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Coyote Optimization Algorithm for Parameters Estimation of Various Models of Solar Cells and PV Modules

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ABSTRACT Recently, building an accurate mathematical model with the help of the experimentally measured data of solar cells and Photovoltaic (PV) modules, as a tool for simulation and performance evaluation of the PV systems, has attracted the attention of many researchers. In this work, Coyote Optimization Algorithm (COA) has been applied for extracting the unknown parameters involved in various models for the solar cell and PV modules, namely single diode model, double diode model, and three diode model. The choice of COA algorithm for such an application is made because of its good tracking characteristics and the balance creation between the exploration and exploitation phases. Additionally, it has only two control parameters and such a feature makes it very simple in application. The Root Mean Square Error (RMSE) value between the data based on the optimized parameters for each model and those based on the measured data of the solar cell and PV modules is adopted as the objective function. Parameters' estimation for various types of PV modules (mono-crystalline, thin-film, and multi-crystalline) under different operating scenarios such as a change in intensity of solar radiation and cell temperature is studied. Furthermore, a comprehensive statistical study has been performed to validate the accurateness and stability of the applied COA as a competitor to other optimization algorithms in the optimal design of PV module parameters. Simulation results, as well as the statistical measurement, validate the superiority and the reliability of the COA algorithm not only for parameter extraction of different PV modules but also under different operating scenarios. With the COA, precise PV models have been established with acceptable RMSE of 7.7547×10^{-4}, 7.64801×10^{-4}, and 7.59756×10^{-4} for SDM, DDM, and TDM respectively considering R.T.C. France solar cell.

INDEX TERMS Solar cells, PV modules, parameter extraction, optimization, coyote optimization algorithm, single diode model, double diode model, three diode model.

I. INTRODUCTION

Due to the availability of solar energy (SE) at a very high rate, the exploration and investigation of the solar energy systems are extensively performed to achieve the best exploitation of this kind of renewable energy sources [1]. As the SE is a clean source, so it contributes effectively in reducing the pollution rates around the earth, besides that it helps to reduce the burdens on the traditional nonrenewable energy systems used for generating the electricity such as steam power stations and hydroelectric power stations [2], [3]. Based on this, plenty of research studies have been carried out for solving the problems appeared as a result of the increased progress in the field of SE [2]. The majority of

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the presented studies have concerned with analyzing the performance of the photovoltaic (PV) modules which are consisting of groups of solar cells (SC) [4]. By the end of the last decade, the demand for the PV modules witnessed a remarkable rising, and at the same time, their prices reduced noticeably.

Despite the fact that the PV has brought great benefits to the grid/micro-grid [5]–[7] and the electricity markets, it suffered from a remarkable challenge related to the operating efficiency which varies according to the weather conditions under which the SC works [8], [9]. This is in addition to its high maintenance cost as reported in Ref. [10], [11]. According to these shortages; robust designing techniques have to be developed to realize the optimal operation of the PV modules and solar cells under different operating conditions. The design procedure for the SC is mainly depending on the equivalent mathematical model of the SC itself. The importance of the SC model is obvious through its ability to stimulate all variables, which manage the dynamic behavior of the real SC. Moreover, through analyzing the behavior using the mathematical model, the current-voltage (I-V) curve can be easily obtained, which contributes effectively in understanding the behavior of SC and PV systems under different weather conditions.

The main two models, which have been used for modelling the SC are the Single-Diode (SD) model and Double-Diode (DD) model. The two models are consisting of electronic elements, which form a circuit that can analyze and incorporate the nonlinearities of the real SC. Both the SD and DD models include a set of components, which are the diode-saturation current, the photo-generated current, the series resistance, and the ideality factor pertinent to the diode. For the SD model, five parameters are utilized to represent the SC operation. Meanwhile, for the DD model, it employs about seven parameters. The key point about deriving an efficient mathematical model depends entirely on the estimation of these parameters, and thus the parameters have to be properly and precisely extracted to achieve a correct balance between the current (I) and voltage (V) for the SC and PV modules as well.

Despite the ability of these modules (SD and DD) to provide better analysis of the SC or PV systems, their utilization had been restricted to the domestic use, which means that their dynamic performance had been tested for a limited number of operating conditions. To overcome this shortage, the Three-Diode (TD) model has been presented [12]. The TD model incorporates nine parameters in order to model and stimulate the behavior of the SC and PV modules. Utilizing the nine parameters of the TD model has enabled the modeling of the real industrial applications of the SC and PV modules with high accuracy and improved efficiency. In general, using the diode models require the configuration of parameters set to achieve the desired performance, and this is considered as a challenge. However, this issue can be treated and formulated in the form of an optimization problem.

Plenty of numerical methodologies are applied to explore the finest model parameters, which achieve the best performance of the PV systems. In [13], a nonlinear least-squares algorithm with the utilization of the Newton model has been implemented to estimate the SC unknown parameters.

Analytical methods and techniques have been applied for introducing I-V characteristics using a co-content function as stated in [14]. In [15], three analytical algorithms have been introduced and compared with each other for extracting the SC parameters depending on the SD model; the conclusion stated that the curve-fitting technique had the best result. In [16], A proposed RMSE expression based on Lambert W function has been proposed as an exact solution for RMSE of 5-parameter single diode PV models. However, in [16], there is no exact analytical solution based on Lambert W function has been reached for DDM or TDM yet because of the high nonlinearity of the current expressions of these models [16]. Lambert W-function was reported in [17], which has been utilized to extract the parameters of the DD model. In [18], Tabular techniques have been adopted for the PV systems with accurate results; however, the computational burden was high. In [19], a detailed comparison between the Levenberg-Marquardt algorithm and the Newton-Raphson technique has been presented for estimating the parameters of PV modules. These types of optimization techniques were called deterministic techniques, which can consider several boundary conditions such as convexity and differentiability to ensure proper implementation. Unfortunately, this action resulted in introducing local optima due to the dependency of the outputs on the primary solutions. The last fact can be investigated in [20], where the Newton-Raphson technique was used to extract the unknown parameters of the DD model. The results introduced a remarkable deviation between the real and estimated values of voltage and current [21], [22]. This is in addition to the high computational burdens of these methodologies.

In the last decade, the evolutionary computation algorithms have been presented and implemented for extracting the model parameters of PV modules and SC. Such algorithms possess various advantages such as they do not need anticipated information about the search space, and they have the ability to carry out a multidimensional exploration in the search spaces using different arrangements until the best solution has appeared [23]. Based on the merits of evolutionary computation algorithms, various approaches have been proposed. In [24], the genetic algorithms (GA) have been utilized to enhance the accuracy of parameters estimation for the DD model of the PV modules and SC. In [25], the particle swarm optimization (PSO) has been adopted to evaluate the parameters of solar cells using both the SD and DD models. An efficient technique has been proposed in [26]. This algorithm is called the Simulated Annealing (SA) method, which has been utilized to determine the parameters of the SD and DD model of SC and PV modules. Moreover, it has been demonstrated that the meta-heuristic (MH) optimization techniques allow building an effective PV modulator according to various criteria such as precision, consistency, convergence speed, calculation efficiency and the reduced number of control parameters [23], [27]–[36]. These algorithms can be classified into four categories, evolutionary algorithms (Genetic Algorithm (GA), differential Evolution (DE), and Confidence-Weighted (SCW), physics-based algorithms (Wind Driven Optimization (WDO), Flower Pollination Algorithm (FPA), and Gravitational Search Algorithm (GSA)), swarm-based algorithms (Artificial bee colony (ABC), particle swarm optimization (PSO), Cat Swarm Optimization (CSO), Whale Optimization Algorithm (WOA), and human-based algorithms (HBA). The following points can be concluded from the introduced review: The influence on the performance of these techniques by noise and change in irradiation and temperature should be taken into account. To find the optimal solution, it is suggested to evaluate the impact of various objective functions on the performance of the MH methods: the error of calculation and estimating energy, the root mean square error, relative mistakes, etc.

To improve the performance of the MH, it is advisable to make combinations between the MH methods and other alternative methods. These combinations include; the chaotic maps methods, opposite learning method, quantum methods, and the hybridization of different MH methods. For example, this helps the MH methods to discover the search area and improve their robustness, behavior, and time complexity; study the impact of the metaheuristic method control parameters on their operation and effectiveness. As most parameters are random, selecting the optimal value will improve the shape of the convergence behavior and prevent the local point from being stuck. The new methods of metaheuristic proposed for extracting the ideal PV cell parameters should reduce their time complexity. Further experiments with different MH methods are required in the three-diode model.

From the abovementioned review, it can be realized that the studies in the literature with regards to parameters' estimation accuracy for the SC and PV modules have been limited to the SD and DD models and they were rarely treated with the TD model, and for this purpose, the current paper introduces a comprehensive study about the estimation of the design parameters of SD, DD and TD models for the SC and PV modules using different optimization algorithms. From this context, Coyote Optimization Algorithm (COA) [37] is applied in this paper to address the problem of optimal estimation of the unknown parameters for different models of SCs and PV modules.

The paper is organized as follows; Section II introduces and analyzes the different diode models for the SC and PV modules. Moreover, section II illustrates the methodology of applying the optimization algorithm to estimate the model parameters of SC. In section III, the proposed optimization technique is introduced and explained. The tests are carried out and discussed in section IV. Finally, the conclusions and outcomes are discussed in section V.

II. MODELS OF SOLAR CELLS

In order to design the SC and PV modules, a mathematical model has to be used to extract the SC parameters analytically. Based upon this, electronic circuits consisting of diodes are used to model the SC. The SD and DD models are the most items used for evaluating the parameters of the SC and PV modules, this is in addition to the TD circuit which is introduced recently [12].

A. SINGLE DIODE (SD) MODEL

As shown in Fig.1, the model has only one diode used for parallelizing the current source I_{ph} that presents the photo-generated current. The diode acts as a half-wave rectifier. The model considers also the non-physical ideality factor of the diode [26]. The model has a very simple form, and thus it is easy to be implemented. The main issue with this simple model is that it contains only five unknown parameters, which have to be precisely determined.

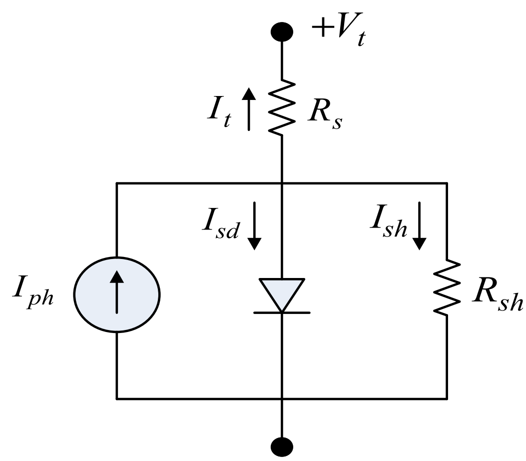

FIGURE 1. Circuit configuration of solar cell single-diode model.

In Fig. 1, the SC current I_t can be identified from the following expression;

$$I_t = I_{ph} - I_{sd} - I_{sh} \tag{1}$$

where I_t, I_{ph}, I_{sd} and I_{sh} refer to the output, photo-generated, diode, and parallel resistance currents, respectively.

It is possible to use the equivalent diode equation developed by Shockley in order to develop a more precise model for the internal parameters of the diode. Thus, (1) can be reformulated by,

$$I_t = I_{ph} - I_{sd}\left[\exp\left(\frac{q\,(V_t + R_s I_t)}{nkt}\right) - 1\right] - \frac{V_t + R_s I_t}{R_{sh}} \tag{2}$$

where V_t is the output cell voltage and I_{sd} is the diode saturation current. $R_s$is the series resistance and R_{sh} represents the shunt resistance; while n refers to the non-physical ideality factor. Moreover, q refers to the charge magnitude on an electron, and $q = 1.602 \times 10^{-19}$ Coulombs (C). k is the Boltzmann constant *and* $k = 1.380 \times 10^{-23}$ (J/K).

T is the solar cell temperature in Kelvin (K). Thus, the proper operation of the model can be achieved through the accurate estimation of these parameters, which will be performed using different optimization algorithms in the next sections.

B. DOUBLE DIODE (DD) MODEL

The SD model is not usually a suitable selection for different applications [36]; and for this reason, the double diode (DD) model is proposed as presented in Fig. 2.

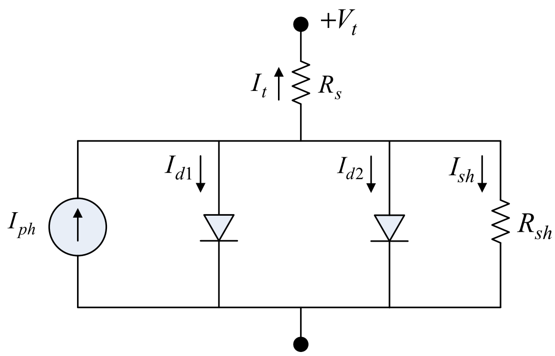

FIGURE 2. Circuit configuration of the solar cell double-diode model.

From Fig. 2, it can be noticed that there are two diodes; the first is acting as a rectifier while the other is used to take into consideration the effect of current results from the recombination and the impact non-idealities of the SC [36]. The current balance in the equivalent circuit of Fig. 2 can be represented by:

$$I_t = I_{ph} - I_{d1} - I_{d2} - I_{sh} \tag{3}$$

where I_{d1}, I_{d2} represent the first and second diode currents, respectively. The Shockley equivalence is utilized in order to update the internal arrangement of the two diodes. Accordingly, Eq. (3) can be reformulated as follows,

$$I_t = I_{ph} - I_{sd1}\left[\exp\left(\frac{q\left(V_t + R_s I_t\right)}{n_1 kt}\right) - 1\right] - I_{sd2}\left[\exp\left(\frac{q\left(V_t + R_s I_t\right)}{n_2 kt}\right) - 1\right] - \frac{V_t + R_s I_t}{R_{sh}} \tag{4}$$

where I_{sd1}, I_{sd2} are the diffusion and saturation currents for each diode (D_1 and $D2$). n_1 and n_2 are the diffusion and re-combination ideality factors of the diodes. The rest of the parameters in (4) are previously presented and defined by (2), and thus the DD model will have seven unknown parameters that need to be estimated R_s, R_{sh}, I_{ph}, I_{sd1}, I_{sd2}, n_1 and n_2.

C. THREE DIODE (TD) MODEL

An accurate model for SC and PV modules is essential for energy system analysis. The three diodes (TD) model is more appropriate for industrial applications [38]. The variable values of n_1 and n_2 illustrate that the DD model is not enough to represent the different current components of SC. The impact of gain boundaries and current losses due to leakage in the circuit have been considered with the

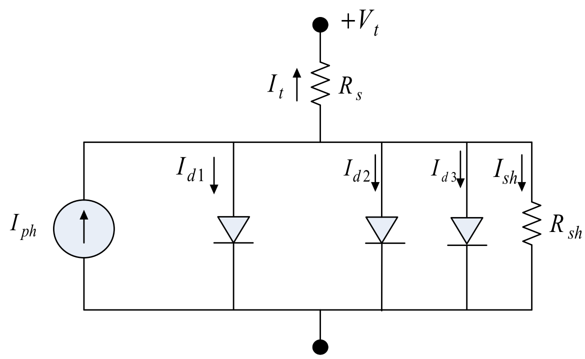

FIGURE 3. Circuit configuration of the solar cell three-diode model.

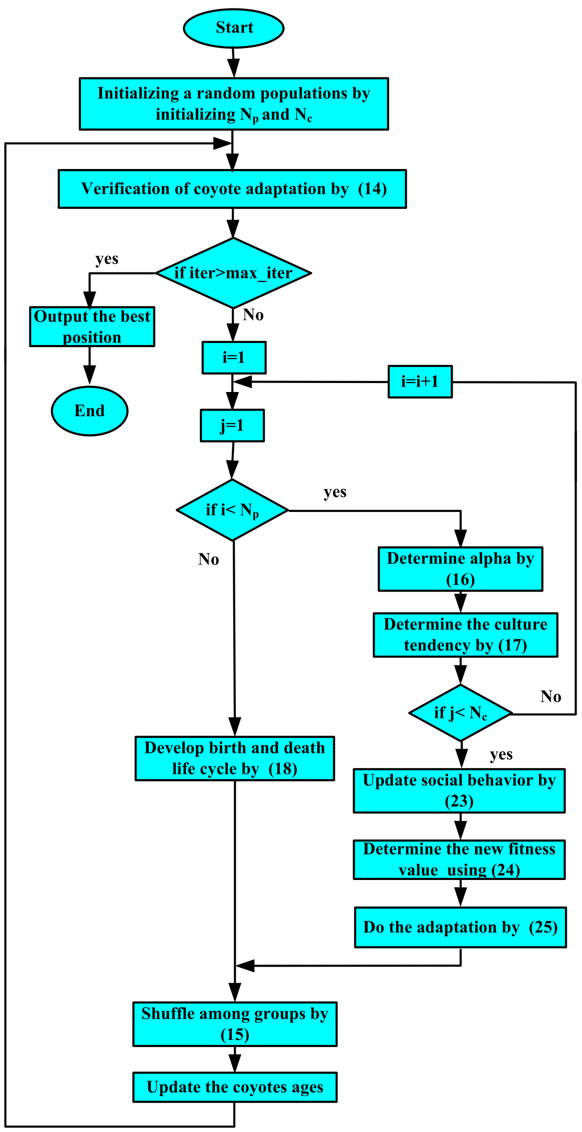

FIGURE 4. Flowchart of COA optimization method.

TABLE 1. Estimated model parameters for SDM of R.T.C. France solar cell, obtained by various optimization methods.

Technique	I_{ph} (A)	I_{sd} (μA)	R_s (Ω)	R_{sh} (Ω)	N	RMSE
COA	0.76076929153	0.3083945801266	0.03655460766	52.82666150326	1.47654776591	7.75470161606E-04
ABSO [40]	0.76080	0.30623	0.03659	52.2903	1.47583	9.9124E-04
HS [36]	0.7607	0.30495	0.03663	53.5946	1.47538	9.9510E-04
PSO [25]	0.7607	0.400	0.0354	59.012	1.5033	1.3900E-03
GA [47]	0.7619	0.8087	0.0299	42.3729	1.5751	1.8704E-02
An.5-Pt. [48]	0.7606	0.2417	0.0422	106.3829	1.4513	7.9602E-03
LW [49]	0.7611	0.2422	0.0373	42	1.4561	9.6964E-03
Newton [50]	0.7608	0.3223	0.0364	53.7634	1.4837	1.0072E-02
CM [51]	0.7608	0.4039	0.0364	49.5050	1.5039	2.8573E-03
PS [52]	0.7617	0.998	0.0313	64.1026	1.6	1.4940E-02

TABLE 2. Estimated model parameters for DDM R.T.C. France solar cell, obtained by various optimization methods.

Technique	I_{ph} (A)	I_{sd1} (μA)	I_{sd2} (μA)	R_s (Ω)	R_{sh} (Ω)	n_1	n_2	RMSE
COA	0.76071947	0.244676601	0.380190150	0.03692707	53.51296961	1.456352519	1.98992353	7.648012794E-04
ABSO [53]	0.76078	0.26713	0.38191	0.03657	54.6219	1.46512	1.98152	9.8344E-04
HS [36]	0.76176	0.12545	0.2547	0.03545	46.82696	1.49439	1.49989	1.2600E-03
PSO [25]	0.7623	0.4767	0.01	0.0325	43.1034	1.5172	2	1.6600E-03
GA [47]	0.7608	0.0001	0.0001	0.0364	53.7185	1.3355	1.481	3.6040E-01
ABC [42]	0.760813	0.192684	0.999587	0.036861	55.933515	1.438003	1.983721	9.8387E-04
SBMO [43]	0.760786	0.200798	0.74373	0.036917	55.104367	1.441256	1.947888	9.8485E-04
SSO [54]	0.760651	0.287201	0.065979	0.036255	55.853271	1.510345	1.433838	9.9129E-04
MSSO [54]	0.760748	0.234925	0.671593	0.036688	55.714662	1.454255	1.995305	9.8281E-04

TD model. Hence, the equivalent circuit of the TD model after the parallel connection of the third diode is shown in Fig. 3.

For the first diode, the current diode I_{d1} is represented by recombination and diffusion processes in the near-neutral region with a volume of $n_1 = 1$ and the second diode with a new diode, I_{d2}, as the space area is replicated to $n_2 = 2$. Due to the recombination that has occurred inside the defect areas, the objective of the addition of a third diode along with both diodes is to consider the contribution of the current diode element I_{d3}. The performance current will be based on the KCL for the previous estimate.

$$I_t = I_{ph} - I_{d1} - I_{d2} - I_{d3} - I_{sh} \tag{5}$$

So,

$$\begin{aligned} I_t = I_{ph} &- I_{sd1}\left[\exp\left(\frac{q\,(V_t + R_s I_t)}{n_1 kt}\right) - 1\right] \\ &- I_{sd2}\left[\exp\left(\frac{q\,(V_t + R_s I_t)}{n_2 kt}\right) - 1\right] \\ &- I_{sd3}\left[\exp\left(\frac{q\,(V_t + R_s I_t)}{n_3 kt}\right) - 1\right] - \frac{V_t + R_s I_t}{R_{sh}} \end{aligned} \tag{6}$$

where, I_{d1} is the current of diffusion, and I_{d2} is the current of recombination. The current recombination contributes to I_{d3} in the region of a defect while n_1, n_2 and n_3 are non-physical ideality factors. So, the TD model will have nine parameters

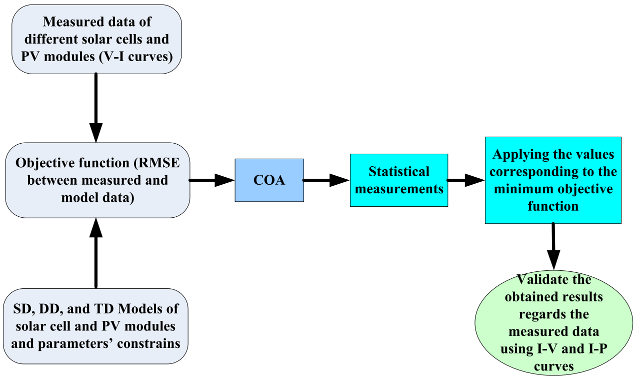

FIGURE 5. Application of COA for extracting the PV model parameters.

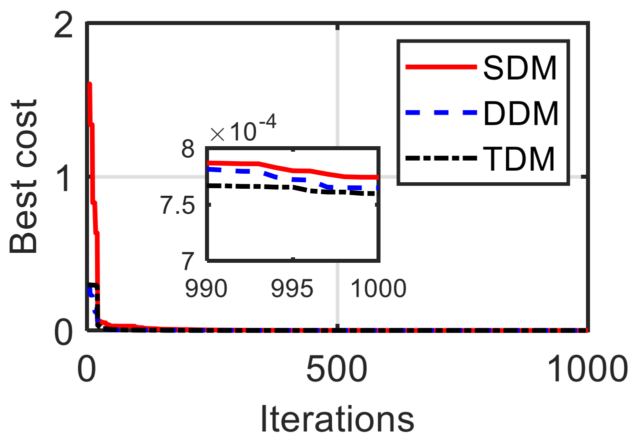

FIGURE 6. Convergence trends of the fitness function for R.T.C. France solar cell using the applied COA-based models.

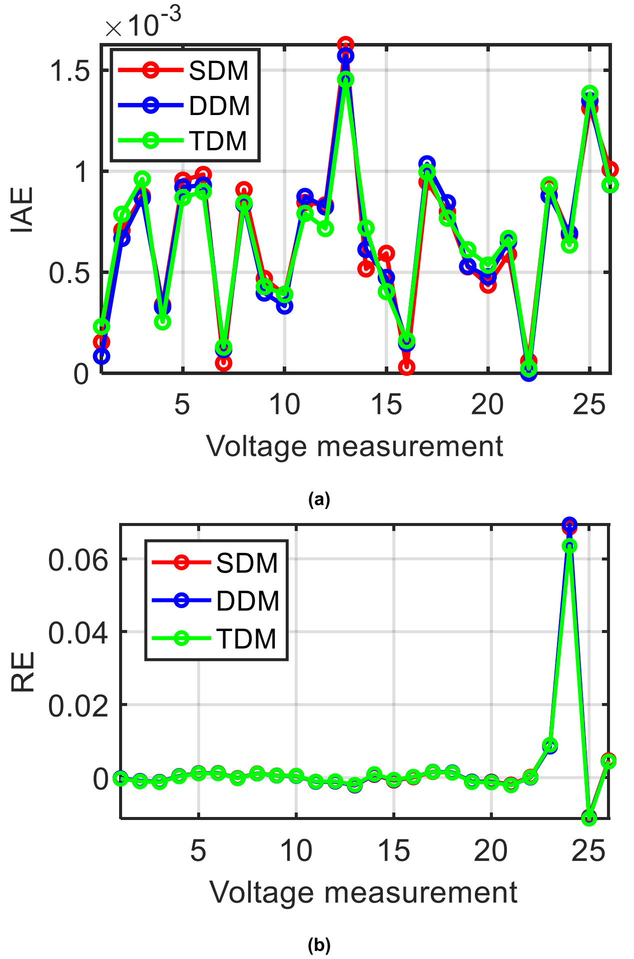

FIGURE 7. Error curves of the computed and measured current values of RTC France solar cell for the three models (a) values of IAE; (b) values of RE.

that need to be extracted (R_s, R_{sh}, I_{ph}, I_{sd1}, I_{sd2}, I_{sd3}, n_1, n_2 and n_3).

D. FORMULATION OF THE OPTIMIZATION PROBLEM OF SOLAR CELLS PARAMETERS IDENTIFICATION

Through using the mathematical model of the SD, DD and TD, it is possible to address each of them as an optimization problem and its solution is the optimal values of the unknown model parameters. At first, a cost function has to be used to check if the estimated parameters are matching their actual values or not. The validity of the estimation procedure can be also investigated through checking the matching degree between the I-V characteristics given in the datasheet of a real solar cell and that estimated based on the optimized parameters of the mathematical empirical model solved based on Newton-Raphson method. Then, for the SD, the objective function can be represented by [39], [40] as follows,

$$f_{SD}(V_t, I_t, x) = I_t - x_3 + x_4\left[\exp\left(\frac{q(V_t + x_1 I_t)}{x_5 kt}\right) - 1\right] - \frac{V_t + x_1 I_t}{x_2} \quad (7)$$

While, for the DD model, the error function is represented by,

$$f_{DD}(V_t, I_t, x) = I_t - x_3 + x_4\left[\exp\left(\frac{q(V_t + x_1 I_t)}{x_6 kt}\right) - 1\right] + x_5\left[\exp\left(\frac{q(V_t + x_1 I_t)}{x_7 kt}\right) - 1\right] + \frac{V_t + x_1 I_t}{x_2} \quad (8)$$

Whereas, for the TD model, the error function can be represented by,

$$f_{TD}(V_t, I_t, x) = I_t - x_3 + x_4\left[\exp\left(\frac{q(V_t + x_1 I_t)}{x_6 kt}\right) - 1\right] + x_5\left[\exp\left(\frac{q(V_t + x_1 I_t)}{x_7 kt}\right) - 1\right] + x_8\left[\exp\left(\frac{q(V_t + x_1 I_t)}{x_9 kt}\right) - 1\right] + \frac{V_t + x_1 I_t}{x_2} \quad (9)$$

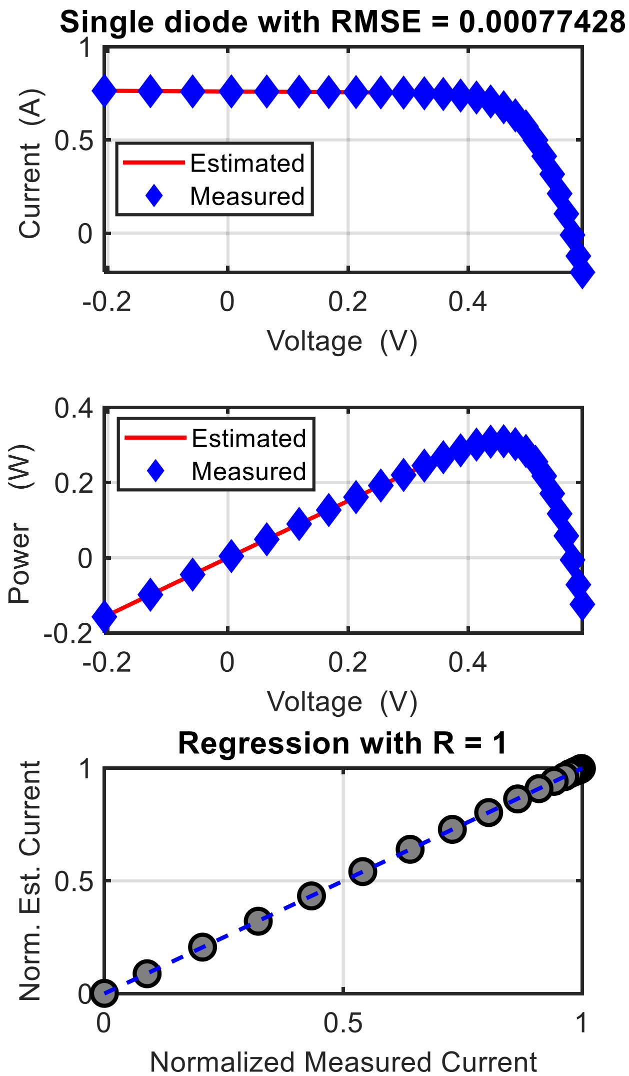

FIGURE 8. Comparison of the characteristics of RTC France solar cell based on measured data and computed ones using SDM.

The values of V_t and I_t are measured values from a real solar cell. In (7), $x = [R_s, R_{sh}, I_{ph}, I_{sd}, n]$ is the solution vector. The solution vector in the case of the DD model is $x = [R_s, R_{sh}, I_{ph}, I_{sd1}, I_{sd2}, n_1, n_2]$ and for the TD model $x = [R_s, R_{sh}, I_{ph}, I_{sd1}, I_{sd2}, I_{sd3}, n_1, n_2, n_3]$. The functions f_{SD}, f_{DD} and f_{TD}) check and measure the similarity rate of the outputs from each circuit regarding the experimentally measured ones. Then, the cost function is formulated on the base of finding the parameters that result in the minimum error between the actual I_t (obtained from measurements) and the estimated I_t (obtained by the diode models). A set of N_E samples is necessary to be used in order to widen the search until the global optima appears, and then the cost function can be defined by,

$$RMSE(x) = \sqrt{\frac{1}{N}\sum_{c=1}^{NE}\left(f_M^c\left(V_t^c, I_t^c, x\right)\right)^2} \quad (10)$$

where the abbreviation *RMSE* denotes the root mean square error and *M* helps in identifying which diode model is to be utilized. COA technique will be used for identifying the optimal values of the unknown parameters of different solar cells and PV modules, which result in the minimum value of the objective function.

Pseudo-code for calculating the RMSE using Newton-Raphson method may be written as the following:

```
% calculating the RMSE using Newton-Raphson;
Input k = 1.3806503E-23; q = 1.60217653E-19;
T= 273.15+33; V_t = k*T/q;
Read TOLER; tolerance to stop iterating
Input the measured voltage vector
Input the measured current vector
Initialize estimated current to zero
Read model parameters I_ph; I_sd; R_s; R_sh; n from
the COA optimizer
for J = 1 to size of measured voltage vector
iniEal guess (I0(J))
while (f>TOLER - tolerance to stop iterating)
f (J) = f(I,J)
f1(J) = f'(I,J)
I1(J) = I (J)– f(J)/f1(J)
I(J) = I1(J)
end while
end for
calculate of RMSE between measured currents and esti-
mated currents
print the RMSE, estimated currents
plot (measured voltage, estimated currents)
```

III. COYOTE OPTIMIZATION ALGORITHM

Coyotes are Canis Latrans species, particularly in North America. The coyote optimization algorithm (COA) is considered as a population-based algorithm that mimics the way that coyotes follow in an adaptation to the surrounding environment and social behaviors. In its operation. COA makes combinations between the swarm intelligence and evolutionary heuristic. For optimization processes, COA provides equilibrium between discovery and development. The COA differs from the gray wolf optimization algorithm [37], [41]. The GWO describes the entire attacking cycle of the prey while the COA represents the social structure and shared understanding between the coyotes [37]. The population in this algorithm is divided into N_P groups, with N_c coyotes in each group. The coyote solution is a candidate and fitness costs are their social behavior. The social behavior of the *c*-th coyote in *p*-th group at a time *t* is presented by a vector of development variables [37].

$$soc_c^{p,t} = x = (x_1, x_2, \ldots..x_D) \quad (11)$$

The value of the fitness feature is taken into account when adapting a coyote with its environment. The coyotes or agents

TABLE 3. Estimated model parameters for TDM R.T.C. France solar cell, obtained by various optimization methods.

Technique	I_{ph} (A)	I_{sd1} (μA)	I_{sd2} (μA)	I_{sd3} (μA)	R_s (Ω)	R_{sh} (Ω)	n_1	n_2	n_3	RMSE
COA	0.7608824	0.2094596	0.1914271	0.237428	0.036921	53	1.753999572	1.439617038	1.9	7.597569E-04
ABC [42]	0.7607	0.2000	0.5	0.2100	0.03687	55.8344	1.4414	1.9	2	9.8466E-04
OBWOA [55]	0.76077	0.2353	0.2213	0.4573	0.03668	55.4448	1.4543	2	2	9.8249 E-04
STBLO [48]	0.7608	0.2349	0.2297	0.2297	0.0367	55.2641	1.4541	2	2	9.8253 E-04

TABLE 4. Statistical measurement of the applied COA method for R.T.C. France solar cell based on different models.

	SDM	**DDM**	**TDM**
Min	0.000774277651108992	0.000764801279458072	0.000759756935254174
Max	0.000798278439833923	0.000786616473995444	0.000764253761539576
Mean	0.000781740849855097	0.000771699396682027	0.000761424974404541
Median	0.000780331801958868	0.000770756168061342	0.000761117517842934
SD	0.000641053602455053	0.000515824427153203	0.000121083539802071
RE	0.289167538366187	0.270584689483363	0.0658647156596761
MAE	7.46319874610470e-06	6.89811722395470e-06	1.66803915036611e-06
RMES	9.76854519577251e-06	8.56180991777169e-06	2.04929407916093e-06
Eff.	99.0517101380103	99.1103672340050	99.7811755269875
		WILCOXON SIGNED RANK TEST	
P	1.7344e-06	1.7344e-06	1.7344e-06
Rank	1	1	1

TABLE 5. Estimated model parameters for SDM of photowatt-PWP201 module, obtained by various optimization methods.

Technique	I_{ph} (A)	I_{sd} (μA)	R_s (Ω)	R_{sh} (Ω)	N	RMSE
COA	1.03152750757054	3.62496529235387	1.19791296762334	940.015655850509	1.40855995901487	0.00294960692837003
Newton [13]	1.0318	3.2875	1.2057	555.5556	1.3474016	0.7805
PS [52]	1.0324	3.1859	1.304	843.5233	48.2467	0.0127
OIS [56]	1.03674	3.1946	1.32897	1184.58	49.0435	0.004783
DAB[49]	1.04276	3.4265	1.73762	948.845	49.2843	0.00536

are pseudo-random within the search area during the COA start process, and the following are formulated:

$$soc_{c,j}^{p,t} = LB_j + r_j \left(UB_j - LB_j\right) \tag{12}$$

where LB_j is the lower limit of the variable j, UB_j denotes the upper limit of the design variable j, and r_j is an arbitrary number ranges between [0, 1]. Therefore, the fitness value of each coyote is calculated according to the following

TABLE 6. Estimated model parameters for DDM of photowatt-PWP201 module, obtained by various optimization methods.

Technique	I_{ph} (A)	I_{sd1} (μA)	I_{sd2} (μA)	R_s (Ω)	R_{sh} (Ω)	n_1	n_2	RMSE
COA	1.03186502	0.50000	2.37492742	1.26304525	884.8402798	39.1366487	1.3110098	2.4041223E-03
WDOWOAPSO [50]	1.03062717	3.17170279	5.00E-06	1.23828868	744.71426	1.317304	1.317305	2.046535E-03
GCPSO [57]	1.03238233	2.51291639	1.0000574E-06	1.2392884	744.71539	1.317304	1.316939	2.0465E-03
TVACPSO [58]	1.031434	2.638124	1.00E-06	1.235632	821.65281	1.320998	2.777778	2.0530E-03
ABC-DE [59]	1.0318	0.32774	2.4305E-06	1.2062	845.2495	1.3443	1.3443	2.400E-03

TABLE 7. Estimated model parameters for TDM of photowatt-PWP201 module, obtained by various optimization methods.

Technique	**I_{ph} (A)**	**I_{sd1} (μA)**	**I_{sd2} (μA)**	**I_{sd3} (μA)**	**R_s (Ω)**	**R_{sh} (Ω)**	**n_1**	**n_2**	**n_3**	**RMSE**
COA	1.032744	5.0891973 E -05	2.092387 E -06	1.090020 E -06	1.256384	700	20	1.29945412	2	2.07378235 E-03

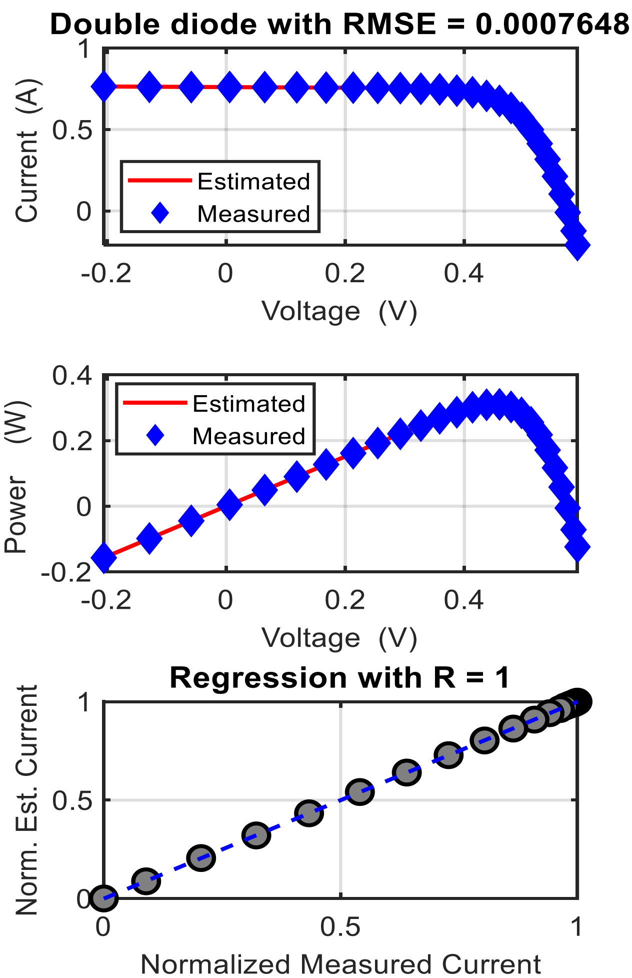

FIGURE 9. Comparison of the characteristics of RTC France solar cell based on measured data and estimated ones using DDM.

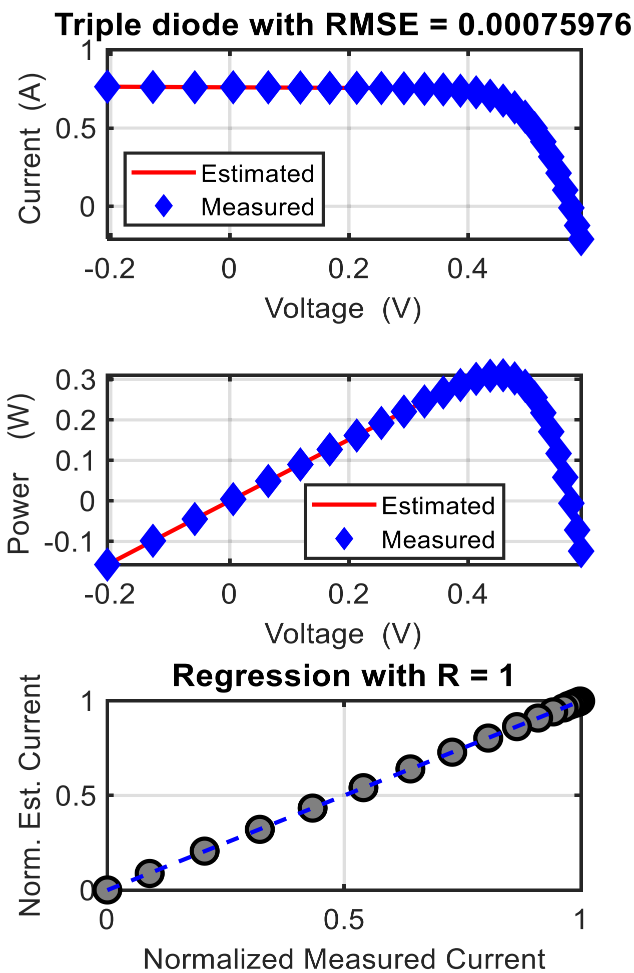

FIGURE 10. Comparison of the characteristics of RTC France solar cell based on measured data and estimated ones using TDM.

expression:

$$fit_c^{p,t} = f\left(soc_c^{p,t}\right) \tag{13}$$

The Coyotes participate randomly in groups at the beginning of the COA but sometimes they switch from group to group. This coyote departure is linked to a probability PL,

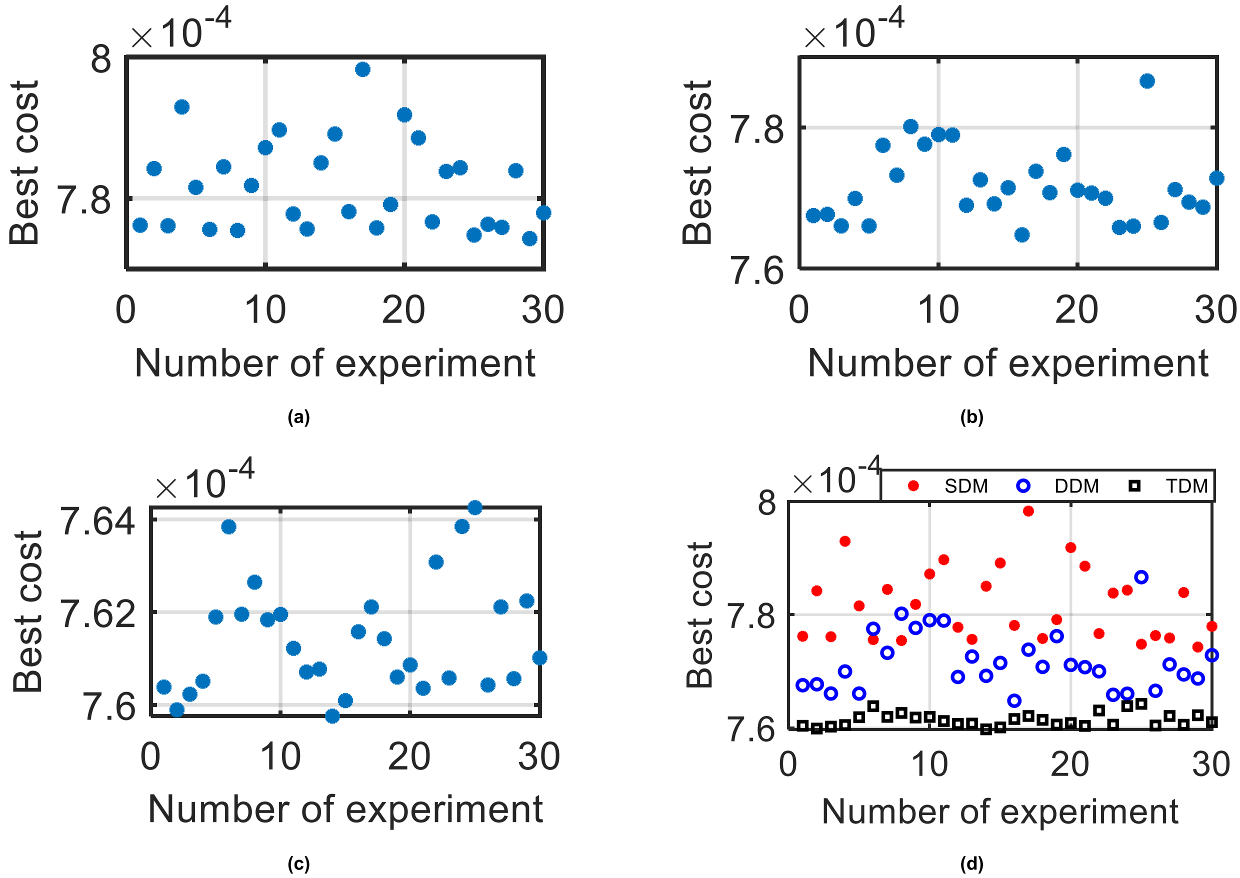

FIGURE 11. Best cost of 30 runs of the COA of RTC France solar cell; (a) SDM, (b) DDM, (c) TDM (d) Comparison SMD, DDM and TDM.

which is formulated as follows:

$$P_e = 0.005 \cdot N_c^2 \tag{14}$$

The suggested mechanism helps to change the culture of coyotes between the groups. In each group, the leader of the coyotes called the Alpha coyote is known as the most environmentally responsible coyote. The mathematical identification of the alpha coyote can be described as follows:

$$alpha^{p,t} = soc_c^{p,t} \quad for \ \min fit_c^{p,t} \tag{15}$$

The COA believes that coyotes are arranged in groups to share the social behavior and to share in the maintenance of the system due to the obvious signs of swarm-intelligence in this species. The COA, therefore, ties all coyote data and estimates it as a cultural trend in the pack.

$$cult_j^{p,t} = \begin{cases} O^{p,t}_{\frac{N_c+1}{2},j}, & N_c \ is \ odd \\ \dfrac{O^{p,t}_{\frac{N_c}{2},j} + O^{p,t}_{\frac{N_c+1}{2},j}}{2} & otherwise \end{cases} \tag{16}$$

where $O^{p,t}$ is the listed social conditions of the group p coyotes at t factor J size Coyotes such as birth and death are taken into account in the COA life cycle. The development of coyotes is a mixture of two parents $'$ social conduct, which is randomly selected within the search area plus an environmental factor. The following is written for this life event:

$$pup_j^{p,t} = \begin{cases} soc^{p,t}_{r1j}, & rnd_j < P_s \quad orj = j_1 \\ soc^{p,t}_{r1j}, & rnd_j \geq P_s + P_a \quad orj = j_2 \\ R_j, & otherwise \end{cases} \tag{17}$$

where, R_j denotes a randomly distributed number within the boundaries of the design variable, while, r_1 and r_2 are the random coyote unit p, j_1 and j_2, two random design variables, P_s and P_a are the scatter plate and association probability, and R_j is the arbitrary number between 0 and 1. These probabilities indicate the cultural diversity of group coyotes and the following equations determine their values:

$$P_s = {}^1/_D \tag{18}$$

$$P_a = {}^{(1-P_s)}/_2 \tag{19}$$

where D is the development variables dimension. The COA uses two factors δ_1 and δ_2 to evaluate the cultural interaction between the different groups.

This behavior can be mathematically formulated as follows:

$$\delta_1 = alpha^{p,t} - soc^{p,t}_{cr1} \tag{20}$$

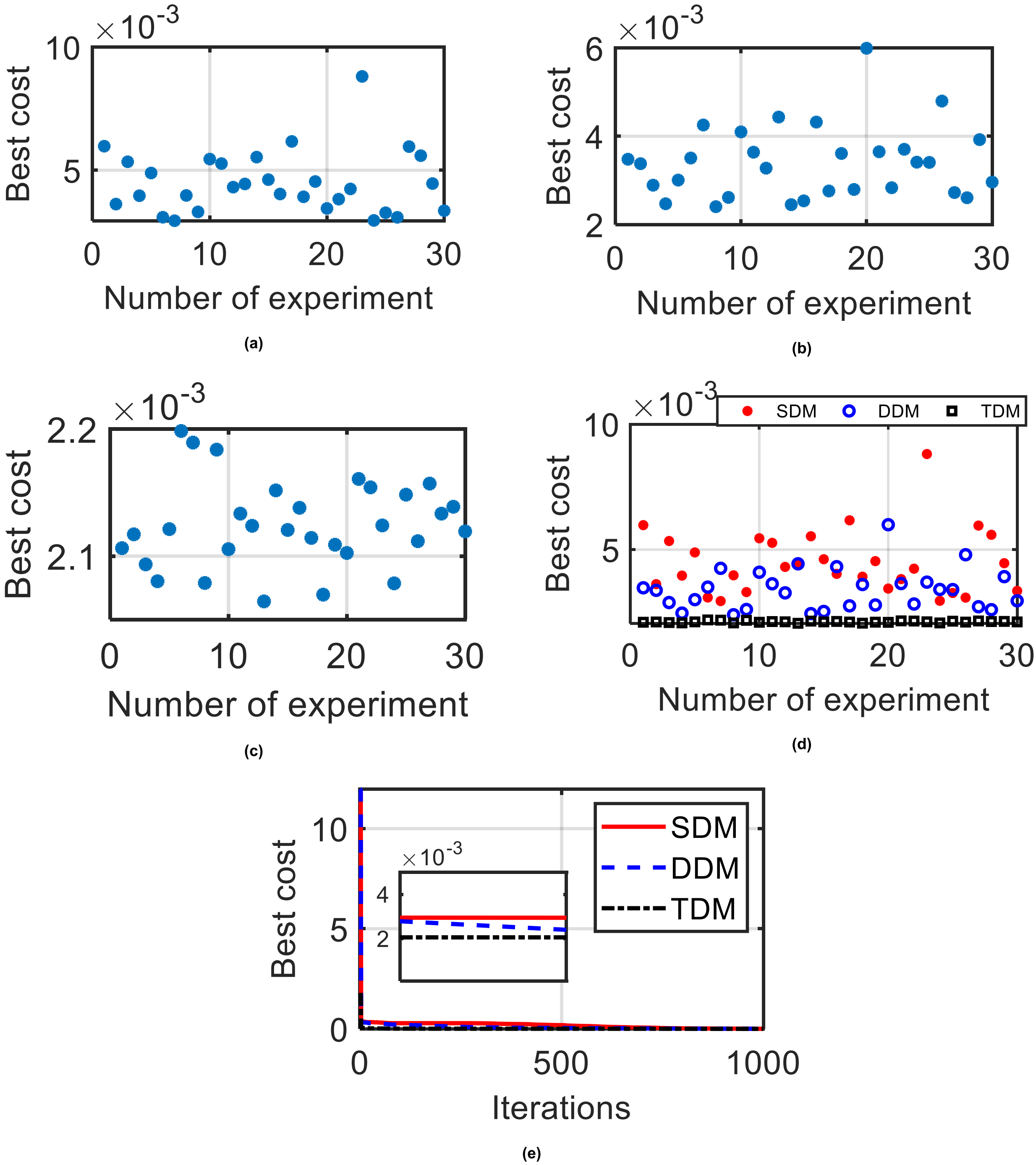

FIGURE 12. Best cost of 30 runs of the COA of Photowatt-PWP201 module; (a) SDM, (b) DDM, (c) TDM (d) Comparison SMD, DDM and TDM; (e) Convergence trends of RMSE for Photowatt-PWP201 module under study corresponding to the COA-based models.

$$\delta_2 = cult^{p,t} - soc^{p,t}_{cr2} \tag{21}$$

where δ_1 denotes the culture deviation between a random coyote (cr_1) and alpha one in the same group and $\delta 2$ denotes the culture difference between a randomly selected coyote (cr_2) and the cultural tendency of the corresponding group.

Then the social behavior of the coyote is revised, and the group control is modified as follows:

$$new\_soc^{p,t}_{c} = soc^{p,t}_{c} + r_1.\delta_1 + r_2.\delta_2 \tag{22}$$

where r_1 and r_2 are arbitrary numbers that range between [0, 1]. The new value of the fitness function of the coyotes is calculated as follows:

$$new\_fit^{p,t}_{c} = f\left(new\_soc^{p,t}_{c}\right) \tag{23}$$

If the social behavior in the present iteration is better than that of the last one, the current behavior will take place the previous one and mathematically presented as

TABLE 8. Comparison of the statistical results of the COA method for Photowatt-PWP201 module.

	SDM	DDM	TDM
Min	0.00294960692837003	0.00240412239424184	0.00206430403915465
Max	0.00881041875316936	0.00599380697943129	0.00219850294385965
Mean	0.00448092862262856	0.00339805592704902	0.00212426670670270
Median	0.00427626542923487	0.00339302532497861	0.00212090938967466
SD	0.127080997376120	0.0815667628752910	0.00341858636800142
RE	15.5748382558698	12.4028652017189	0.871422034894700
MAE	0.00153132169425854	0.000993933532807176	5.99626675480498e-05
RMES	0.00197637855375366	0.00127712193057180	6.87403738655446e-05
Eff.	70.3272228708607	74.2693587325444	97.2014843087579

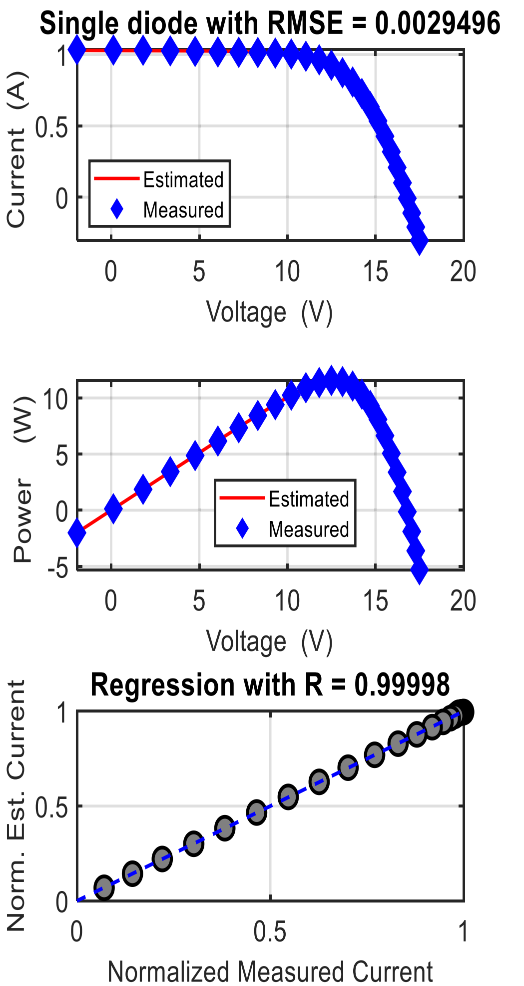

FIGURE 13. Comparison of the characteristics of Photowatt-PWP201 module regards the measured and computed data for SDM.

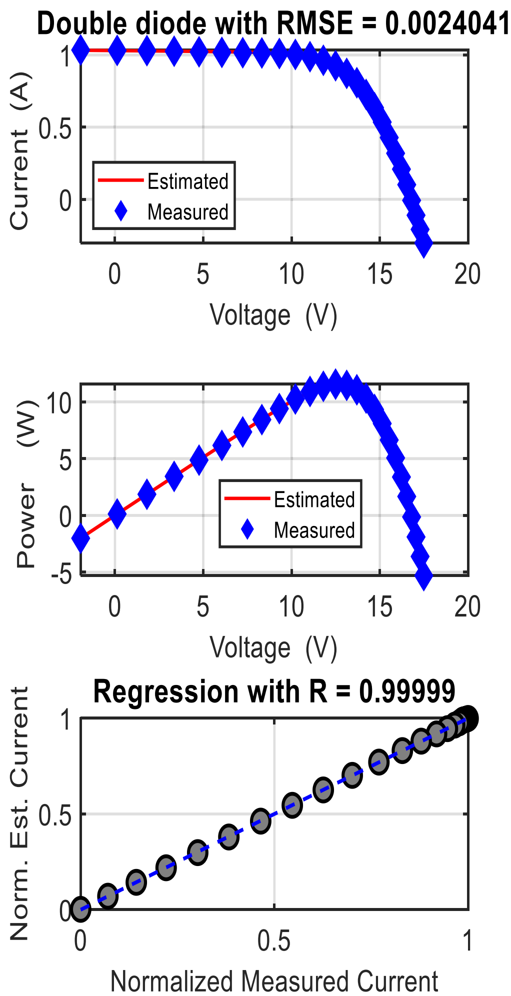

FIGURE 14. Comparison of the characteristics of Photowatt-PWP201 module regards the measured and computed data for DDM.

follows:

$$new\_soc_c^{p,t+1} = \begin{cases} new\_soc_c^{p,t+1} & new\_fit_c^{p,t+1} < fit_c^{p,t} \\ soc_c^{p,t} & otherwise \end{cases} \tag{24}$$

In the last stage of the process, the best environmental adaptation social behavior is chosen as the best solution. A flowchart describing the operation of the COA optimization technique is shown in Fig. 4.

TABLE 9. The estimated parameters for the three PV modules by COA under different intensities of solar radiation and temperature of 25 °C (SDM).

Parameters	Mono-crystalline SM55	Thin-film ST40	Multi-crystalline KC200GT
G = 200 W/m^2			
I_{ph} (A)	0.695089324292734	0.527071414840972	0.937651912463544
I_{sd} (μA)	0.363056132949365	6.00000000000000	0.0940382092630837
R_s (Ω)	0.100000000000000	0.477449571006788	0.100000000000000
R_{sh} (Ω)	500	400.517757109621	500
N	1.46307751656628	1.95997021021409	1.33410089677294
RMSE	**0.00411909959414489**	**0.00198470310379258**	**0.00425496418565285**
G = 400 W/m^2			
I_{ph} (A)	1.38398211270454	1.05489747741394	1.87951070177823
I_{sd} (μA)	0.138021418595535	26.8205408942278	0.0502251732631330
R_s (Ω)	0.299752478358883	0.500000000000000	0.152686762299794
R_{sh} (Ω)	500	747.657311839121	655.285740469907
N	1.37198156512298	2.22499972255344	1.27483789342934
RMSE	**0.00380815285548938**	**0.00536624448579899**	**0.00697613194149980**
G = 600 W/m^2			
I_{ph} (A)	2.07205761675800	1.59191974455525	2.82393092424223
I_{sd} (μA)	0.398115836331959	50.000000000000	0.0180034965721288
R_s (Ω)	0.246933702194268	0.500000000000000	0.253275036041129
R_{sh} (Ω)	500	1003.74110337125	500
N	1.46811863502122	2.33339608320952	1.20602711900850
RMSE	**0.00899688721654527**	**0.0101144411319791**	**0.0100592741776913**
G = 800 W/m^2			
I_{ph} (A)	2.76353292877318	2.13277439215547	3.76231828751002
I_{sd} (μA)	0.656635715256805	50.00000000000000	0.805454791902349
R_s (Ω)	0.239758992173154	0.500000000000000	0.165246794556397
R_{sh} (Ω)	500	373.683594125632	2000
N	1.51451177997289	2.31344067437848	1
RMSE	**0.00560769307110582**	**0.0205169516019723**	**0.0310433820780210**
G = 1000 W/m^2			
I_{ph} (A)	3.45247001099432	2.69474682116483	4.69257605043991

TABLE 9. *(Continued.)* **The estimated parameters for the three PV modules by COA under different intensities of solar radiation and temperature of 25 °C (SDM).**

I_{sd} (μA)	0.229525281533209	50.0000000000000	0.844289063332462
R_s (Ω)	0.340027043704648	0.500000000000000	0.168489561122347
R_{sh} (Ω)	500	167.705330257259	1999.79877039580
N	1.42106600544294	2.29619857437508	1
RMSE	**0.00383778930072070**	**0.0439439718112795**	**0.0301855486003366**

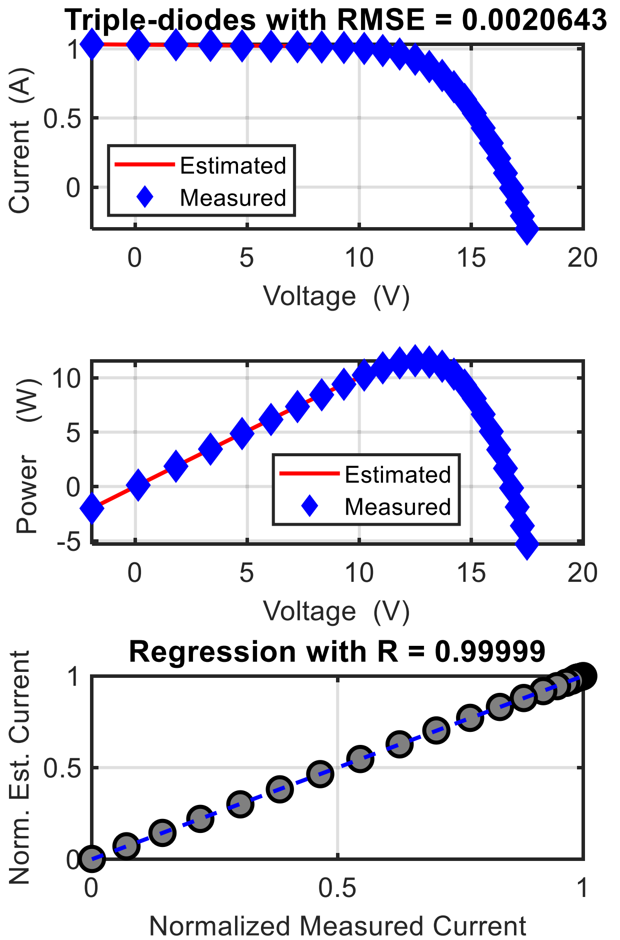

FIGURE 15. **Comparison of the characteristics of Photowatt-PWP201 module regards the measured and computed data for TDM.**

IV. RESULTS AND DISCUSSION

The applied COA optimization algorithm has been validated by estimating the optimal parameters of the different models of SCs and PV modules. The estimating models SDM, DDM, and TDM have been used for computing the PV characteristics as curves of power via voltage and current via voltage. The estimated performance (I/V) of each model has been compared with those of the datasheet of the tested cells and modules. The COA optimization algorithm has been applied to estimate the design parameters for models of the following commercial cells and PV modules; a typical (RTC France) silicon solar cell, (Photo Watt-PWP 201) PV module, Mono-crystalline SM55 module, Thin-film ST40 module, and Multi-crystalline module. The measured data and characteristics of the tested SCs and PV modules have been reported from several manufacturer's datasheets and Refs. [42]–[46]. For the applied optimization technique, the maximum number of iterations is adjusted at 1000 iterations while each population consists of 5 packs with 20 coyotes in each group. For each model, the optimization program has been implemented 30 times. The validation of the used optimization techniques has been taking place using the platform of MATLAB R2018a. Figure 5 shows the flow process of the application of COA for extracting the model parameters of SCs and PV modules. The results of the applied COA algorithm have been compared with those of other techniques based on the criterion of the best optimal value of the objective function.

A. CASE STUDY 1: R.T.C. FRANCE SOLAR CELL

In this case of the study, the applied COA optimization algorithm was utilized to extract the parameters of the three proposed models of R.T.C. France solar cell. The measured data of the (I-V) characteristic curves of R.T.C. France solar cell are reported in [42], [43]. The optimization algorithm of COA is applied for extracting the parameters of the SDM, DDM, and TDM. The results of the optimized parameters based on the COA-based SDM model are listed in Table 1. Table 1 also includes the results of the estimated parameters based on COA and those estimated based on other optimization techniques such as ABSO [40], HS [36], PSO [25], GA [47], An.5-Pt. [48], LW [49], Newton [50], CM [51], and PS [52]. From this table, it can be noticed that for the SDM model, the application of the proposed COA algorithm results in the minimum value of the RMSE that is equal to 7.75470161606E-04.

Moreover, Table 2 listed the results obtained from the application of the COA technique for extracting the parameters of DDM of the R.T.C. France solar cell. For validating the applied technique, the table also introduces the results of the application of other techniques of ABSO [53], HS [36],

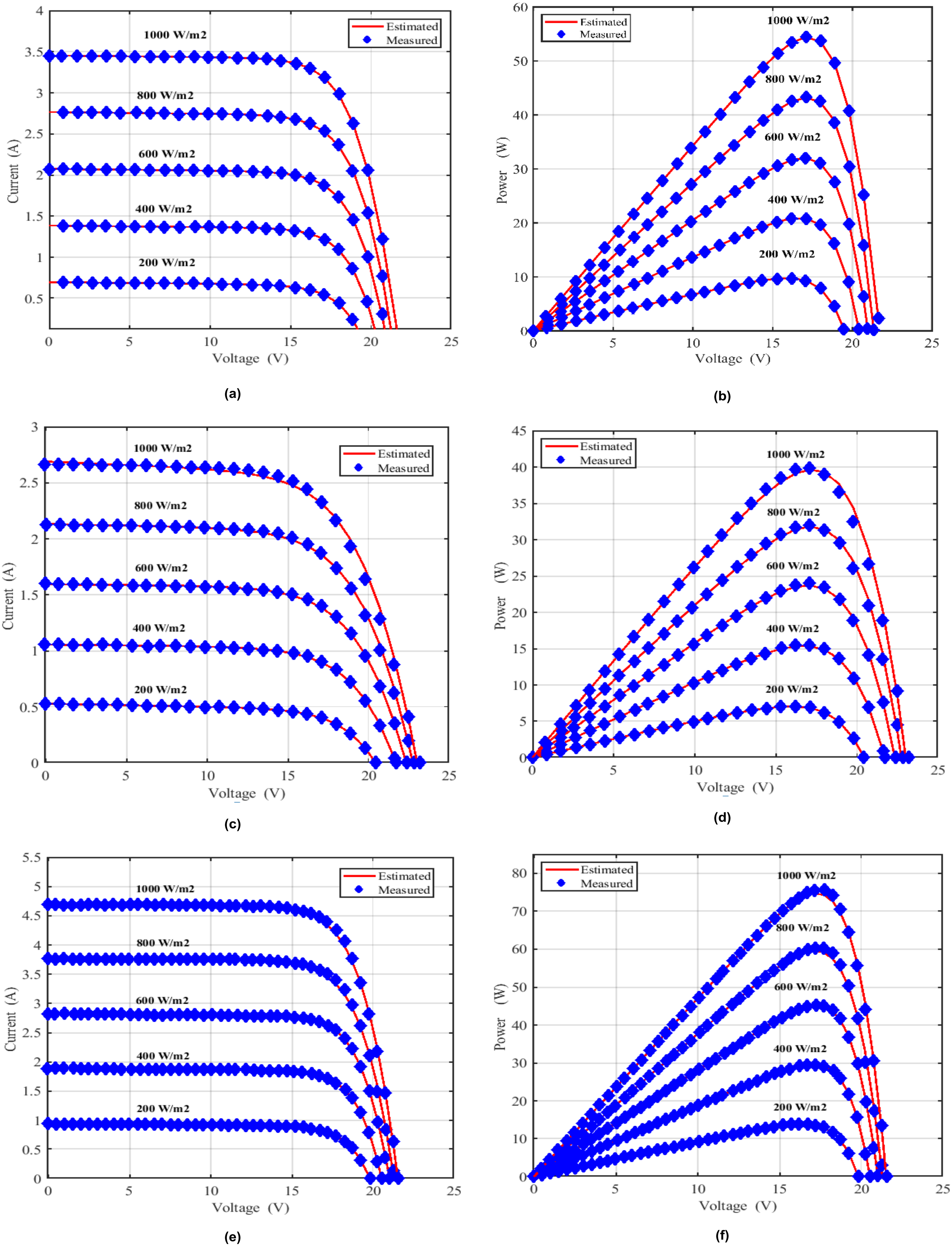

FIGURE 16. **Comparison between experimentally measured data and the estimated results by COA at different solar radiation (SDM): (a) I-V curves for Mono-crystalline SM55, (b) P-V curves for Mono-crystalline SM55, (c) I-V curves for Thin-film ST40, (d) P-V curves for Thin-film ST40, (e) I-V curves for Multi-crystalline KC200GT, (f) P-V curves for Multi-crystalline KC200GT.**

TABLE 10. **Statistical measurement of the COA technique for the three PV modules under different intensities of solar radiation and temperature of 25 °C (SDM).**

Parameters	Mono-crystalline SM55	Thin-film ST40	Multi-crystalline KC200GT
$G = 200\ W/m^2$			
Min	0.00411909959414489	0.00198470310379258	0.00425496418565285
Max	0.00954467669266017	0.00253146008475823	0.0168254375311001
Mean	0.00564166853134763	0.00205921773873173	0.00922141567990866
Median	0.00536113743922479	0.00200969147155217	0.00931459108305422
SD	0.137859299941892	0.0118172730213278	0.292622385879897
RE	18.4818174749525	1.87722372169313	58.3606732931150
MAE	0.00152256893720274	7.45146349391480e-05	0.00496645149425582
RMES	0.00411909959414489	0.00198470310379258	0.00425496418565285
Eff.	76.9085367620674	96.6588179836676	51.6076796581940
$G = 400\ W/m^2$			
Min	0.00380815285548938	0.00536624448579899	0.00697613194149980
Max	0.0113441871124246	0.00619917251461558	0.0247626673170301
Mean	0.00603909462414818	0.00556903001803267	0.0122522159343164
Median	0.00543789574126146	0.00550014921344601	0.0111137803680891
SD	0.179764956928793	0.0217061799773781	0.351036518616492
RE	29.2916520596453	1.88945483913684	37.8152537614010
MAE	0.00223094176865879	0.000202785532233686	0.00527608399281659
RMES	0.00380815285548938	0.00536624448579899	0.00697613194149980
Eff.	67.6129114525798	96.4957130370123	60.8672528863072
$G = 600\ W/m^2$			
Min	0.00899688721654527	0.0101144411319791	0.0100592741776913
Max	0.0119189071932049	0.0106765920843176	0.0306914880402477
Mean	0.00989309029631902	0.0101648863679962	0.0240071526131966
Median	0.00986960607374666	0.0101255787367879	0.0245616381735888
SD	0.0640258741136014	0.00938443449325435	0.418674668956351
RE	4.98062862300663	0.249372334856897	69.3284534705185
MAE	0.000896203079773755	5.04452360170854e-05	0.0139478784355052
RMES	0.00899688721654527	0.0101144411319791	0.0100592741776913

TABLE 10. ***(Continued.)*** **Statistical measurement of the COA technique for the three PV modules under different intensities of solar radiation and temperature of 25 °C (SDM).**

Eff.	91.2999473521256	99.5117755982047	43.8332599222507
G = 800 W/m^2			
Min	0.00560769307110582	0.0205169516019723	0.0310433820780210
Max	0.0134452756113104	0.0207846994125937	0.0527995684516991
Mean	0.00793198322567784	0.0205560585798637	0.0409156556560628
Median	0.00754577081310999	0.0205233806279038	0.0410907739389174
SD	0.194215501619335	0.00734201142821782	0.666495037251899
RE	20.7241206419458	0.0953040652677314	15.9007700147327
MAE	0.00232429015457202	3.91069778913852e-05	0.00987227357804176
RMES	0.00560769307110582	0.0205169516019723	0.0310433820780210
Eff.	74.3522419240923	99.8109932507984	77.9398624489121
G = 1000 W/m^2			
Min	0.00383778930072070	0.0439439718112795	0.0301855486003366
Max	0.0220961747438654	0.0461895131922798	0.0346954058318772
Mean	0.0116396119051750	0.0441425410077509	0.0305292596162494
Median	0.0115198652828366	0.0440017562036206	0.0302180877077643
SD	0.418199638122591	0.0370644582940314	0.0808804961138184
RE	101.644749009400	0.225934511932757	0.569330411157415
MAE	0.00780182260445431	0.000198569196471366	0.000343711015912835
RMES	0.00383778930072070	0.0439439718112795	0.0301855486003366
Eff.	38.3533456047214	99.5568331601504	98.9365596852111

PSO [25], GA [47], ABC [42], SBMO [43], SSO [54], MSSO [54]. The table shows that the applied COA optimization technique has the best results with the minimum objective function of the RMSE that is 7.648012794E-04.

For more validation, the COA algorithm has been applied for extracting the parameters of the TDM. The results of the TDM have been listed in Table 3. The results of the applied COA algorithm have been compared with those of other techniques of ABC [42], OBWOA [55], STBLO [48]. The recorded results of Table 3 validate that the applied COA optimization algorithm is better than the other techniques. The value of RMSE using the applied COA algorithm is the minimum and equals to 7.59756935254174E-04.

Moreover, a comparison between the results of the three different models of SDM, DDM, and TDM based on the COA optimization technique has been introduced. Fig. 6 shows the convergence trends of the objective function (RMSE) for R.T.C. France solar cell based on COA for the three models (SDM, DDM, and TDM). From Fig. 6 and Tables 1, 2 and 3, it is noticeable that the convergence curve of the TDM is better than those of SDM and DDM. However, the results of the SDM and DDM are better than those of the reported methods from literature as listed in Figs. 1 and 2.

Error curves of the estimated and measured current data of RTC France solar cell for the three models based on the indices of individual absolute error (IAE) values and relative error (RE) values have been shown in Fig. 7 in order to confirm the precision of the optimized parameters and power of the applied optimization technique. Furthermore, the characteristics of the tested solar cell have

TABLE 11. The estimated parameters for the three PV modules based on COA at various intensities of solar radiation and temperature of 25 °C (DDM).

Parameters	Mono-crystalline SM55	Thin-film ST40	Multi-crystalline KC200GT
G = 200 W/m²			
Iph (A)	0.693799164721238	0.527023117416469	0.937410555055258
Isd1 (μA)	0.00500000000000000	5.91768700019003	0.00500000000000000
Isd2 (μA)	42.6889464668989	5.00000000000000E-06	50.0000000000000
Rs (Ω)	0.00100000000000000	0.500000000000000	0.416723497386382
Rsh (Ω)	700	400	614.448315935343
n1	1.15231652941039	1.95812158887750	1.13290058742385
n2	2.44962151350706	4	3.04545912462352
RMSE	**0.00275155467851258**	**0.00199347893161887**	**0.00403983562333558**
G = 400 W/m²			
Iph (A)	1.38255903537353	1.05424944194447	1.88782040895441
Isd1 (μA)	0.00500000000000000	26.4144586373664	0.00500000000000000
Isd2 (μA)	2.46503118084914	0.0569037031259570	5.00000000000000E-06
Rs (Ω)	0.302164959933764	0.500000000000000	0.300000000000000
Rsh (Ω)	616.944307484922	791.337673177186	400
n1	1.16433277615499	2.22151399000585	1.12672785704533
n2	1.80716520744595	3.68445346208108	1.83444675594453
RMSE	**0.00379671778253555**	**0.00538161620132653**	**0.00805088698091338**
G = 600 W/m²			
Iph (A)	2.06959723598160	1.58994206788707	2.82373565125433
Isd1 (μA)	0.796550771428225	9.30100759867214	0.00500000000000
Isd2 (μA)	6.00000000000000	50.0000000000000	6.32478839207350
Rs (Ω)	0.194855379839586	0.500000000000000	0.289231138355350
Rsh (Ω)	631.651303315793	1667.99381482668	426.029818598805
n1	1.53686157148203	2.40599053814200	1.12914692231741
n2	3.23340786688370	2.36669765754094	4
RMSE	**0.00890502730228717**	**0.00992342776192367**	**0.00679590505427059**
G = 800 W/m²			
Iph (A)	2.75921734943033	2.12182397029598	3.77078444570045

TABLE 11. *(Continued.)* **The estimated parameters for the three PV modules based on COA at various intensities of solar radiation and temperature of 25 °C (DDM).**

Isd1 (μA)	6.00000000000000	50.0000000000000	0.803758901151742
Isd2 (μA)	0.799057484846359	50.00000000000000	5.00000000000000E-06
Rs (Ω)	0.233981877306971	0.500000000000000	0.161201153370009
Rsh (Ω)	694.940871467512	1862.10471783469	700
n1	3.80725620957814	2.42791400871664	1
n2	1.53417246709497	2.53114765246777	4
RMSE	**0.00537939933688529**	**0.0148198476605245**	**0.0325857589161442**
G = 1000 W/m^2			
Iph (A)	3.44988276312576	2.67616770954910	4.70151088373944
Isd1 (μA)	1.32807983063024	50.0000000000000	0.00500000000000
Isd2 (μA)	0.116784423715483	50.00000000000000	0.838428586676899
Rs (Ω)	0.363175297194880	0.500000000000000	0.166333108103859
Rsh (Ω)	480.765037948483	353.179288408815	700
n1	4	2.45467322081916	1
n2	1.36570562186626	2.44680579081875	1
RMSE	**0.00354124832803315**	**0.0345617459921048**	**0.0317422493819409**

been plotted based on the estimated parameters for the three different models compared with the measured ones as presented in Figs 8, 9, and 10 for SDM, DDM, and TDM, respectively.

Statistical analysis should be performed in order to trust the performance of the optimization technique and evaluate the robustness behavior of the COA. So, the optimization algorithm of COA has been executed for 30 implements. For each run, the best minimum objective function has been recorded and reported. Moreover, statistical indices such as the mean, standard deviation, relative error, the minimum and maximum over the 30 runs have been computed. The results of the statistical analysis of the application of the applied COA for the three different models have been listed in Table 4. The end values of the objective function over the 30 runs are shown in Fig. 11. The results of the statistical analysis prove that the COA algorithm is an effective algorithm for solving the optimization problem of parameters' identification of various mathematical models of R.T.C. France solar cell.

Moreover, the **Wilcoxon signed-rank test** has been applied for more validation of the applied algorithm. The results have been shown in Table 4. From the table, the P-value of the results for the SDM, DDM, and TDM are 1.7344E-06, 1.7344E-06, and 1.7344E-06, respectively while the Ranke is 1 for the three models. At the default 5% significance level, the value h = 1 indicates that the test rejects the null hypothesis of zero medians. The results of the P-values in Table 4 generated from the Wilcoxon test show that the results of COA are statistically significant.

B. CASE STUDY 2; PHOTOWATT-PWP201 MODULE

For more validating of the applied COA technique, the Effectiveness of the COA is assessed with the estimation of the optimal parameters of different models of the Photowatt-PWP201 PV module, which consists of 36 series connected silicon cells under operating condition of 1000 W/m^2 solar radiation and cell temperature of 45 °C [42], [43]. In this case of study, to validate the effectiveness and precision of the applied methodology, the obtained results have been compared with those reported in literature based on other techniques.

The superior performance of the COA optimization algorithm has been tested for determining the parameters of the SDM regarding such module. The results have been listed in Table 5. The table also introduces a comparison with the

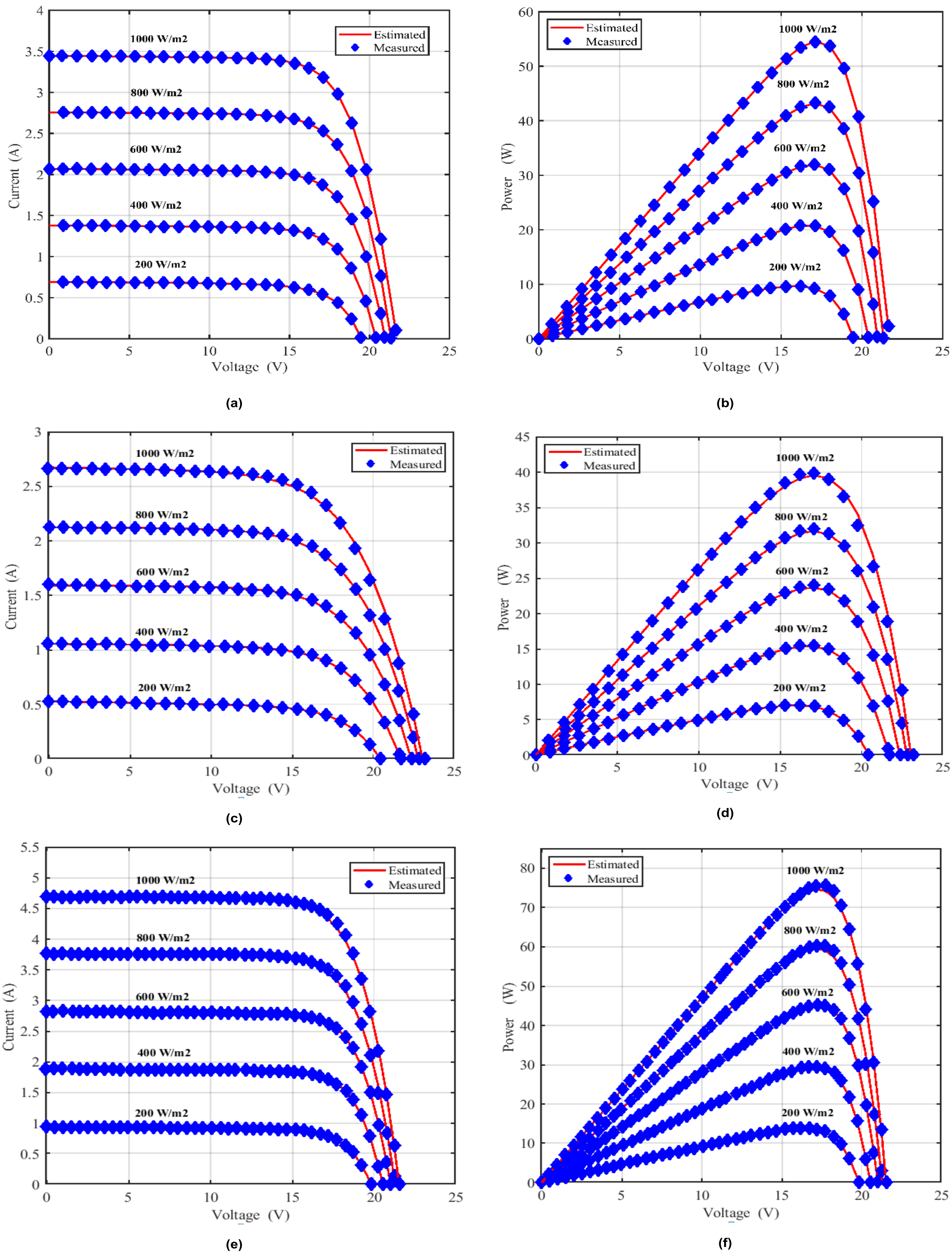

FIGURE 17. Comparison between experimentally measured data and the estimated results by COA at different solar radiation (DDM): (a) I-V curves for Mono-crystalline SM55, (b) P-V curves for Mono-crystalline SM55, (c) I-V curves for Thin-film ST40, (d) P-V curves for Thin-film ST40, (e) I-V curves for Multi-crystalline KC200GT, (f) P-V curves for Multi-crystalline KC200GT.

TABLE 12. Statistical measurements of the COA technique for the three PV modules under different intensities of solar radiation and temperature of 25 °C (DDM).

Parameters	Mono-crystalline SM55	Thin-film ST40	Multi-crystalline KC200GT
G = 200 W/m^2			
Min	0.00275155467851258	0.00199347893161887	0.00403983562333558
Max	0.0118617508236926	0.00343074935362843	0.0168998539768497
Mean	0.00674887990655449	0.00224340759300184	0.00769013764593756
Median	0.00683898748930378	0.00221397637726309	0.00669613971948731
SD	0.246345303209914	0.0235483463451697	0.348595247735745
RE	72.6375757541325	6.26865570081558	45.1788434350706
MAE	0.00399732522804191	0.000249928661382968	0.00365030202260199
RMES	0.00275155467851258	0.00199347893161887	0.00403983562333558
Eff.	47.2787551779869	89.6371189070129	62.2899655606052
G = 400 W/m^2			
Min	0.00379671778253555	0.00538161620132653	0.00805088698091338
Max	0.0200170244083859	0.0107340618372768	0.0412289793117723
Mean	0.00772198619765794	0.00623415430946954	0.0162294122690120
Median	0.00649707232666079	0.00604534282803483	0.0124554685990621
SD	0.359595599341559	0.0815698623192028	0.919600595139466
RE	51.6929179353041	7.92083712633457	50.7926971741613
MAE	0.00392526841512239	0.000852538108143015	0.00817852528809861
RMES	0.00379671778253555	0.00538161620132653	0.00805088698091338
Eff.	58.0215990454412	87.3553648459903	62.9815124727814
G = 600 W/m^2			
Min	0.00890502730228717	0.00992342776192367	0.00679590505427059
Max	0.0104763397401031	0.0104041853213377	0.0513092303017570
Mean	0.00960382221375883	0.0101012311331149	0.0273972006142801
Median	0.00952553480644080	0.0101026960863977	0.0277009790663740
SD	0.0412434119345528	0.00821481358671273	1.03582225628189
RE	3.92359780464783	0.895876785002757	151.571390385035
MAE	0.000698794911471658	0.000177803371191186	0.0206012955600095
RMES	0.00890502730228717	0.00992342776192367	0.00679590505427059

TABLE 12. *(Continued.)* **Statistical measurements of the COA technique for the three PV modules under different intensities of solar radiation and temperature of 25 °C (DDM).**

Eff.	92.8900662607530	98.2460920619101	31.2474028210152
G = 800 W/m^2			
Min	0.00537939933688529	0.0148198476605245	0.0325857589161442
Max	0.0117365205513733	0.0192858169509663	0.0554579220757864
Mean	0.00730322835366049	0.0167705105224424	0.0418705276896157
Median	0.00705801693854048	0.0166994488572410	0.0398037980386105
SD	0.146526553970444	0.113598502810032	0.755457409520366
RE	17.8814482463121	6.58125139543057	14.2466664615129
MAE	0.00192382901677520	0.00195066286191791	0.00928476877347154
RMES	0.00537939933688529	0.0148198476605245	0.0325857589161442
Eff.	76.3741736545304	88.7604714176860	80.2393197500545
G = 1000 W/m^2			
Min	0.00354124832803315	0.0345617459921048	0.0317422493819409
Max	0.0219489412562130	0.0452407186982594	0.0638376983875050
Mean	0.00957799781439171	0.0380887263230879	0.0454705069218035
Median	0.00836768733496460	0.0378193497014830	0.0442436151985547
SD	0.451830846998509	0.254630593534460	1.11411499477669
RE	85.2347664885654	5.10243367303967	21.6245820746291
MAE	0.00603674948635856	0.00352698033098318	0.0137282575398625
RMES	0.00354124832803315	0.0345617459921048	0.0317422493819409
Eff.	44.9057589408605	91.1217525396243	74.1211749270147

results of other techniques of Newton [13], PS [52], OIS [56] and 1DAB [49]. The comparison validated the effectivity of the COA with respect to the other techniques. The RMSE based on the application of COA for extracting the parameters of SDM equals 2.94960692837E-3 which is the best one.

For more validating, the COA is applied for estimating the parameters of the DDM and TDM models of Photowatt-PWP201 PV module. The optimized parameters of the DDM and TDM based on COA have been introduced in Table 6 and Table 7, respectively. Table 6 is also for comparing the results of the DDM-based COA with other techniques of WDOWOAPSO [50], GCPSO[57], TVACPSO [58], and ABC-DE [59]. The table validates the superiority of the applied COA algorithm with respect to the minimum value of the RMSE which equals 2.40412239424184E-3. Moreover, Table 7 shows the results of the COA for extracting the parameter of the TDM model for the Photowatt-PWP201 PV module and the value of the RMSE is 2.07378235398E-03. All results which are presented in Table 5 to Table 7 prove that the COA is effective with high accuracy to estimate the parameters of the different models of the Photowatt-PWP201 PV module, which is reflected in the reduction of RMSE value as the objective function. The convergence characteristics of the RMSE for the Photowatt-PWP201 module based on COA optimization method according to the three applied models have been illustrated in Fig. 12. Also, Fig. 12 shows the best value of the

TABLE 13. The estimated parameters for the three PV modules based on COA under various intensities of solar radiation and temperature of 25 °C (TDM).

Parameters	Mono-crystalline SM55	Thin-film ST40	Multi-crystalline KC200GT
G = 200 W/m^2			
I_{ph} (A)	0.694615202084278	0.527023117416469	0.936242417996148
I_{sd1} (μA)	0.0050000000000000	5.91768700019003	18.0953486046186
I_{sd2} (μA)	23.1195618705210	5.00000000000000E-06	0.0050000000000000
I_{sd3} (μA)	5.00000000000000E-06	0.500000000000000	33.9176983610058
R_s (Ω)	0.0239274556379481	400	0.355229343601832
R_{sh} (Ω)	700	1.95812158887750	678.366884318574
n_1	1.15435654362784	4	4
n_2	2.27236073580213	0.527023117416469	1.13356590239110
n_3	3.77222119518670	5.91768700019003e-06	2.79801108037379
RMSE	**0.00314769185968629**	**0.00199347893161887**	**0.00384994234788785**
G = 400 W/m^2			
I_{ph} (A)	1.38199587990978	1.05424944194447	1.87350775615866
I_{sd1} (μA)	4.37585205553345	26.4144586373664	4.65834818181635
I_{sd2} (μA)	0.128916508580290	0.569037031259570	0.111794634886598
I_{sd3} (μA)	1.03327018761313	0.500000000000000	6.00000000000000
R_s (Ω)	0.300725137490565	791.337673177186	0.110523939382685
R_{sh} (Ω)	600	2.22151399000585	2000
n_1	2.58885457571473	3.68445346208108	2.94444950596361
n_2	1.36768694178151	1.05424944194447	1.33541145891280
n_3	2.75097183293812	2.64144586373664e-05	3.26906028985750
RMSE	**0.00390673719456728**	**0.00538161620132653**	**0.00830786466427263**
G = 600 W/m^2			
I_{ph} (A)	2.07418297041956	1.58994206788707	2.80287504532070
I_{sd1} (μA)	0.853829829305257	9.30100759867214	3.67687336978609E-04
I_{sd2} (μA)	0.187886326713947	50.0000000000000	5.00000000000000E-06
I_{sd3} (μA)	2.86962737629971	0.500000000000000	5.00000000000000E-06
R_s (Ω)	0.300000000000000	1667.99381482668	0.376178881019567

TABLE 13. ***(Continued.)*** **The estimated parameters for the three PV modules based on COA under various intensities of solar radiation and temperature of 25 °C (TDM).**

R_{sh} (Ω)	439.124520984213	2.40599053814200	1992.67669598477
n_1	2.09269538153337	2.36669765754094	1.00028814312353
n_2	1.40259879874136	1.58994206788707	1
n_3	3.71460702845824	9.30100759867214e-06	1.79522058471836
RMSE	**0.00962173228389160**	**0.00992342776192367**	**0.0153697702423048**
G = 800 W/m²			
I_{ph} (A)	2.75718251829089	2.12182397029598	3.76348850604426
I_{sd1} (μA)	50.0000000000000	50.0000000000000	5.00000000000000E-06
I_{sd2} (μA)	1.15294292263234	50.0000000000000	0.806008655952287
I_{sd3} (μA)	5.00000000000000E-06	0.500000000000000	5.00000000000000E-06
R_s (Ω)	0.207601859584581	1862.10471783469	0.167777264360613
R_{sh} (Ω)	1034.42832571954	2.42791400871664	2000
n_1	4	2.53114765246777	4
n_2	1.57227704231615	2.12182397029598	1
n_3	2.80890475091387	5.00000000000000e-05	4
RMSE	**0.00592493660678422**	**0.0148198476605245**	**0.0310879585632136**
G = 1000 W/m²			
I_{ph} (A)	3.45549706866238	2.67616770954910	4.69110432148946
I_{sd1} (μA)	5.00000000000000E-06	50.0000000000000	5.00000000000000E-06
I_{sd2} (μA)	0.148603862029068	50.0000000000000	0.847295949601338
I_{sd3} (μA)	6.00000000000000	0.500000000000000	5.00000000000000E-06
R_s (Ω)	0.349499411129426	353.179288408815	0.165119758493480
R_{sh} (Ω)	368.294455027093	2.45467322081916	1965.76193589482
n_1	4	2.44680579081875	4
n_2	1.38520115840378	2.67616770954910	1
n_3	4	5.00000000000000e-05	2.93182823157729
RMSE	**0.00440333868599190**	**0.0345617459921048**	**0.0303263993408586**

cost function for 30 separately run of the estimation process.

The optimized parameters for the SDM, DDM, and TDM have been applied to plot the estimated I-V and P-V curves of the Photowatt-PWP201 module. The measured and the estimated curves based on COA have been visualized in Figs 13 to 15 for SDM, DDM and TDM models, respectively. The figures show that the estimated curves

TABLE 14. Statistical measurements of the COA technique for the three PV modules at different intensities of solar radiation and temperature of 25 °C (TDM).

Parameters	Mono-crystalline SM55	Thin-film ST40	Multi-crystalline KC200GT
G = 200 W/m^2			
Min	0.00314769185968629	0.00199347893161887	0.00384994234788785
Max	0.0115625821054789	0.00343074935362843	0.0192600166892521
Mean	0.00533493623360287	0.00224340759300184	0.00746931318350531
Median	0.00484466883762805	0.00221397637726309	0.00619491034911639
SD	0.174827001487376	0.0235483463451697	0.376211626565671
RE	34.7436228102482	6.26865570081558	47.0055199346443
MAE	0.00218724437391658	0.000249928661382968	0.00361937083561747
RMES	0.00314769185968629	0.00199347893161887	0.00384994234788785
Eff.	64.4362642828067	89.6371189070129	61.7134772446017
G = 400 W/m^2			
Min	0.00390673719456728	0.00538161620132653	0.00830786466427263
Max	0.0197150712627842	0.0107340618372768	0.0198381008557071
Mean	0.0102775775249788	0.00623415430946954	0.0126054416565240
Median	0.00966572340203994	0.00604534282803483	0.0122231913005442
SD	0.461267119468542	0.0815698623192028	0.277876178118626
RE	81.5365868386391	7.92083712633457	25.8645101113214
MAE	0.00637084033041152	0.000852538108143015	0.00429757699225138
RMES	0.00390673719456728	0.00538161620132653	0.00830786466427263
Eff.	47.7705499379629	87.3553648459903	69.0190410304311
G = 600 W/m^2			
Min	0.00962173228389160	0.00992342776192367	0.0153697702423048
Max	0.0319572969632267	0.0104041853213377	0.0555019085144984
Mean	0.0153505815267135	0.0101012311331149	0.0314758667099507
Median	0.0141564864809804	0.0101026960863977	0.0288851050824668
SD	0.480998004398992	0.00821481358671273	0.739975268515513
RE	29.7703629335696	0.895876785002757	52.3953716084655
MAE	0.00572884924282193	0.000177803371191186	0.0161060964676459
RMES	0.00962173228389160	0.00992342776192367	0.0153697702423048

TABLE 14. *(Continued.)* **Statistical measurements of the COA technique for the three PV modules at different intensities of solar radiation and temperature of 25 °C (TDM).**

Eff.	68.0524535233512	98.2460920619101	51.4218905944343
G = 800 W/m^2			
Min	0.00592493660678422	0.0148198476605245	0.0310879585632136
Max	0.0217559915875299	0.0192858169509663	0.0540715330742753
Mean	0.0142315270891611	0.0167705105224424	0.0416852843345208
Median	0.0137809822242479	0.0166994488572410	0.0415839753846473
SD	0.388885397412343	0.113598502810032	0.711095783855336
RE	70.0985599817690	6.58125139543057	17.0441004509171
MAE	0.00830659048237685	0.00195066286191791	0.0105973257713072
RMES	0.00592493660678422	0.0148198476605245	0.0310879585632136
Eff.	45.5373689490813	88.7604714176860	76.7731635676169
G = 1000 W/m^2			
Min	0.00440333868599190	0.0345617459921048	0.0303263993408586
Max	0.0207382207462483	0.0452407186982594	0.0600038890215845
Mean	0.0109150676703575	0.0380887263230879	0.0455862550268742
Median	0.00959613385602562	0.0378193497014830	0.0470724185792311
SD	0.437375957451836	0.254630593534460	0.859778583146268
RE	73.9408145582922	5.10243367303967	25.1593595311133
MAE	0.00651172898436562	0.00352698033098318	0.0152598556860156
RMES	0.00440333868599190	0.0345617459921048	0.0303263993408586
Eff.	47.5709510083908	91.1217525396243	69.1148847684377

based on COA agreed with the experimental data. Moreover, the regression between the computed and experimentally measured curves is 1, which validates the COA based methodology. The statistical analysis has been applied to prove the robustness of COA optimization technique. The results of the statistical analysis have been listed in Table 8. The table shows that the COA algorithm has acceptable indices of statistical analysis such as standard division (SD) and relative error (RE) for the three estimated models.

From the results, it is shown that the WDOWOAPSO [44], GCPSO [50] and TVACPSO [51] algorithms have RMSE values, which are better than that of COA with the DDM for Photowatt-PWP201 module. This may be one of COA limitations. However, the results of the COA are the best with the cases of SDM andi TDM.

C. CASE 3. DIFFERENT TYPES OF PV MODULES

For this case study, the parameters of SDM, DDM and TDM have been estimated based on the COA optimization algorithm for three different PV modules of Mono-crystalline SM55, Thin-film ST40 and Multi-crystalline KC200GT. The estimated parameters have been extracted for the three PV modules under different operating conditions of solar radiation ranges between 200 W/m^2 and 1000 W/ m^2 while the cell temperature is kept constant at 25 °C. To further investigate effectiveness, the applied COA algorithm was utilized to estimate the parameters of the SDM, DDM and TDM of the

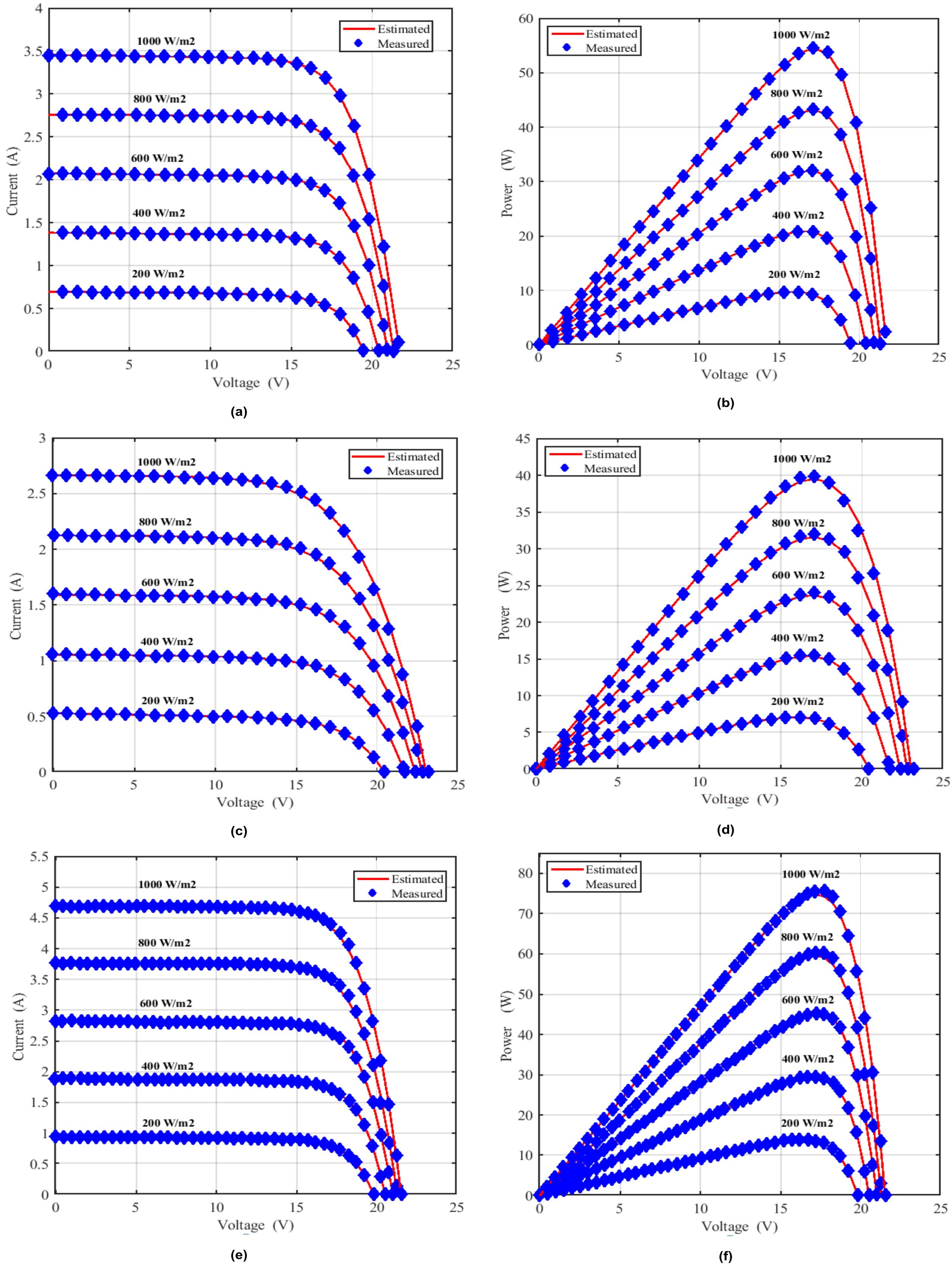

FIGURE 18. Comparison between experimentally measured data and the estimated results by COA at different solar radiation (TDM): (a) I-V curves for Mono-crystalline SM55, (b) P-V curves for Mono-crystalline SM55, (c) I-V curves for Thin-film ST40, (d) P-V curves for Thin-film ST40, (e) I-V curves for Multi-crystalline KC200GT, (f) P-V curves for Multi-crystalline KC200GT.

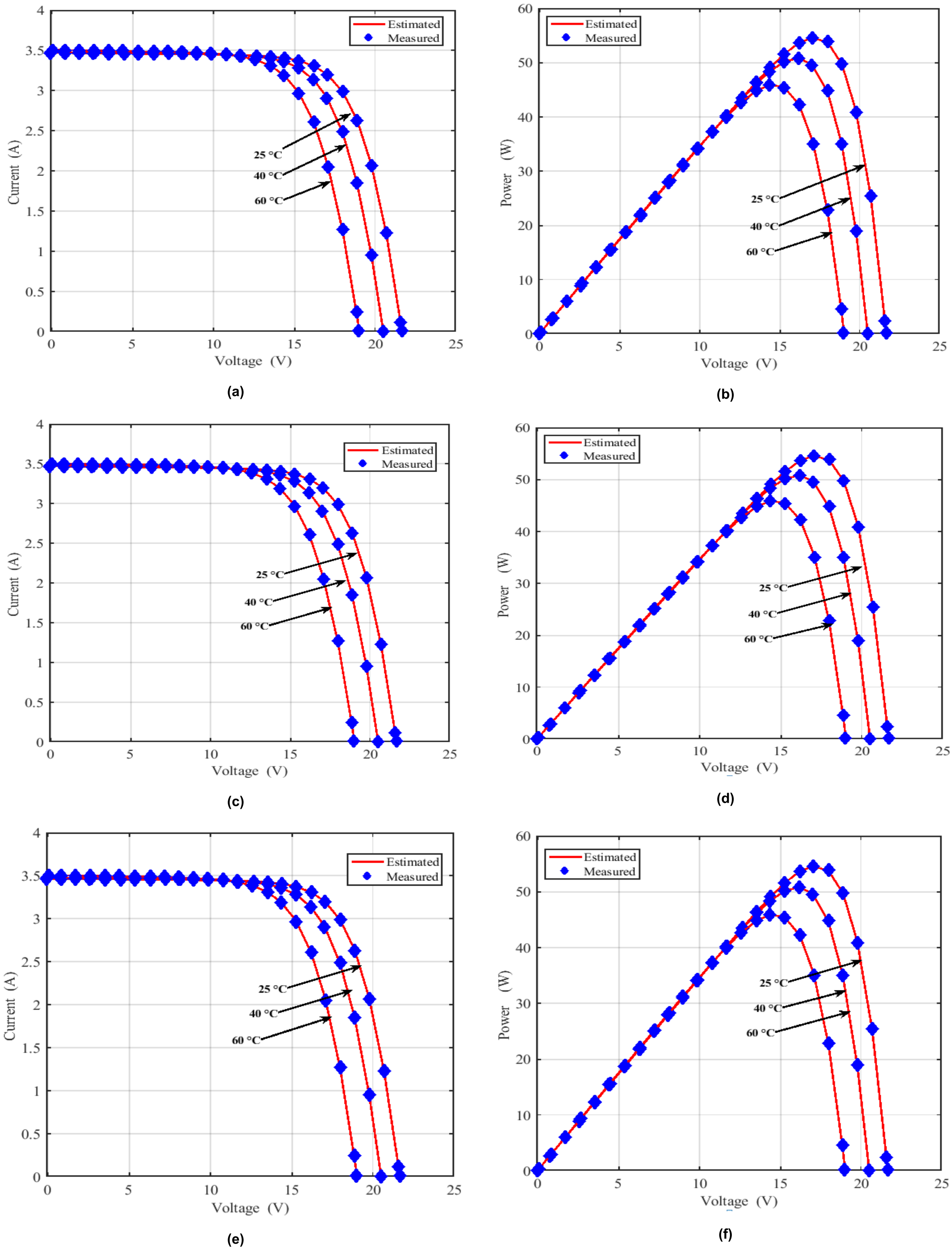

FIGURE 19. Comparison between experimentally measured data and the estimated results by COA at different temperature for Mono-crystalline SM55 module: (a) I-V curves (SDM), (b) P-V curves (SDM), (c) I-V curves (DDM), (d) P-V curves (DDM), (e) I-V curves (TDM), (f) P-V curves (TDM).

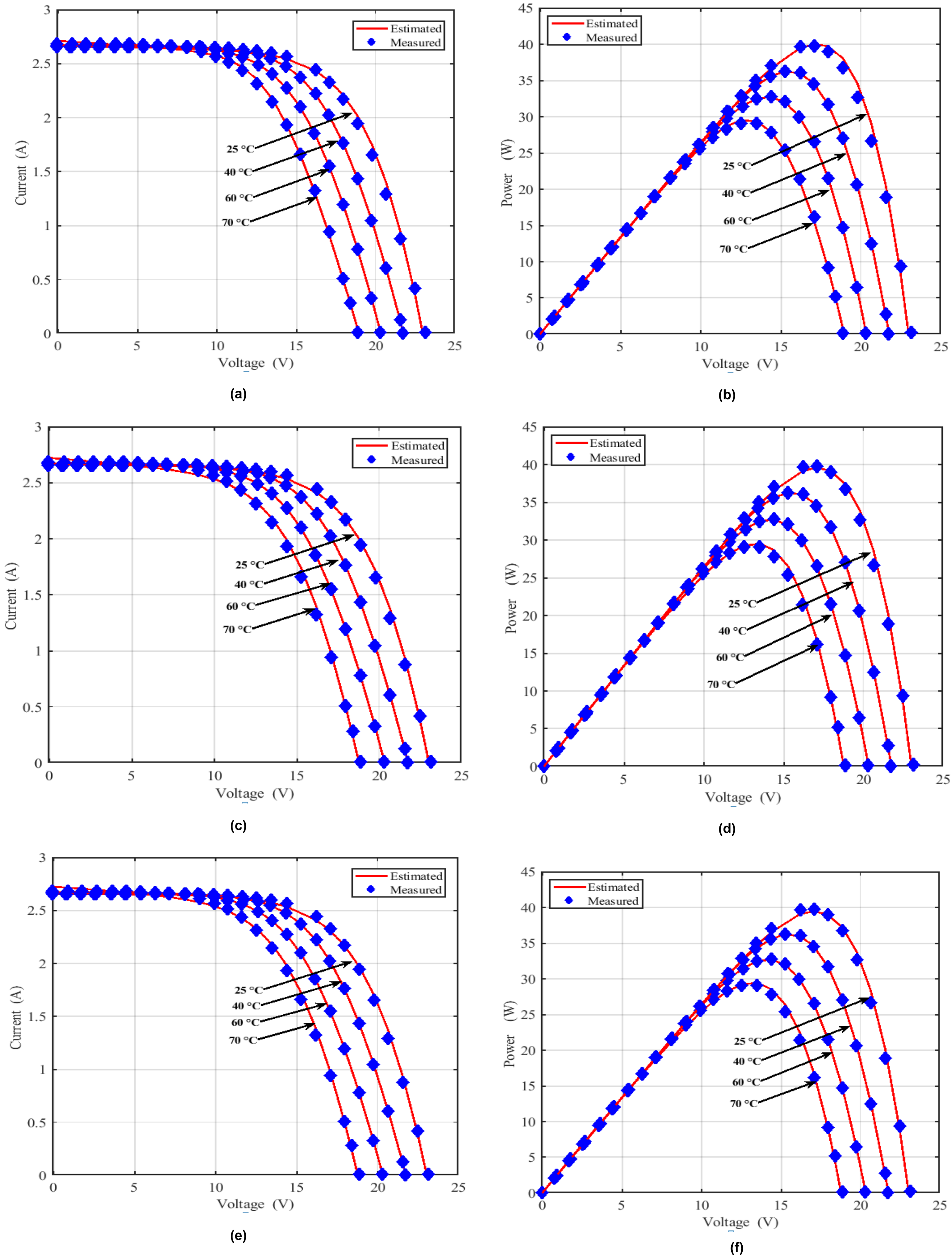

FIGURE 20. Comparison between experimentally measured data and the estimated results by COA at different temperature for Thin-film ST40 module: (a) I-V curves (SDM), (b) P-V curves (SDM), (c) I-V curves (DDM), (d) P-V curves (DDM), (e) I-V curves (TDM), (f) P-V curves (TDM).

TABLE 15. The estimated parameters using COA method for Mono-crystalline SM55 under various temperature and 1000 W/m2.

Parameters	Temperature		
	(25 °C)	**(50 °C)**	**(75 °C)**
	SDM		
I_{ph} (A)	3.46878894583400	3.48115216559805	3.50788954167678
I_{sd} (μA)	0.406710425622900	1.33267558020648	6.00000000000000
R_s (Ω)	0.301064462956973	0.300000000000000	0.307180366239241
R_{sh} (Ω)	500	400	295.665809140824
n	1.46872850194442	1.43079305284531	1.38880880429379
RMSE	**0.00689427418006831**	**0.00503848223321871**	**0.0133833511242449**
	DDM		
I_{ph} (A)	3.46851098597112	3.48123875563892	3.50275458067988
I_{sd1} (μA)	0	5.87286358386257	6.00000000000000
I_{sd2} (μA)	0.406223423412375	1.35330893959044	6.00000000000000
R_s (Ω)	0.300000000000000	0.300000000000000	0.300000000000000
R_{sh} (Ω)	500	400	400.748496044697
n_1	1.97014395926831	4	1.77145203763797
n_2	1.46856114122626	1.43238929658924	1.39464922030534
RMSE	**0.00690785969359715**	**0.00502809615504274**	**0.0128755576444319**
	TDM		
I_{ph} (A)	3.46468650826435	3.48037944689498	3.50536418701292
I_{sd1} (μA)	6.00000000000000	5.00000000000000E-06	6.00000000000000
I_{sd2} (μA)	0.411025640439695	6.00000000000000	5.42437205016578
I_{sd3} (μA)	5.00000000000000E-06	1.38360152387738	5.45801275333350
R_s (Ω)	0.300000000000000	0.300000000000000	0.300000000000000
R_{sh} (Ω)	600	417.637280201146	357.609340815138
n_1	3.41121817258066	4	1.39346163027418
n_2	1.46974067968189	3.53265023916382	2.96485544947216
n_3	4	1.43450275435242	1.79240496487185
RMSE	**0.00676597412004445**	**0.00506140100764541**	**0.0128941775386055**

TABLE 16. Comparison of the statistical results of the COA method for Mono-crystalline SM55 under various values of temperature and 1000 W/m2.

Parameters	Temperature		
	(25 °C)	(40 °C)	(60 °C)
	SDM		
Min	0.00689427418006831	0.00503848223321871	0.0133833511242449
Max	0.0216605899797845	0.00840208665563704	0.0149853025130824
Mean	0.0104121560127288	0.00575474206366704	0.0138703032315398
Median	0.00908238193573627	0.00549065951938471	0.0136527654188536
SD	0.375611935125435	0.0744327944249636	0.0464873898843701
RE	25.5130688218844	7.10789278689953	1.81924580314114
MAE	0.00351788183266047	0.000716259830448334	0.000486952107294936
RMES	0.00689427418006831	0.00503848223321871	0.0133833511242449
Eff.	72.5942460585489	88.7874277844507	96.5917708294361
	DDM		
Min	0.00690785969359715	0.00502809615504274	0.0128755576444319
Max	0.0301804034713853	0.0104161196028361	0.0147581736615543
Mean	0.0135893957369471	0.00623808181522791	0.0135107213465851
Median	0.0122606516737592	0.00578244003094129	0.0135058583067466
SD	0.612942002777879	0.134115834923267	0.0411707672110827
RE	48.3618395546091	12.0322446396701	2.46654832238630
MAE	0.00668153604334993	0.00120998566018517	0.000635163702153232
RMES	0.00690785969359715	0.00502809615504274	0.0128755576444319
Eff.	60.3943374455479	83.5814402772510	95.3832338097387
	TDM		
Min	0.00676597412004445	0.00506140100764541	0.0128941775386055
Max	0.0273983082835970	0.0168749148280784	0.0142413798154625
Mean	0.0119604051496091	0.00650313050522985	0.0133699044417436
Median	0.00991760123290990	0.00596141039099556	0.0132774102121257
SD	0.555276494773372	0.197424001683461	0.0393783767108451
RE	38.3864240196839	14.2423954889828	1.84473535327775
MAE	0.00519443102956468	0.00144172949758444	0.000475726903138109
RMES	0.00676597412004445	0.00506140100764541	0.0128941775386055
Eff.	66.3279612332971	81.8547122091178	96.5223802546967

TABLE 17. The estimated parameters using COA method for Thin-film ST40 under various values of temperature and 1000 W/m2.

Parameters	Temperature			
	(25 °C)	**(40 °C)**	**(60 °C)**	**(70 °C)**
		SDM		
I_{ph} (A)	2.66389281896230	2.74689279386192	2.67246756656938	2.66033951615929
I_{sd} (μA)	50.0000000000000	1.00000000000000	46.5176894713381	12.1059277071142
R_s (Ω)	0.500000000000000	1.43693115108811	1.05776170960538	1.06105892432814
R_{sh} (Ω)	400	102.258149430273	1985.36261478095	2000
n	2.28845336585994	1.32299200697402	1.82420556092792	1.66304263886589
RMSE	**0.0471343830412605**	**0.0212216562064389**	**0.00326982483059946**	**0.00643384709004758**
		DDM		
I_{ph} (A)	2.67134317473653	2.74729862645703	2.67245373777643	2.66033223170861
I_{sd1} (μA)	50.00000000000000	50.00000000000000	43.9666031445780	50.00000000000000
I_{sd2} (μA)	50.00000000000000	50.00000000000000	45.7175242243331	10.4239822674468
R_s (Ω)	0.500000000000000	0.800000000000000	1.06108247296107	1.06922181504232
R_{sh} (Ω)	428.697593469744	79.0303012250384	2000	2000
n_1	2.46631865143415	1.88244605219148	1.81551032959393	3.78194644389980
n_2	2.43125227220200	1.94072992912420	3.71352364293845	1.69299849785932
RMSE	**0.0349592021522724**	**0.0406553521827573**	**0.00325837750130131**	**0.00648062502627141**
		TDM		
I_{ph} (A)	2.65421950639464	2.74863054607358	2.67295146773152	2.65899381837396
I_{sd1} (μA)	44.5854226580386	50.00000000000000	2.28674887104503	14.819948311719
I_{sd2} (μA)	50.0000000000000	50.0000000000000	5.00000000000000E-06	5.00000000000000E-06
I_{sd3} (μA)	50.0000000000000	50.0000000000000	50.0000000000000	5.00000000000000E-06
R_s (Ω)	0.500000000000000	0.800000000000000	1.04910469016443	1.04438531366087
R_{sh} (Ω)	2000	86.2146075597150	1930.26749669210	4581.20847360194
n_1	2.44708171981627	2.05530306701811	3.08831414008709	1.69050844622031
n_2	2.59339210101682	2.10411591579523	4	3.89416376530338
n_3	2.60469569230814	1.88576713733071	1.83624562854596	3.94705492383948
RMSE	**0.0306854974814170**	**0.0360395218264921**	**0.00328763464243095**	**0.00637135473197821**

three PV modules at cell temperature ranges between 25 °C and 75 °C with 1000 W/m^2 solar radiation intensity.

1) DIFFERENT INTENSITIES OF SOLAR RADIATION AND TEMPERATURE OF 25 °C

The results of the extracting parameters of the SDM for the three PV modules under different intensities of solar radiation and temperature of 25 °C have been listed in Table 9. The table shows that under each intensity of solar radiation, the COA optimization algorithm is capable to estimate the parameters of SDM with acceptable values of RMSE for each PV module. The characteristics of the three different PV modules have been shown in Fig. 16. The figure shows a good agreement between the actual and estimated curves for the

TABLE 18. Comparison of the statistical results of the COA method for Thin-film ST40 under various values of temperature and 1000 W/m2.

Parameters	Temperature			
	(25 °C)	(40 °C)	(60 °C)	(70 °C)
		SDM		
Min	0.0471343830412605	0.0212216562064389	0.00326982483059946	0.0064338470900475
Max	0.0471416389113695	0.0234319605398170	0.00550239397793822	0.0100393531816166
Mean	0.0471346105722198	0.0217002190459801	0.00364346219329994	0.0073744271978166
Median	0.0471343849395686	0.0215052158238710	0.00350211585547126	0.0071111288131496
SD	0.0001036572657409	0.0523909283682665	0.0460148612757505	0.0823421513709123
RE	0.000241364100553	1.12753414456878	5.71341558122530	7.30962435541877
MAE	2.275309593581e-07	0.0004785628395411	0.00037363736270048	0.0009405801077690
RMES	0.0471343830412605	0.0212216562064389	0.00326982483059946	0.0064338470900475
Eff.	99.9995173215187	97.8486039904150	90.8738287303929	88.1935173812192
		DDM		
Min	0.0349592021522724	0.0406553521827573	0.00325837750130131	0.0064806250262714
Max	0.0452085991182135	0.0508914410892188	0.00709675807903832	0.0103128082282580
Mean	0.0379703623007773	0.0455705066890927	0.00367835492099563	0.0076019753724945
Median	0.0373245346895391	0.0456414996579463	0.00342318575248697	0.0073118843769963
SD	0.234910128900941	0.250144005837289	0.0683278437915141	0.101239161500400
RE	4.30667744559664	6.04490459735823	6.44457892811059	8.65156016338951
MAE	0.0030111601485048	0.0049151545063353	0.00041997741969432	0.0011213503462231
RMES	0.0349592021522724	0.0406553521827573	0.00325837750130131	0.0064806250262714
Eff.	92.3944104849514	89.4793941802703	90.6052289701530	86.5962054821880
		TDM		
Min	0.0306854974814170	0.0360395218264921	0.00328763464243095	0.0063713547319782
Max	0.0405934724853591	0.0502210053623696	0.00566017066449624	0.0141088839770055
Mean	0.0354291806540235	0.0444594599032655	0.00381321243066060	0.0078912087068102
Median	0.0352056477469656	0.0445185980371158	0.00356494983803575	0.0076004172239941
SD	0.230963296772345	0.307359030957757	0.0587788893915174	0.142963904086215
RE	7.72951974378011	11.6815341187242	7.99325115763224	11.9272434102896
MAE	0.00474368317260655	0.0084199380767734	0.00052557778822966	0.0015198539748320
RMES	0.0306854974814170	0.0360395218264921	0.00328763464243095	0.00637135473197821
Eff.	86.9739083434153	81.4565893258502	87.9203221876714	82.9119392194757

TABLE 19. The estimated parameters using COA method for Multi-crystalline KC200GT under various values of temperature and 1000 W/m2.

Parameters	Temperature		
	(25 °C)	(40 °C)	(60 °C)
	SDM		
I_{ph} (A)	4.66251941522634	4.73884574442924	4.74929053602854
I_{sd} (μA)	0.871738730280996	9.36978876748732	2.05222797300499
R_s (Ω)	0.152312825599889	0.207103103852460	0.322544655219147
R_{sh} (Ω)	2000	2000	2000
n	1	1	1.25930776368609
RMSE	**0.0284480990231585**	**0.0233245056202733**	**0.0220319520684519**
	DDM		
I_{ph} (A)	4.66049202112645	4.73871194153190	4.75052866472153
I_{sd1} (μA)	0.00500000000000000	9.37211230929485	1.86286817506839
I_{sd2} (μA)	5.00000000000000E-06	1.00000000000000E-06	50.0000000000000
R_s (Ω)	0.285894724142538	0.206743752338275	0.322181374824221
R_{sh} (Ω)	633.772891056069	1994.99159131646	1995.29092019124
n_1	1.12698762973570	1	1.25078586369370
n_2	2.43275188376311	1	4
RMSE	**0.00910637104110895**	**0.0233267185310228**	**0.0222031026707030**
	TDM		
I_{ph} (A)	4.66097577505660	4.73550817374537	4.75211121957017
I_{sd1} (μA)	1.00000000000000E-06	0.121835964969577	2.11394168324621
I_{sd2} (μA)	0.259174017933050	50.0000000000000	1.00000000000000E-06
I_{sd3} (μA)	50.0000000000000	1.30099904333170	11.6518454786101
R_s (Ω)	0.187564436579575	0.279225428252353	0.320684344280452
R_{sh} (Ω)	2000	2000	2000
n_1	4	2.80076838845876	1.26164510721196
n_2	1.39138057829235	3.11604176159777	2.36862139408454
n_3	4	1.30565714600646	3.81495864919014
RMSE	**0.0208726379196747**	**0.0185108263621156**	**0.0221474648457524**

current and the power against voltage. For further validation of the COA based estimator; a comparison of the statistical results of the COA method for the three PV modules under study at various solar radiations and cell temperature of 25 °C according to the SDM have been listed in Table 10. The results prove that the COA can be used for extracting the PV

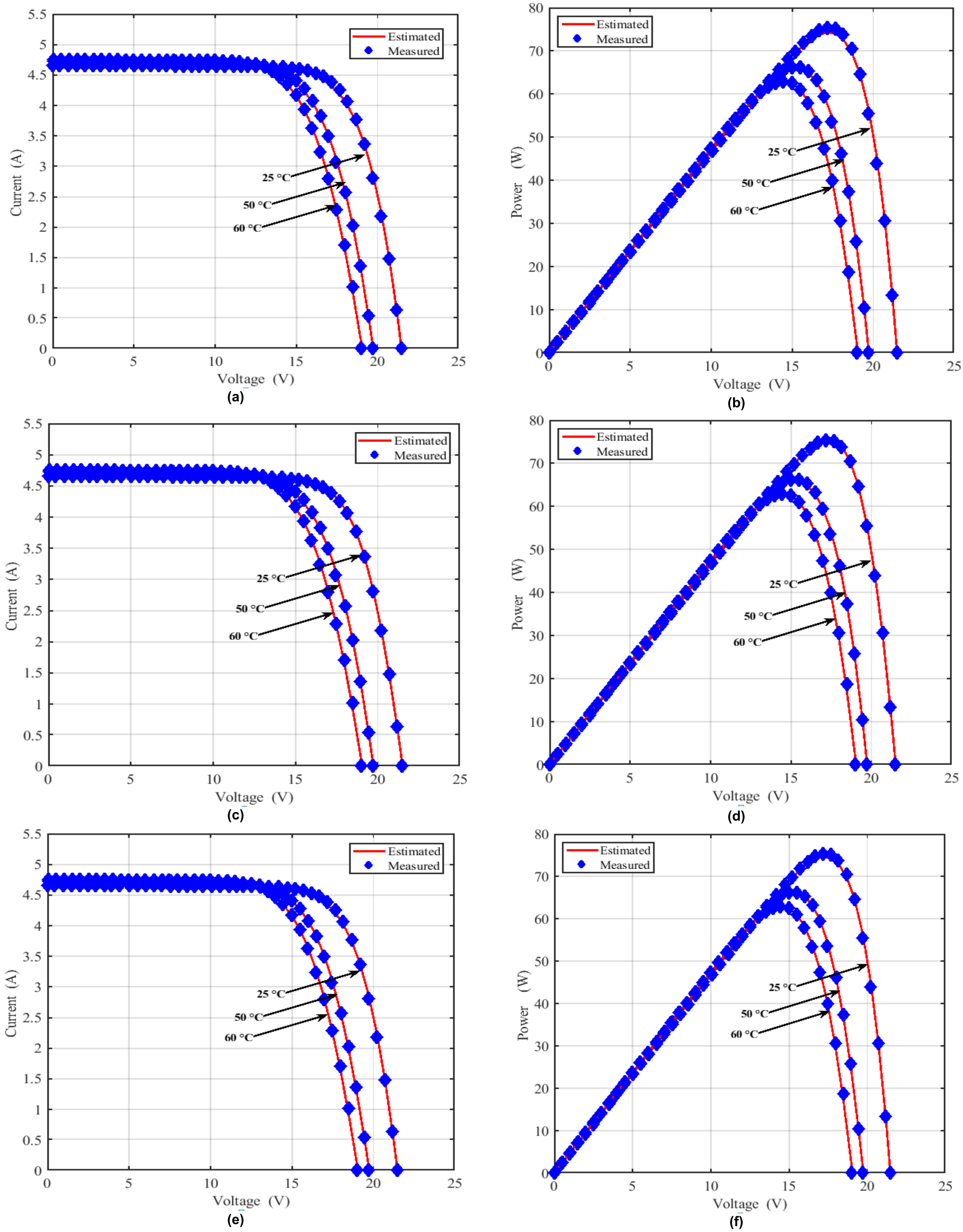

FIGURE 21. Comparison between experimentally measured data and the estimated results by COA at different temperature for Multi-crystalline KC200GT module: (a) I-V curves (SDM), (b) P-V curves (SDM), (c) I-V curves (DDM), (d) P-V curves (DDM), (e) I-V curves (TDM), (f) P-V curves (TDM).

TABLE 20. Comparison of the statistical results of the COA method for Multi-crystalline KC200GT under various values of temperature and 1000 W/m2.

Parameter	Temperature		
	(25 °C)	**(50 °C)**	**(60 °C)**
	SDM		
Min	0.0284480990231585	0.0233245056202733	0.0220319520684519
Max	0.0405784072220034	0.0352374673966211	0.0391482086294683
Mean	0.0299205482853660	0.0252452920924292	0.0290768148213972
Median	0.0287839286794726	0.0238371422964083	0.0291087400578175
SD	0.266459240871070	0.308265268954206	0.413558907859276
RE	2.58795721466096	4.11752879873785	15.9878315163753
MAE	0.00147244926220745	0.00192078647215596	0.00704486275294531
RMES	0.0284480990231585	0.0233245056202733	0.0220319520684519
Eff.	95.6930428896812	93.5064750653732	77.3012400951141
	DDM		
Min	0.00910637104110895	0.0233267185310228	0.0222031026707030
Max	0.0668435003947055	0.0336037052371308	0.0386505630317724
Mean	0.0443287339396176	0.0250367081167295	0.0291357950002499
Median	0.0504744029632997	0.0239171286332775	0.0291165899416434
SD	1.79613726654841	0.242238278237376	0.387976310232982
RE	193.394068501624	3.66530248014218	15.6119899825861
MAE	0.0352223628985087	0.00170998958570673	0.00693269232954689
RMES	0.00910637104110895	0.0233267185310228	0.0222031026707030
Eff.	28.4358890508070	93.9008769258613	77.5592040061854
	TDM		
Min	0.0208726379196747	0.0185108263621156	0.0221474648457524
Max	0.0679578537999007	0.0390379523307873	0.0425911389959800
Mean	0.0547982278400683	0.0282499313683490	0.0296362932692392
Median	0.0595138198180394	0.0287707007866448	0.0290134175761448
SD	1.02404389018757	0.598902458272348	0.561779350019584
RE	81.2680937861116	26.3065106217124	16.9067396102517
MAE	0.0339255899203935	0.00973910500623336	0.00748882842348677
RMES	0.0208726379196747	0.0185108263621156	0.0221474648457524
Eff.	40.3153587964012	68.6366988052971	77.3261214979784

model parameters under the different conditions of the solar radiation.

For DDM, Table 11 shows the extracted parameters of the DDM of the three PV modules under different intensities of solar radiation and temperature of 25 °C. Moreover, Fig. 17 shows the characteristics of the PV modules based on the estimated parameters. The results show a good matching between the estimated and datasheet characteristics under the different intensities of solar radiation. Table 12 has the results of the statistical analysis of the COA method for the three PV modules under different solar radiation and cell temperature of 25 °C based on the DDM.

Furthermore, the parameters of TDM for each PV modules have been estimated based on the optimization algorithm of COA. The results of the TDM parameters have been listed in Table 13. Moreover, Fig. 18 shows that the estimated characteristics of each PV modules have a good agreement with actual characteristics under the different intensities of solar radiation. Table 14 has the results of the statistical analysis of the COA method for the three PV modules under different solar radiation and cell temperature of 25 °C using TDM.

2) OPERATION UNDER DIFFERENT TEMPERATURES

To further validate the COA, the optimization algorithm has been tested in order to estimate the unknown design parameters of different models for the three PV modules under different cell temperatures. The optimized results of such case of studies have been illustrated in Table 15 to Table 20 and Figs 19 to 21. Table 15, Table 17 and Table 19 show the estimated parameters for Mono-crystalline SM55 and Thin-film ST40 Multi-crystalline KC200GT, respectively, using COA method at different temperature and 1000 W/m^2. While the statistical results of the COA method for Mono-crystalline SM55, Thin-film ST40 and Multi-crystalline KC200GT at different temperatures and 1000 W/m^2 have been listed in Tables 16, 18 and 20, respectively. The tables show that the COA can accurately extract the parameters of the SDM, DDM and TDM for the three PV modules. The characteristics of the different PV modules of Mono-crystalline SM55, Thin-film ST40 and Multi-crystalline KC200GT have been shown in Figs 19, 20 and 21, respectively.

V. CONCLUSION

In this paper, a recent coyote optimization algorithm has been utilized for tackling with the optimization problem of parameters' identification of solar cells and various PV modules. To evaluate the power of the applied optimization method, data from the datasheet of the manufacturer and measured data obtained from the literature for different solar cells and PV modules at various intensities solar radiations and temperature have been used. Three different models of solar cells and PV modules, namely single diode model (SDM), double diode model (DDM), and three diode model (TDM), have been involved in this study. The results obtained from the application of the COA have been compared with the results reported in the literature for other optimization methods, where the applied COA achieves the best values of the objective function (RMSE). In addition, three different types of PV modules; mono-crystalline, thin-film, and multi-crystalline have been used for the validation of the applied technique under different intensities of solar radiation and module temperature. Furthermore, parametric and non-parametric statistical study of the results of the optimization of the parameters of solar cells and PV modules have been conducted in order to ensure the accurateness and stability of the COA in solving the optimization problem. Accordingly, the simulation results proved the good agreement between the V-I characteristics based on the optimized parameters and the corresponding ones reported in the datasheet of the manufacturer. Finally, the applied COA successes to introduce itself as a competitor to other optimization algorithms for parameter extraction of different solar cells and PV modules. The application of COA for extracting the maximum power point of PV under partial shading may be considered in the future work. Moreover, the COA can be applied to optimize other engineering problems in numerous research areas such as smart grids and other renewable energy systems.

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