

Fig. 5. Convergence characteristics of the PSO, advanced PSO, ABC and hybrid ABC-PSO algorithms

TABLE I. SEARCH SPACE OF ESTIMATED PARAMETERS IN THE DOUBLE-DIODE SOLAR PV CELL MODEL

Parameter	Lower bound	Upper bound
I_{ph} (A)	0	1
I_{01} and I_{02}(A)	0	1
R_s (Ω)	0	0.5
R_{sh} (Ω)	0	100
n_1 and n_2	1	2

TABLE II. PARAMETERS OF THE PSO, ADVANCED PSO, ABC AND HYBRID ABC-PSO ALGORITHMS

Algorithm	Parameter
PSO	+ The population size, $N = 50$; + The maximum iteration number, $Iter_{max} = 1000$; + **The inertia weight, *w* = 0.9**; + The acceleration coefficients, $c_1 = c_2 = 2$.
Advanced PSO	+ The population size, $N = 50$; + The maximum iteration number, $Iter_{max} = 1000$; + **The inertia weight, *w* is a chaotic map**; + The acceleration coefficients, $c_1 = c_2 = 2$.
ABC	+ The population size, $N = 50$; + The maximum iteration number, $Iter_{max} = 1000$; + **The rand(0,1) is used**.
Hybrid ABC-PSO	+ The population size, $N = 50$; + The maximum iteration number, $Iter_{max} = 1000$; + **Using the search equation (14) in the onlooker bee stage**.

TABLE III. ESTIMATED PARAMETERS OF THE DOUBLE-DIODE SOLAR PV CELL USING THE PSO, ADVANCED PSO, ABC AND HYBRID ABC-PSO ALGORITHMS

Parameter	PSO	Advanced PSO	ABC	Hybrid ABC-PSO
I_{ph} (A)	0.7380	0.7485	0.7601	0.7607
I_{01} (µA)	0.2918	0.3016	0.3119	0.0407
I_{02} (µA)	0.2918	0.3016	0.3119	0.2868
R_s (Ω)	0.0309	0.0321	0.0359	0.0366
R_{sh} (Ω)	51.2678	52.3526	53.3562	53.7704
n_1	1.2728	1.3183	1.4809	1.4496
n_2	1.2728	1.3183	1.4809	1.4886

TABLE IV. CONVERGENCE OF THE PSO, ADVANCED PSO, ABC AND HYBRID ABC-PSO ALGORITHMS

Algorithm	Convergence value	Convergence speed
PSO	0.0088	553th iteration
Advanced PSO	0.0065	458th iteration
ABC	0.0036	419th iteration
Hybrid ABC-PSO	0.000086	216th iteration

V. CONCLUSION

This paper proposed the hybrid ABC-PSO algorithm to enhance the convergence ability of the ABC algorithm through the balance improvement between the exploration and exploitation for the parameter estimation of the detailed solar PV cell model which is described with the double-diode equivalent circuit. The seven unknown parameters of the solar PV cell using the hybrid ABC-PSO algorithm have been estimated and compared those of using the PSO, advanced PSO and hybrid ABC-PSO algorithms. The comparison have shown that the hybrid ABC-PSO algorithm's result is the best. The convergence value and speed of the hybrid ABC-PSO algorithm have always been better than those of the PSO, advanced PSO and hybrid ABC-PSO algorithms.

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TABLE V. THE VOLTAGE AND CURRENT OF THE DOUBLE-DIODE SOLAR PV CELL

Data	Measured voltage (V)	Measured current (A)	Estimated current (A)	Current error (A)	Error percentage of current (%)
1	0.0057	0.7605	0.7607	0.0002	0.03
2	0.0646	0.7600	0.7599	0.0001	0.01
3	0.1185	0.7590	0.7588	0.0002	0.03
4	0.1678	0.7570	0.7572	0.0002	0.03
5	0.2132	0.7570	0.7569	0.0001	0.01
6	0.2545	0.7555	0.7558	0.0003	0.04
7	0.2924	0.7540	0.7539	0.0001	0.01
8	0.3269	0.7505	0.7506	0.0001	0.01
9	0.3585	0.7465	0.7466	0.0001	0.01
10	0.3873	0.7385	0.7388	0.0003	0.04
11	0.4137	0.7280	0.7282	0.0002	0.03
12	0.4373	0.7065	0.7068	0.0003	0.04
13	0.4590	0.6755	0.6756	0.0001	0.01
14	0.4784	0.6320	0.6322	0.0002	0.03
15	0.4960	0.5730	0.5728	0.0002	0.03
16	0.5119	0.4990	0.4989	0.0001	0.02
17	0.5265	0.4130	0.4128	0.0002	0.05
18	0.5398	0.3165	0.3166	0.0001	0.03
19	0.5521	0.2120	0.2121	0.0001	0.05
20	0.5633	0.1035	0.1036	0.0001	0.10