

Research Article

Calculation of Seven Photovoltaic Cells Parameters Using Parallelized Successive Discretization Algorithm

Adrian M. Deaconu ¹, Daniel T. Cotfas ², and Petru A. Cotfas ²

¹Faculty of Mathematics and Computer Science, Transilvania University of Brasov, Braşov, Romania

²Faculty of Electrical Engineering and Computer Science, Transilvania University of Brasov, Braşov, Romania

Correspondence should be addressed to Adrian M. Deaconu; a.deaconu@unitbv.ro

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Some parameters must be calculated with very good accuracy for the purpose of designing, simulating, and evaluating the performance of a photovoltaic system. The seven parameters of the photovoltaic cell and panels for the two-diode model are determined using a parallelized metaheuristic algorithm based on successive discretization. The parameters obtained for a photovoltaic cell and four panels using the proposed algorithm are compared with the ones calculated through over twenty methods from recent research literature. The root mean square error is used to prove the superiority of the Parallelized Successive Discretization Algorithm (PSDA). The smallest values for root mean square error (RMSE) in both cases, photovoltaic cell and panels, are obtained for the algorithm presented in this paper. The seven parameters for three panels known in the specialised literature, Kyocera KC200GT, Leibold Solar Module LSM 20, and Leybold Solar Module STE 4/100 are determined for the first time using PSDA.

1. Introduction

Fossil fuel is inevitable exhausting, and its price has continually increased in the last decades. There is also an increasing concern on the environmental pollution and on the climate changes related to the use of fossil fuel. It is strongly believed that the renewable energy is the clean alternative solution of today and for the future. Many researchers have focused on renewable solar energy in general and, in particular, on the generation of electric power using photovoltaic cells which is desired to become in the near future one of the most important energy sources.

Nowadays, there are many photovoltaic cells types, some of them relatively new, such as Perovskite or multijunctions—triple or four junctions, which must be analyzed and characterized to optimize their efficiency. Very good photovoltaic panels are achieved if the photovoltaic cells used are “twins.” This can be realized if the photovoltaic cells are characterized before the fabrication process of the photovoltaic panels, and they are selected so that the parameters have the same values.

The characterization process must be very fast so as to increase the productivity.

Some parameters must be calculated with very good precision for the purpose of designing, simulation, and evaluation of the performance of a photovoltaic system. Nowadays, the estimation of these parameters is an important research topic, for which researchers develop new methods and algorithms. The parameters of the photovoltaic cells and panels can be determined using the current voltage characteristic, called I-V characteristic in the following, equivalent circuit, and the mathematical model [1, 2]. The one-diode model is generally used to determine the parameters of the photovoltaic cells, due to the simplicity and good agreement for the parameters results [3]. Lately, the researchers are using the two-diode model to determine the photovoltaic cells parameters, especially for the monocrystalline and polycrystalline silicon photovoltaic cells and panels. In this case, both mechanisms, the diffusion and the generation and recombination, are taken into account. Using the two-diode model leads to growth accuracy with which the parameters of the photovoltaic cells are determined.

The parameters of the photovoltaic cells and panels were determined using graphical analysis and numerical analysis with different approximation [1]. The metaheuristic algorithms based on natural phenomena were used lately with success because are suitable for nonlinear multimodal as is the problem for photovoltaic devices. The parameters of the photovoltaic cells and panels using the metaheuristic algorithms are calculated with high accuracy due to avoiding the errors made through approximation in the other methods, and the necessary time for their determination is reduced continuously due to the optimization of the algorithms and use of the hybrid algorithms [3].

We shall briefly present below the best currently known algorithms for determining the solar cell parameters. They are taken into consideration to compare their performance against the Parallelized Successive Discretization Algorithm (PSDA) presented in this paper. Most of these algorithms are metaheuristic methods inspired from the behavior of populations of different groups of people or from the behavior of swarms of animals or insects. Population classification evolution algorithm (PCE) is an evolutionary algorithm, with a fast convergence speed and a very good accuracy [4]. Simplified TBLO (STBLO) [5] and generalized oppositional TBLO (GOTBLO) [6] are improved versions of teaching-learning-based optimization (TLBO) algorithm which is a population-based method. Improved shuffled complex evolution (ISCE) is an improved version of complex evolution strategy (SCE) which was applied with success to calculate the parameters of one-diode and two-diode models for photovoltaic cell and for panel [7]. Rcr-IJADE has better performance than other classic or adaptive differential evolution algorithms [8]. MABC is a modified version of artificial bee colony (ABC) algorithm with better results than the regular ABC [9]. EHA-NMS and NM-MPSO are hybrid algorithms and are based on Nelder–Mead and MABC [10] and, respectively, particle swarm optimization PSO [9]. Cat swarm optimization algorithm (CSO) is developed by analyzing the behaviors of cats. The performance of CSO surpasses that of PSO [11]. Bird mating optimizer (BMO) tries to imitate the mating strategies of bird species, without premature convergence, and thus, its solution is close to the global one [12]. Chaotic whale optimization algorithm (CWOA) is an algorithm developed on the hunting mechanism of humpback whales, and it can refine complex and multimodal objective functions [13]. Artificial bee swarm optimization algorithm (ABSO) is based on the intelligent behaviors of honey bees such as collection and processing of nectar [12]. Innovative global harmony search (IGHS) and grouping-based global harmony search (GGHS) algorithms are improved versions of the harmony search algorithm trying to imitate the improvisation process of musicians [14]. Simulated annealing (SA) is a single-searcher algorithm with less chance to find the global minimum [15]. Guaranteed convergence particle swarm optimization (GCP SO) [16] is an improved version of the PSO algorithm, and it has the ability to avoid premature convergence and to determine the parameters of the photovoltaic panels quickly and accurately. Time-varying acceleration coefficients particle swarm optimization (TVACPSO) is an improved PSO. WDOWOAPSO is a

hybrid method based on PSO and the wind-driven optimization (WDO) technique [17]. Artificial Bee Colony-Differential Evolution (ABC-DE) resulted from ABC, and its performance is improved for finding the global optimum and for convergence speed [18]. Flexible particle swarm optimization (FPSO) improves the PSO algorithm through increasing the ability of global search [19].

In this paper, a metaheuristic algorithm based on the discretization process of functions that systematically try to improve the approximate solution is presented. Discretization is defined in Mathematics as the continuous functions, variables, models, and equations transferred into discrete counterparts. It usually represents the first stage of achieving proper values for numerical evaluation or implementation on digital computers. Such techniques are implemented in order to solve miscellaneous problems [20], among the optimizing ones [21]. If continuous data is discretized, discretization error appears in various amounts. The aim is decreasing the errors down to a negligible value in terms of modeling scope.

The idea of successive discretization algorithm (SDA) applied for parameter estimation of PV cells is to compute a set of approximate solutions selected from values obtained by a discretization process and having the minimum root mean square error. Around each of these selected values, a more refined discretization is performed and a new set of approximate solutions is selected and so on. The successive discretization process performed a preset number of iterations or until no better solution is found than the best solution found so far in the previous iteration.

In this paper, we adapt and implement SDA in parallel for the two-diode model, and we compare the obtained solution with the solutions given by the best known methods at the moment. The novelty and the contributions of the paper are

- (i) the new algorithm PSDA is presented in the paper
- (ii) the results obtained for the RMSE for all devices under analysis are the best in comparison with the other algorithms from the specialised literature
- (iii) the time needed to extract the parameters of the photovoltaic cell and panels for the two-diode model increases, and the PSDA algorithm is the proper tool to reduce it; the duration is reduced 6 times using the PSDA in comparison with SDA algorithm
- (iv) three datasets are analyzed for the first time using the two-diode model: Kyocera KC200GT, Leibold Solar Module LSM 20, and Leybold Solar Module STE 4/100.

2. Method

2.1. Models for Photovoltaic Cell and Panel. The equivalent circuit of the photovoltaic panel is presented in Figure 1, and the mathematical model is given by Eq. (1). The following seven parameters can be determined: the photogenerated current I_{ph} , the reverse saturation current I_{od} and ideality factor of diode n_d which correspond to diffusion mechanism,

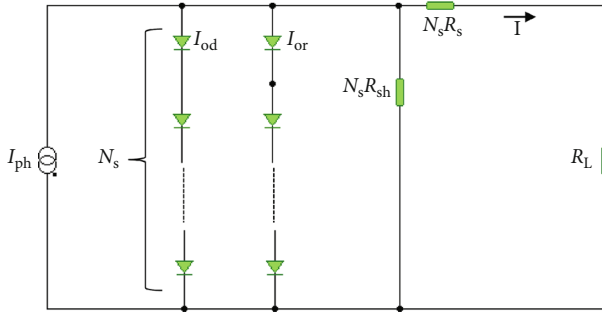


FIGURE 1: Equivalent circuits of photovoltaic panel. Two-diode model.

the reverse saturation current I_{or} and ideality factor of diode n_r which correspond to generation and recombination mechanism, and the parasitic resistance–series resistance R_s and shunt resistance R_{sh} [1]. N_s is the number of the photovoltaic cells connected in series. N_s is one in case of the photovoltaic cell.

$$I = I_{ph} - I_{od} \left(e^{\frac{V + I N_s R_s}{n_d N_s V_T}} - 1 \right) - I_{or} \left(e^{\frac{V + I N_s R_s}{n_r N_s V_T}} - 1 \right) - \frac{V + I N_s R_s}{N_s R_{sh}} \quad (1)$$

2.2. Parallelized Successive Discretization Algorithm. SDA algorithm was successfully applied for the one-diode model in [3]. It was compared with other methods used to determine the parameters of the photovoltaic cells and panels. SDA proved to be the best among the known methods at the moment the article was published. In this paper, we adapt SDA to solve the more complex problem of estimating the seven parameters for the two-diode model. Since the amount of calculations is considerably higher than for the one-diode model, a direct adaptation of SDA for the two-diode model leads to a very slow algorithm or to an algorithm that finds a low-quality solution. Therefore, a parallel implementation of SDA is needed, fast enough and able to compute very good solutions. In the production process of photovoltaic panels, it is very important to accurately and quickly estimate the cell parameters.

2.2.1. Discretization Process. The PSDA algorithm is based on discretization, which transfers continuous functions and equations into discrete counterparts. When the continuous data are discretized, some errors can appear, and the target is to reduce them [3].

We denote by

$$F_{I,V}^2(I_{ph}, I_{od}, n_d, I_{or}, n_r, R_s, R_{sh}) = I_{ph} - I_{od} \left(e^{\frac{V + I R_s}{n_d V_T}} - 1 \right) - I_{or} \left(e^{\frac{V + I R_s}{n_r V_T}} - 1 \right) - \frac{V + I R_s}{R_{sh}} - I. \quad (2)$$

Using Equations (1) and (2), the following equation is obtained:

$$F_{I,V}^2(I_{ph}, I_{od}, n_d, I_{or}, n_r, R_s, R_{sh}) = 0. \quad (3)$$

The root mean square error (RMSE), given by Equation (4), has to be minimized for the photovoltaic cell and panel parameters, I_{ph} , I_{od} , n_d , I_{or} , n_r , R_s , and R_{sh} calculated for the given pairs of current and voltage (I , V).

$$RMSE(I_{ph}, I_{od}, n_d, I_{or}, n_r, R_s, R_{sh}) = \sqrt{\frac{\sum (F_{I,V}^2(I_{ph}, I_{od}, n_d, I_{or}, n_r, R_s, R_{sh}))^2}{p}}, \quad (4)$$

where p represents the number of the given (I , V) pairs.

The intervals $J_i = [a_i, b_i]$ ($i = 1, 2, \dots, 7$) are considered for the definition of domains for the seven parameters enumerated before.

The function $F_{I,V}^2$ is continuous on the 7-dimensional interval $J_1 \times J_2 \times J_3 \times J_4 \times J_5 \times J_6 \times J_7$, which is called the discretization 7D interval. The discretization process is applied to the objective function $F_{I,V}^2$. The solution is searched in $J_1 \times J_2 \times J_3 \times J_4 \times J_5 \times J_6 \times J_7$. This 7D interval is the given boundaries for the searched solutions.

For each interval J_i , a positive integer $d_i \in N^*$ is considered ($i = 1, 2, \dots, 7$). Inside each of these 7 intervals, the values v_j^i ($j = 1, \dots, d_i$) are taken so that

$$a_i < v_1^i < v_2^i < \dots < v_{d_i}^i < b_i. \quad (5)$$

The values v_j^i ($j = 1, \dots, d_i$) are calculated using Equation (6) in order to obtain a good uniform distribution of the points in the interval J_i :

$$v_j^i = a_i + j l_i, \quad (6)$$

where l_i is calculated using the following relation:

$$l_i = \frac{b_i - a_i}{d_i + 1}. \quad (7)$$

Using Equations (6) and (7), the following relations are obtained:

$$v_1^i = a_i + l_i \text{ and } v_{d_i}^i = b_i - l_i. \quad (8)$$

For the photovoltaic cell or panel, the following set of septets of parameters is considered:

$$G = \left\{ \left(v_{j_1}^1, v_{j_2}^2, v_{j_3}^3, v_{j_4}^4, v_{j_5}^5, v_{j_6}^6, v_{j_7}^7 \right) \mid j_i = 1, \dots, d_i, i = 1, \dots, 7 \right\}. \quad (9)$$

PSDA calculates $(v_{k_1}^1, v_{k_2}^2, v_{k_3}^3, v_{k_4}^4, v_{k_5}^5, v_{k_6}^6, v_{k_7}^7)$ so that

$$RMSE \left(v_{k_1}^1, v_{k_2}^2, v_{k_3}^3, v_{k_4}^4, v_{k_5}^5, v_{k_6}^6, v_{k_7}^7 \right) = \min_{g \in G} RMSE(g). \quad (10)$$

The septet $(v_{k_1}^1, v_{k_2}^2, v_{k_3}^3, v_{k_4}^4, v_{k_5}^5, v_{k_6}^6, v_{k_7}^7)$ is an approximate solution of Equation (3).

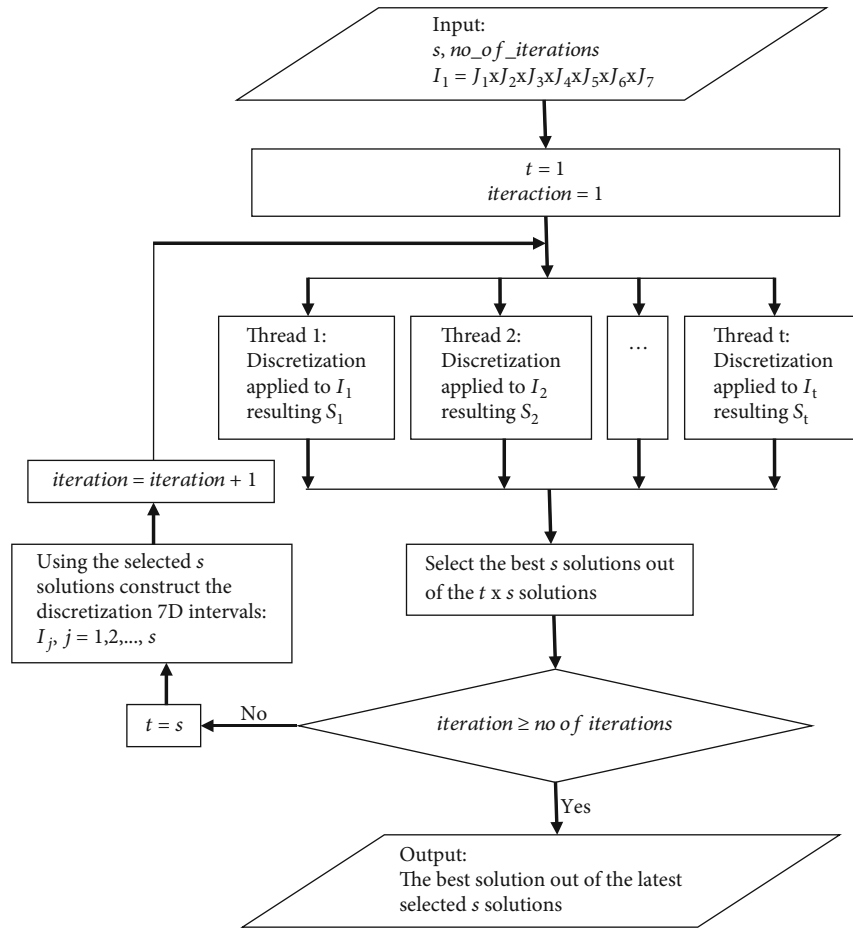


FIGURE 2: Flowchart of the parallel implementation of the algorithm.

TABLE 1: The seven parameters of the RTC photovoltaic cell.

Algorithm	I_{ph} A	I_{od} μA	I_{or} μA	n_d	n_r	R_s Ω	R_{sh} Ω	RMSE E-04
PSDA	0.76077943	0.22615047	0.74934181	1.4510581	2.00119185	0.03674321	55.48427327	9.82473
PCE [4]	0.760781	0.226015	0.749340	1.450923	2.000000	0.03674	55.483160	9.8248
STLBO [5]	0.76078	0.22566	0.75217	1.45085	2.00000	0.03674	55.4920	9.8248
ISCE [7]	0.76078108	0.22597409	0.74934898	1.4510167	2.000000	0.03674043	55.48544409	9.82484
Rcr-IJADE [8]	0.76078108	0.22597414	0.74934851	1.45101670	2.000000	0.03674043	55.48543800	9.824849
EHA-NMS [10]	0.76078108	0.22597420	0.74934836	1.45101674	2.000000	0.03674043	55.48544722	9.824849
NM-MPSO [10]	0.76078	0.22476	0.75524	1.45054	1.99998	0.03675	55.5296	9.825
CSO [11]	0.76078	0.22732	0.72785	1.45151	1.99769	0.036737	55.3813	9.8252
FPSO [19]	0.76078	0.22731	0.72786	1.45160	1.99969	0.036737	55.3923	9.8253
BMO [12]	0.76078	0.21110	0.87688	1.44533	1.99997	0.03682	55.8081	9.8262
CWOA [13]	0.76077	0.24150	0.60000	1.45651	1.9899	0.03666	55.2016	9.8272
MABC [9]	0.7607821	0.24102992	0.6306922	1.4568573	2.0000538	0.03671215	54.7550094	9.8276
GOTLBO [6]	0.760752	0.220462	0.800195	1.448974	1.999973	0.036783	56.075304	9.83177
ABSO [12]	0.76078	0.26713	0.38191	1.46512	1.98152 4	0.03657	54.6219	9.834
ICHS [14]	0.76079	0.16791	0.97310	1.42814	1.92126	0.03690	56.8368	9.8635
GGHS [14]	0.76056	0.37014	0.13504	1.49638	1.92998	0.03562	62.7899	10.684
SA [15]	0.7623	0.4767	0.01	1.5172	2	0.0345	43.1034	166.4

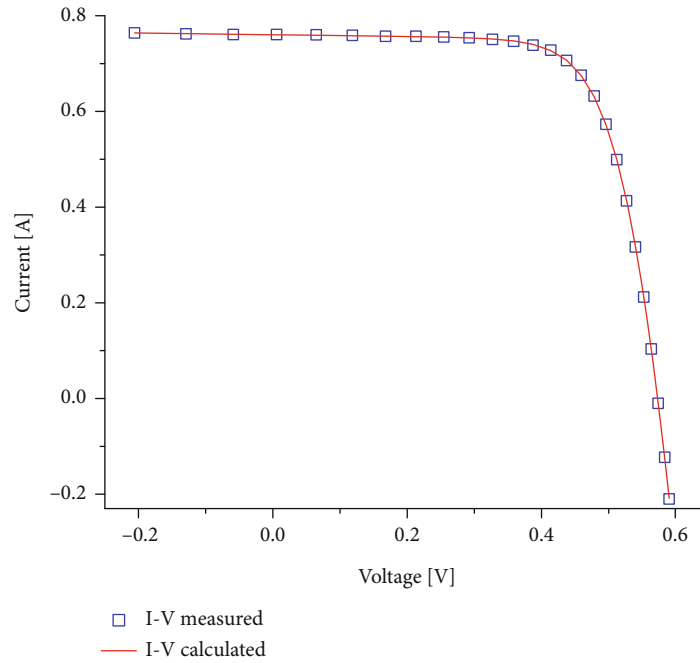


FIGURE 3: The I-V characteristics for RTC photovoltaic.

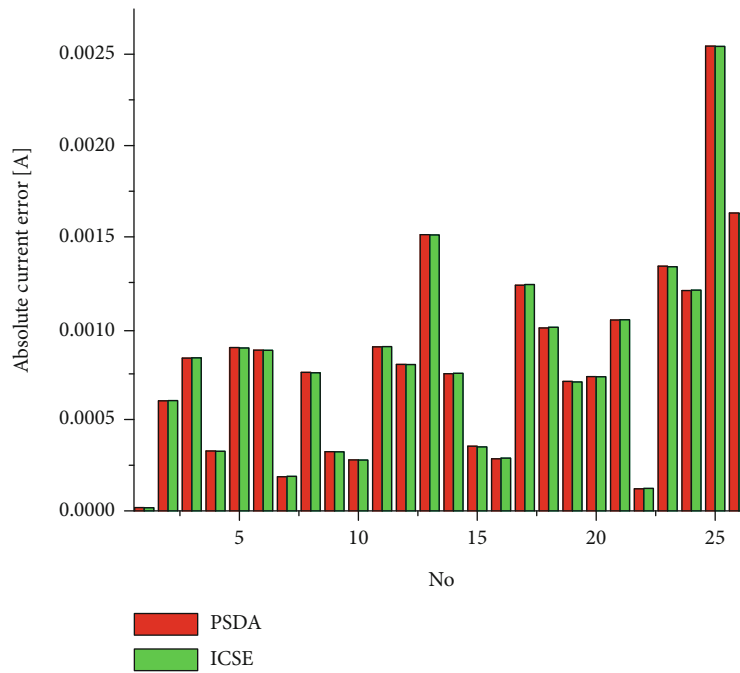


FIGURE 4: Absolute current error comparison for RTC.

2.2.2. *Improving the Solution by Successive Discretization.* The best approximate solution for Equation (3) can be improved using a successive discretization–refining initial solution.

The best $s \geq 1$ (“s” is established at the beginning of the algorithm) septets are considered $g_j = (v_{k_1^j}^1, v_{k_2^j}^2, v_{k_3^j}^3, v_{k_4^j}^4, v_{k_5^j}^5, v_{k_6^j}^6, v_{k_7^j}^7)$ ($j = 1, \dots, s$) in the set G , having the smallest RMSE errors (Cotfas D.T., [3]). For each septet g_j , the

solutions are refined for Equation (3) in the neighborhood of g_j :

$$J_1^j \times J_2^j \times J_3^j \times J_4^j \times J_5^j \times J_6^j \times J_7^j, \tag{11}$$

where

$$J_i^j = [v_{k_i^j}^i - l_i, v_{k_i^j}^i + l_i], i = 1, \dots, 7. \tag{12}$$

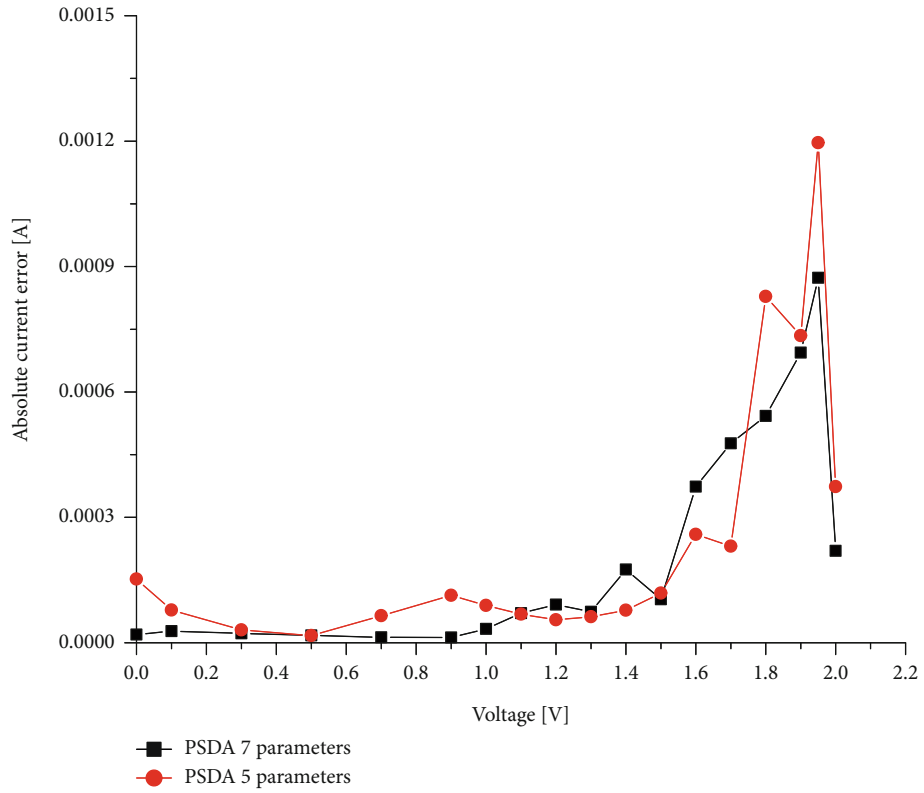


FIGURE 5: Comparison between the two-diode and one-diode model for RTC.

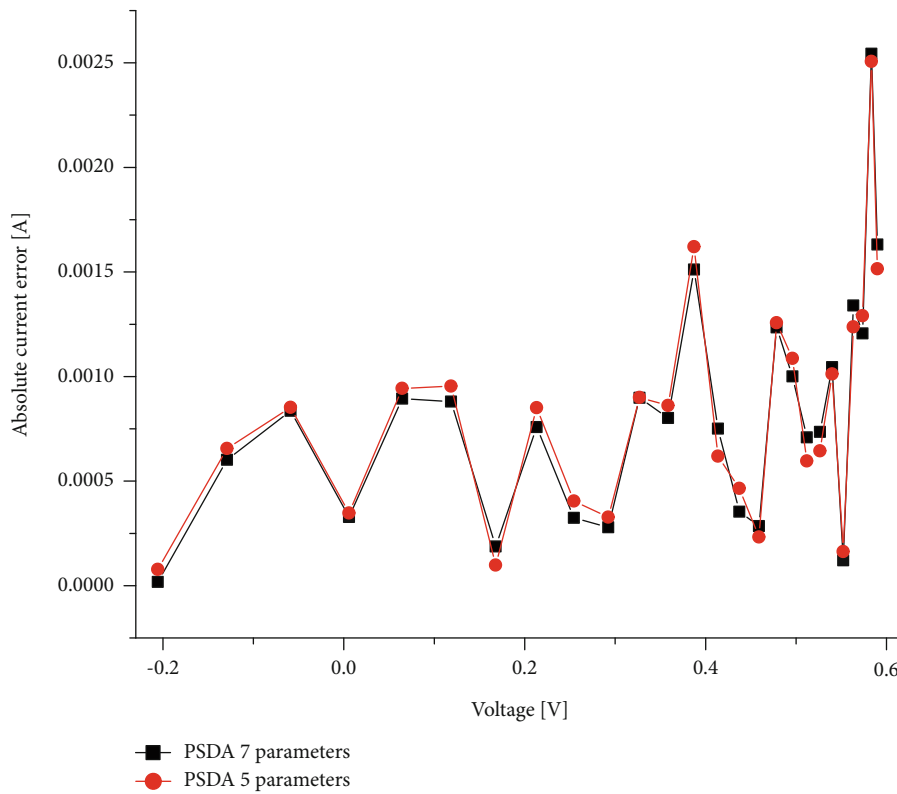


FIGURE 6: Comparison between the two-diode and one-diode model for STE 4/100 panel.

TABLE 2: The seven parameters of the PWP201 photovoltaic panel.

Algorithm	I_{ph} A	I_{od} μ A	I_{or} pA	n_d	n_r	R_s Ω	R_{sh} Ω	RMSE E-03
PSDA	1.032534389	2.511410784	1.14561846	1.317303011	1.31739967	1.234479859	721.503996	2.010645
GCPSO [16]	1.03238233	2.51291639	1.00005742	1.31730465	1.31693992	1.2392884	744.7153985	2.0465
WDOWOAPSO [17]	1.03238234	1.72494775	0.78796322	1.31730435	1.31730449	1.23928868	744.7142646	2.046535
TVACPSO [17]	1.031434	2.6381241	1	1.3209988	2.7777778	1.235632	821.65281	2.0530
ABC-DE [18]	1.0318 E-01	0.32774	2.4305	1.3443	1.3443	1.2062	845.2495	2.4000

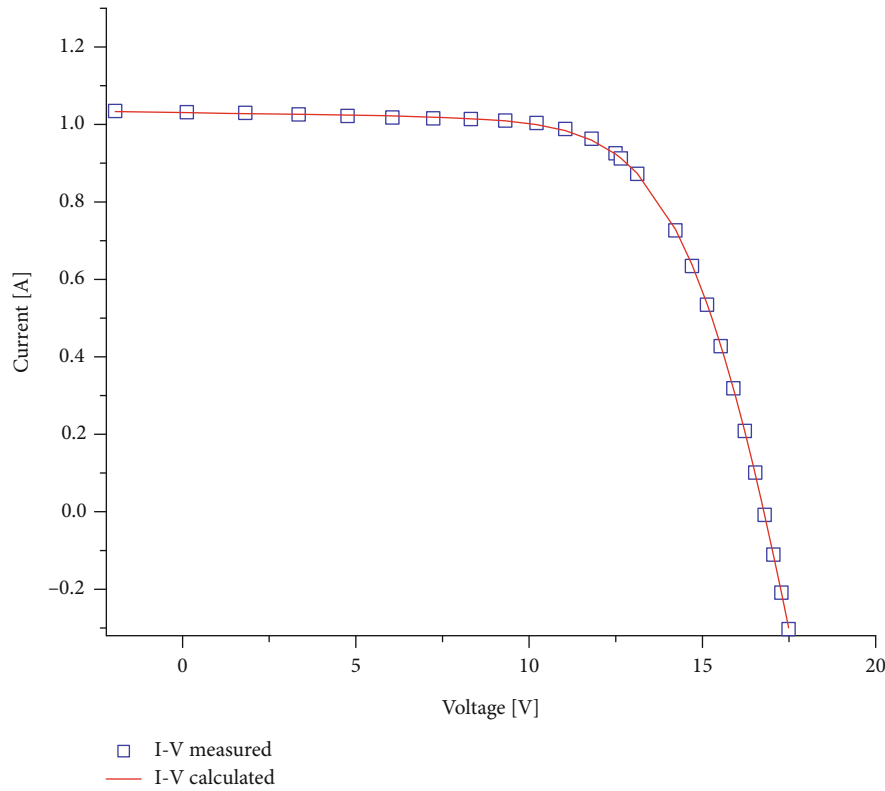


FIGURE 7: The I-V characteristics for PWP201 photovoltaic panel.

A total of s septets are calculated for each interval from Equation (11) ($j = 1, \dots, s$). From these s^2 values, the best s solutions are selected, and the refining discretization is applied again. A predefined number of refining iterations are performed, and, in the end, the best overall septet is considered the final solution for Equation (3) (having the smallest RMSE error).

2.2.3. PSDA for Double-Diode Solar Cell Model. The idea of the algorithm is as follows. Discretizations are performed on given 7D intervals (see (11) and (12)). At the end of each iteration of the algorithm, “ s ” good solutions are constructed. In the vicinity of each of these solutions, a new discretization is applied to refine that solution. These discretizations can be performed in parallel on different machines or on different parallel threads on the same machine. The flowchart of the parallel implementation of the algorithm is presented in Figure 2.

Every discretization is executed t times on parallel threads. In the first iteration, there is only one thread, but starting from the second iteration, there are s parallel threads. Before starting the threads, all the values in the vector “finished” are set to the value *false*. Each discretization gets a 7D interval I_j , constructs s solutions, and returns them in the set S_j . When the j -th discretization is finished, the j -th component of the vector “finished” is set to the value *true*. After all the values in the vector “finished” are *true*, it means that all the discretization threads are terminated, and all the sets S_j ($j = 1, \dots, t$) are constructed.

On an 8-thread I7 processor by performing in parallel the discretization calls the algorithm finishes more than 6 times faster than the nonparallel implementation of the algorithm that computes the discretization on one thread. The above implementation of the algorithm proved to bring the processor utilization across all cores of the computer almost to the maximum (over 98%).

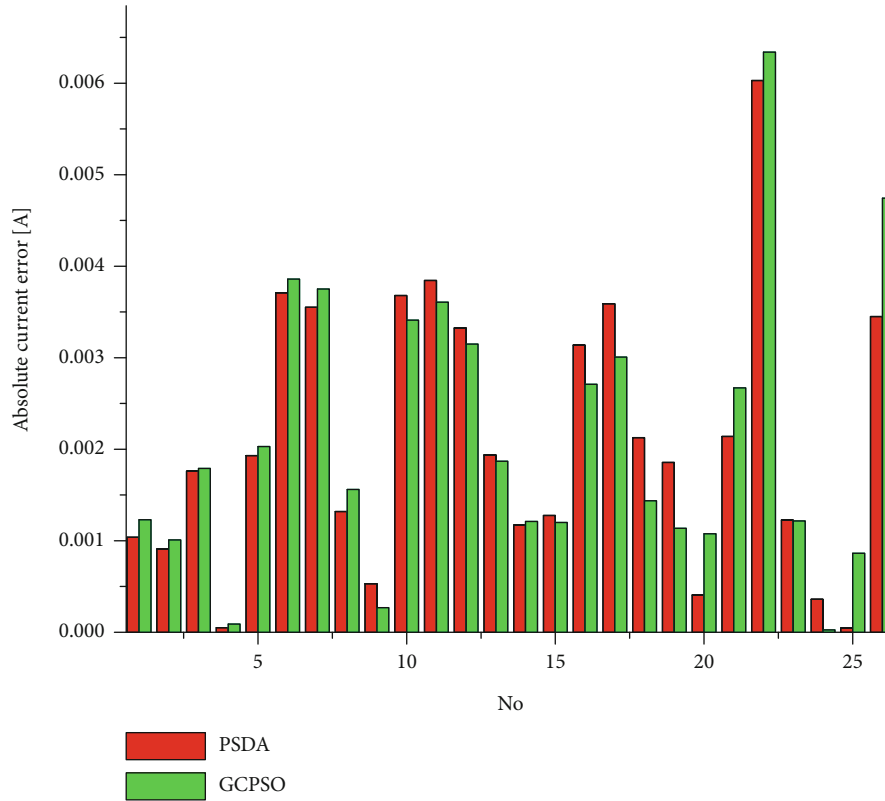


FIGURE 8: Absolute current error comparison for PWP201.

TABLE 3: The seven parameters of the Kyocera KC200GT photovoltaic panel.

Algorithm	I_{ph} A	I_{od} μ A	I_{or} pA	n_d	n_r	R_s Ω	R_{sh} Ω	RMSE E-03
PSDA	8.199056758	3.603852195E-4	3.79468615E-5	60.779659859	49.6103408	0.286457209	110.644764	11.98170

3. Results and Discussion

The PSDA algorithm is applied for five datasets—one for RTC photovoltaic cell and the others for four photovoltaic panels: PWP201 [22], Kyocera KC200GT [23], Leibold Solar Module LSM 20 [24], and STE 4/100 [24]. The seven parameters for three out of these four panels are determined for the first time in this paper. The current voltage (I-V) characteristic for RTC is measured at 1000 W/m^2 , and the temperature of the photovoltaic cell was 33°C ; PWP201 panel is measured at 1000 W/m^2 , and the temperature of the photovoltaic panel was 45°C ; Kyocera KC200GT panel is measured at 1000 W/m^2 irradiance and 25°C temperature; for LSM 20 panel, the I-V characteristic is measured at 360 W/m^2 , and the temperature of the photovoltaic panel was 24°C . The STE 4/100 panel is measured at 900 W/m^2 irradiance and 22°C temperature. The limit intervals for the seven parameters of photovoltaic cell and panel are chosen to be similar with the ones used in the other algorithms [7] for the RTC photovoltaic cell and PWP201 panel. For the Kyocera KC200GT panel, Leibold Solar Module LSM 20, and STE 4/100 panel, the two-diode model is applied for the first time.

3.1. RTC Photovoltaic Cell. The points of RTC photovoltaic cell and the current calculated using PSDA algorithm are shown in Table S1. The seven parameters of the RTC photovoltaic cell and the root mean square error determined by the PSDA algorithm and the values calculated by other algorithms are presented in Table 1.

The I-V pairs of the RTC photovoltaic cell measured and calculated with PSDA algorithm are compared (see Figure 3). A very good matching can be observed, also proven by the lowest value of the root mean square error (see Table 1).

The absolute current error for RTC photovoltaic cell obtained with two algorithms, PSDA and ICSE, is presented in Figure 4. The PSDA absolute current error is lower than for ICSE ones for all measurement points without a uniform distribution. The highest values of the absolute error are around the open circuit voltage cell. The same distribution of the absolute current error is reported in [25].

In the absolute current error for RTC photovoltaic cell calculated with the two-diode model—the seven parameters and with the one-diode model—five parameters are presented in Figures 5 and 6. It can be observed that the absolute current error calculated with the two-diode model is lower

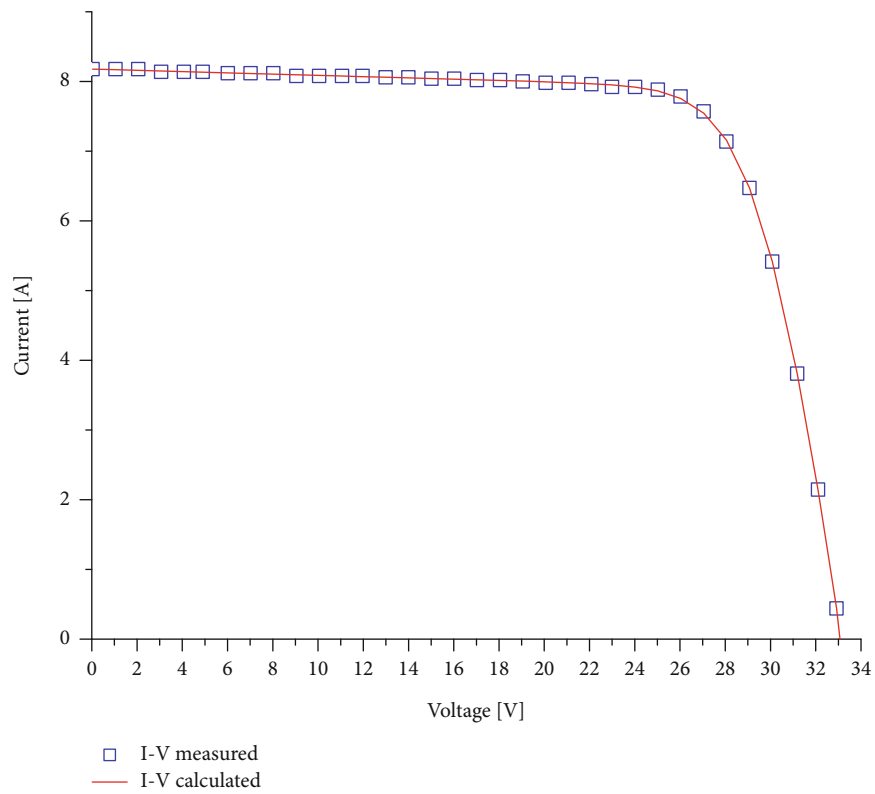


FIGURE 9: The I-V characteristics for Kyocera KC200GT photovoltaic panel.

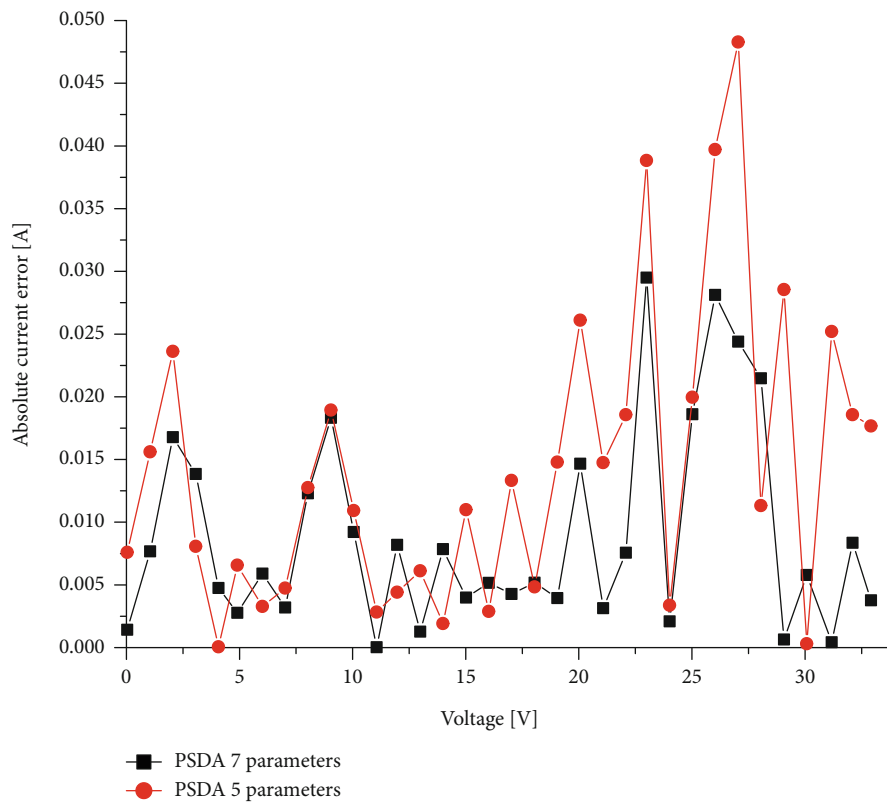


FIGURE 10: Comparison between the two-diodes and one-diode model for the Kyocera KC200GT panel.

TABLE 4: The seven parameters of the LSM 20 photovoltaic panel.

Algorithm	I_{ph} A	I_{od} μA	I_{or} μA	n_d	n_r	R_s Ω	R_{sh} Ω	RMSE E-04
PSDA	0.153932108	2.988457072E-3	3.17136807E-3	26.632811966	26.75109623	6.1728707055	3546.219520	17.5889

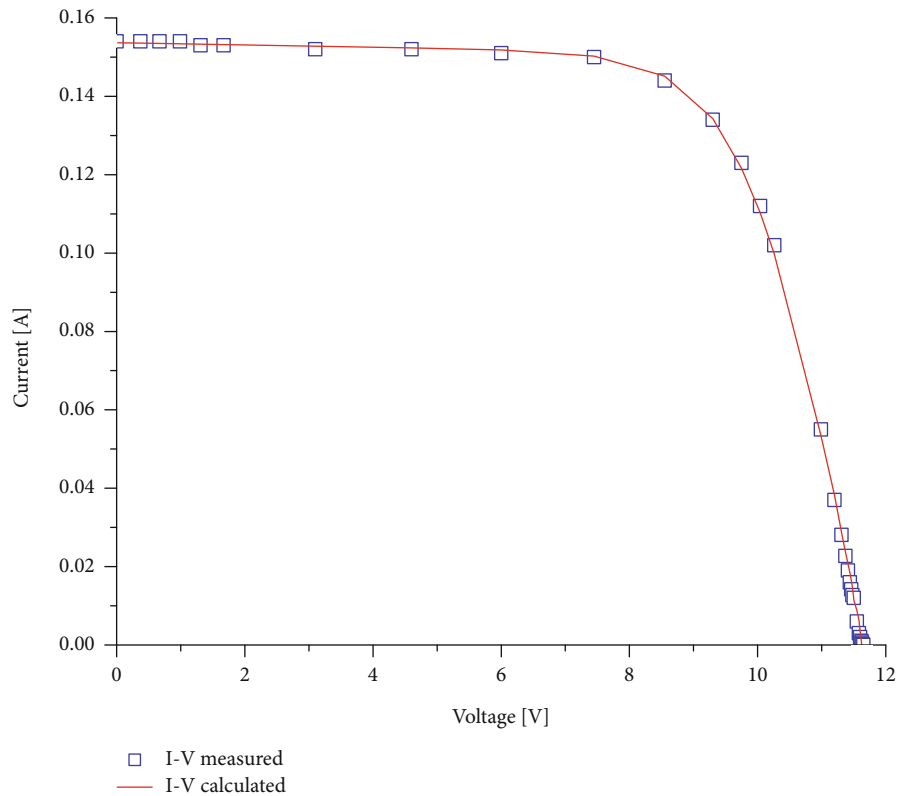


FIGURE 11: The I-V characteristics for LSM 20 photovoltaic panel.

than the ones determined with the one-diode model. This shows that the best solution for the photovoltaic cell parameters is obtained using the two-diode model.

3.2. PWP201 Photovoltaic Panel. The points of PWP201 photovoltaic panel and the current calculated using PSDA algorithm are shown in Table S2. The seven parameters of the PWP201 photovoltaic panel and the root mean square error determined through the PSDA algorithm and the values calculated through other algorithms are presented in Table 2.

The seven parameters of the PWP201 photovoltaic panel, the root mean square error determined through the PSDA algorithm, and the values calculated through other four algorithms are presented in Table 2. PSDA gives similar solutions to other algorithms but with the lowest root mean square error.

By comparing the five algorithms taken into account for PWP201 photovoltaic panel, it can be observed that all seven parameters fluctuate in the function of the applied algorithm. These fluctuations are higher than the ones for RTC photovoltaic cell. The number of I-V pairs is the same for the two photovoltaic devices, but the voltage interval is much higher

for the panel than for the photovoltaic cell, and the calculations are made for fewer points. The I-V characteristics of the PWP201 photovoltaic panel measured and calculated with PSDA algorithm are compared (see Figure 7), and the matching is very good.

The absolute current error for PWP201 photovoltaic panel calculated with two algorithms, PSDA and GCPSO, is presented in Figure 8. The PSDA absolute current error is lower than for GCPSO ones for the majority of the measurements.

The seven parameters for the next three panels are determined for the first time using PSDA. In the literature, there are no other values for the two-diode model to compare with, and so, the solutions are compared with the best ones obtained for the one-diode model.

3.3. Kyocera KC200GT Photovoltaic Panel. The points of Kyocera KC200GT photovoltaic panel and the current calculated using PSDA algorithm are shown in Table S3. The seven parameters of the Kyocera KC200GT photovoltaic panel and the root mean square error determined through the PSDA algorithm are presented in Table 3.

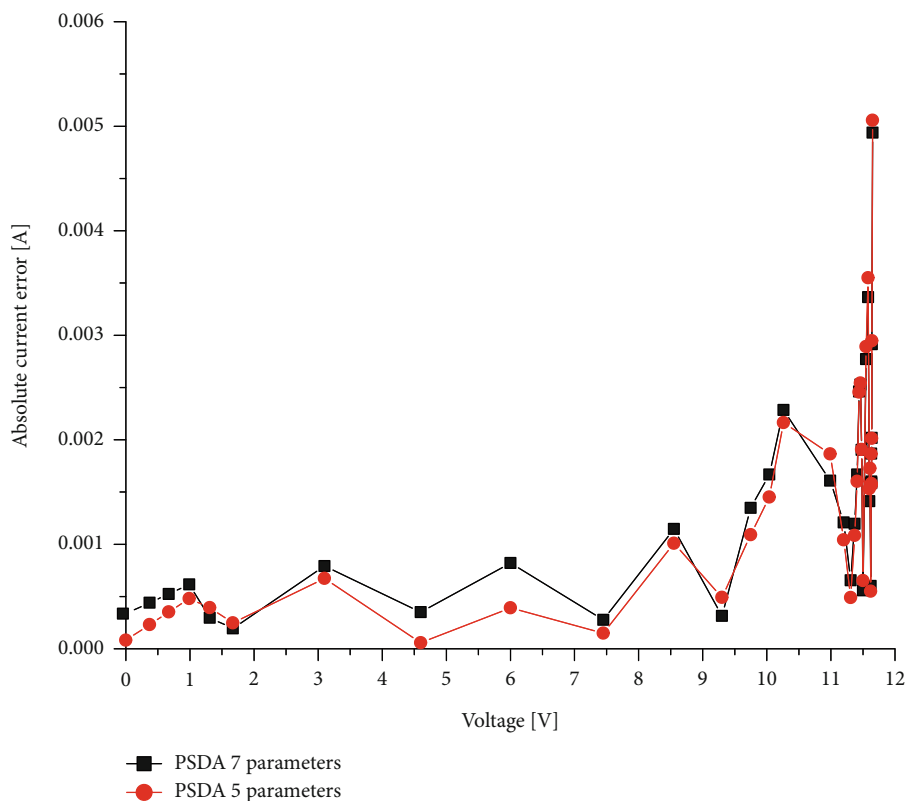


FIGURE 12: Comparison between the two-diode and one-diode model for LSM 20 panel.

TABLE 5: The seven parameters of the STE 4/100 photovoltaic panel.

Algorithm	I_{ph} A	I_{od} μA	I_{or} μA	n_d	n_r	R_s Ω	R_{sh} Ω	RMSE E-04
PSDA	0.026434533	7.468752134E-5	4.91018373E-3	4.2799344307	5.199781435	1.1820913872	2109.248002	3.348041

The calculated I-V characteristic of the Kyocera KC200GT photovoltaic panel using PSDA algorithm, which consists 54 multicrystalline silicon photovoltaic cells connected in series, is matching with the I-V points measured [23] (Figure 9).

The comparison between the absolute errors of the current for the one and two-diode models shows that the last model gives for the majority of the I-V points better results (Figure 10). The two-diode model has to be used when the accuracy in calculation of the photovoltaic panel parameters is crucial.

3.4. *Leibold Solar Module LSM 20.* The points of LSM 20 photovoltaic panel and the current calculated using PSDA algorithm are shown in Table S4. The seven parameters of the LSM 20 photovoltaic panel RMSE determined through the PSDA algorithm are presented in Table 4.

The I-V characteristics of the Leibold Solar Module LSM 20 measured and calculated with PSDA algorithm are compared (see Figure 8). The matching for the measured and calculated points is very good; this is confirmed by the root mean square error which is very small (Table 4) (Figure 11).

Figure 12 illustrates the absolute error for the current, obtained for the LSM 20 photovoltaic panel, using the one- and two-diode models. The RMSE obtained with the two-diode model is smaller than the one obtained with the one-diode model, which is 17.64E-4. This is confirmed by the absolute error obtained through both models. The higher values of the absolute error are splitted for the two models used.

3.5. *Leybold Solar Module STE 4/100.* The points of STE 4/100 photovoltaic panel and the current calculated using PSDA algorithm are shown in Table S5. The seven parameters of the STE 4/100 photovoltaic panel and the root mean square error determined through the PSDA algorithm are presented in Table 5.

The I-V pairs of the Leybold Solar Module STE 4/100 measured and calculated with PSDA algorithm are compared (see Figure 13). A very good matching can be observed, also proven by the lowest value of the root mean square error (see Table 5).

The absolute current error for STE 4/100 photovoltaic panel calculated with the two-diode model and with the

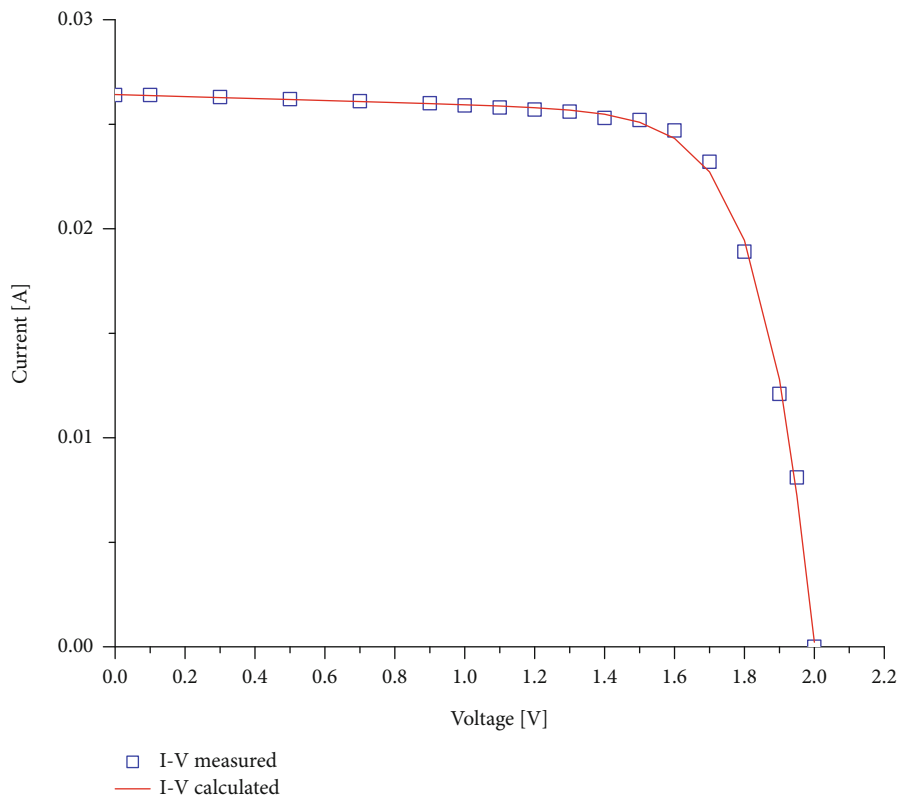


FIGURE 13: The I-V characteristics for STE 4/100 photovoltaic panel.

one-diode model is presented in Figure 5. It can be observed that the absolute current error calculated for the majority points with the two-diode model is lower than the ones determined with the one-diode model. The RMSE obtained with the one-diode model is $4.0853E-4$ (Figure 6).

PSDA algorithm was executed with $s = 10$ and with a total of 4 iterations on an 8-thread I7 processor at 1.9 GHz. It ended in 46 seconds. The nonparallel implementation took almost 5 minutes to finish (more than 6 times slower).

4. Conclusions

The estimation of the parameters for the solar cells and panels is very important for designing, simulation, and evaluation of the performance of photovoltaic systems. This problem is currently intensively studied by many researchers. In this paper, the Parallelized Successive Discretization Algorithm is developed and presented to deal with this problem. It is a metaheuristic approach that proved to be a powerful tool for approximating the solution of the implicit transcendental equation problem of finding the seven parameters for the two-diode model. The problem is transformed into a multidimensional optimization problem of minimizing the root mean square error and then solved using multiple and increasing in refining discretizations. The parallel implementation helped to speed up the algorithm since the amount of computations is high and complex. PSDA proves to be fast and reliable that gives very good (the best) estimation of

parameters among the current known algorithms used for the two-diode model. In this paper, the results given by PSDA for one photovoltaic cell and for four panels were given for the two-diode model. The parameters were obtained for the first time for three panels for which only the parameters of one-diode model were determined in the literature.

The sensitivity analysis of the PSDA algorithm is one of the future research directions, and another is to use the PSDA algorithm to extract the parameters of the other photovoltaic cells and panels, for example organic photovoltaic cell using a proper equivalent circuit and the corresponding mathematical model.

Data Availability

Data in supplementary information files.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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Supplementary Materials

Table S1: the current calculated using the PSDA algorithm and the relative error, calculated by subtracting the calculated from the measured current values for RTC photovoltaic cell. Table S2: the current calculated using the PSDA algorithm and the relative error for PWP201 photovoltaic panel. Table S3: the current calculated using the PSDA algorithm and the relative error for LSM 20 photovoltaic panel. Table S4: the current calculated using the PSDA algorithm and the relative error for LSM 20 photovoltaic panel. Table S5: the current calculated using the PSDA algorithm and the relative error for LSM 20 photovoltaic panel. (*Supplementary Materials*)

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