

Optimal Extraction of Photovoltaic Model Parameters Using Gravitational Search Algorithm Approach

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Abstract

Extraction of accurate Photo Voltaic (PV) model parameters is a challenging task for PV simulator developers. To mitigate this challenging task a novel approach using Gravitational Search Algorithm (GSA) for accurate extraction of PV model parameters is proposed in this paper. GSA is a population based heuristic optimization method which depends on the law of gravity and mass interactions. In this optimization method, the searcher agents are collection of masses which interact with each other using laws of gravity and motion of Newton. The developed PV model utilizes mathematical equations and is described through an equivalent circuit model comprising of a current source, a diode, a series resistor and a shunt resistor including the effect of changes in solar irradiation and ambient temperature. The optimal values of photo-current, diode ideality factor, series resistance and shunt resistance of the developed PV model are obtained by using GSA. The simulations of the characteristic curves of PV modules (SM55, ST36 and ST40) are carried out using MATLAB/Simulink environment. Results obtained using GSA are compared with Differential Evolution (DE), which shows that GSA based parameters are better optimal when compared to DE.

Keywords

GSA, Photo Voltaic, Parameter Extraction, MATLAB/Simulink

1. Introduction

World's primary energy consumption is increasing by about 2.5% in every year. Though most of the energy demand is shared by conventional energy sources, the en-

vironmental impact on usage of these sources has been disintegrative with the issues such as pollution, global warming, and excessive greenhouse effect. To overcome the above mentioned effects, finding sustainable alternatives is becoming increasingly urgent. To meet considerable percentage of demand, renewable energy sources are installed to share 3.9% of global power generation. The rapid growth of renewable power generation continues and this opens a new era for solar power generation. Solar energy is obviously environmentally advantageous relative to any other energy source. The increase in demand for solar industry over the past several years has expanded the importance of PV system design and application for more reliable and efficient operation.

PV module represents the fundamental power conversion unit of a PV generator system. PV module is a series connection of PV cells where each cell exhibits non-linear characteristics. To use PV module in the simulation environment, it is necessary that the model should produce the PV cell non-linear characteristics. For efficient design of the PV array in simulation environment, it is essential to use the accurate magnitudes of the panel parameters. But, these parameters are usually unknown to the user and hence the parameters are needed to be extracted by a proper extraction method before designing the PV array. Nowadays, a single diode PV model with a photo current source I , a single diode D , a series resistance R_{se} and a shunt resistance R_{sh} is used as the equivalent circuit of a PV cell [1] [2]. Hence, the parameters needed to be extracted are photo current, diode ideality factor, series resistance and shunt resistance. For parameter extraction process, the values of PV array open circuit voltage V_{oc} , short circuit current I_{sc} , voltage at maximum power point V_{mpp} , current at maximum power point I_{mpp} , temperature coefficient of open circuit voltage K_v , temperature coefficient of short circuit current K_i and the maximum peak output power P_{mp} are necessary. Generally, all these values for a PV array are available in manufacturers' data-sheet. Hence, most of the parameter extraction methods are based on manufacturers' data-sheet. In single diode PV model, the unknown currents are obtained by nodal analysis. The other parameters R_{se} and R_{sh} are calculated from PV cell characteristics [3]. However, finding R_{se} and R_{sh} from characteristics curve may not be more accurate. In addition to that, the value of these resistances depends on solar irradiation and ambient temperature. To resolve these issues, optimization techniques are introduced to optimize accurately the value of photo-current, diode ideality factor, series resistance and shunt resistance.

Genetic algorithm based optimization of the circuit parameters is slow and takes larger computation time [4]-[8]. In Particle Swarming Optimization, to extract the optimal value for R_{se} and R_{sh} , a large number of iterations are to be evaluated, though the results are close to possible values [9]-[11]. Gravitational Search Algorithm (GSA) is a newly developed heuristic optimization method based on the law of gravity and mass interactions [12]. GSA has been confirmed to give higher performance in solving various nonlinear functions, compared with some well-known search methods. In [13], GSA was introduced to apply in parameter identification of hydraulic turbine governing system. Subsequent to the development of GSA, researchers tried to implement this algorithm to different applications. In this study GSA is implemented to optimize single

diode PV model parameters. This paper is organized as follows: Section 2 provides an introduction to GSA. Section 3 provides a brief review of GSA for PV model parameters extraction, and the proposed objective function. Section 3.2 describes the procedure of GSA to the PV parameters optimization problem in a detailed manner. The results obtained are elaborated in Section 4.

2. Gravitational Search (GS) Algorithm

Over the last two decades, many researches has to be done for various types of algorithms like Evolutionary Approach (EA), Differential Evolution (DE), Particle Swarm Optimization (PSO) and etc. [9]-[11] to solve the optimal parameter extraction of PV modules. Rashedi *et al.*, proposed one of the newest heuristic algorithm which is successfully applied to various benchmark problems [12]. GSA proved that it gives better convergence than GA and PSO under various conditions. This algorithm is mainly based on the Newton's law of gravity, "The gravitational force between two particles is directly proportional to the product of their masses and inversely proportional to the square of the distance between them". This algorithm gives the better optimal results which are obtained by various applications in an effective manner [13] [14]. To find the optimal value of series and parallel resistances in photo voltaic array, this paper adapts the above mentioned heuristic algorithm.

In the proposed GS algorithm, agents are considered as objects and their performance is measured by their masses. All these objects attract each other by the gravitational force and this force causes a global movement of all objects towards each other with heavier masses. Hence, masses cooperate using a direct form of communication, through gravitational force. The heavy masses—which correspond to good solutions—move more slowly than lighter ones and this guarantees the exploitation step of the algorithm.

As per GS algorithm, each mass (agent) has four specifications:

- 1) Position;
- 2) Inertial mass;
- 3) Active gravitational mass and;
- 4) Passive gravitational mass.

The position of the mass corresponds to a solution of the problem and its gravitational and inertial masses are determined using a fitness function. In other words, each mass presents a solution and the algorithm is navigated by properly adjusting the gravitational and inertial masses. By lapse of time, we expect that the masses may be attracted by the heaviest mass. This mass will present an optimal solution in the search space.

3. GS Algorithm for PV Model Parameters Extraction

3.1. Modelling of PV Array

The building block of PV array is the Solar cell, which is basically a PN semiconductor junction that directly converts light energy into electricity. PV cells are grouped in larger

units called PV modules which are further interconnected in a parallel-series configuration to form PV arrays or PV generators. **Figure 1** shows the equivalent circuit of a PV cell. To extract the PV array parameters like I_{pv} , a , R_{se} and R_{sh} a PV mathematical model is used according to the following set of equations [1] [2].

The voltage-current characteristic equation of a solar cell is given as,

$$I = I_{pv} - I_o \left[\exp \left(\frac{q(V + IR_{se})}{KTA} \right) - 1 \right] - \left[\frac{V + IR_{se}}{R_{sh}} \right] \tag{1}$$

where, I_{pv} is a light-generated current or photocurrent, I_o is the cell saturation of dark current, q ($=1.6 \times 10^{-19}$ C) is an electron charge, K ($=1.38 \times 10^{-23}$ J/K) is a Boltzmann's constant, T is the cell's working temperature, " a " is an ideal factor, R_{sh} is a shunt resistance and R_{se} is a series resistance of solar cell. The photo-current I_{pv} mainly depends on the solar insolation and cell's working temperature and is given by,

$$I_{pv} = [I_{sc} + K_i(T - T_n)]H \tag{2}$$

where, I_{sc} is the cell's short-circuit current at 25°C and 1 kW/m², K_i is the cell's short-circuit current temperature coefficient, T_n is the cell's reference temperature and H is the solar insolation in kW/m². The cell's saturation current I_o varies with the cell temperature is

$$I_o = \left[\frac{I_{sc} + K_i(T - T_n)}{\exp \left[\frac{V_{oc} + K_v(T - T_n)}{aN_sV_t} \right] - 1} \right] \tag{3}$$

where, V_{oc} is the cell's open circuit current at 25°C and 1 kW/m², K_v is the cell's open circuit voltage temperature coefficient, N_s is the number of cells connected in series per string and V_t is the thermal voltage given by, $V_t = KT/q$. The terminal equation of PV array for the current is given as,

$$I = N_p I_{pv} - N_p I_o \left[\exp \left(\frac{q(V + IR_{SM})}{N_s KTA} \right) - 1 \right] \tag{4}$$

$$R_{SM} = N_s R_{se} / N_p$$

where, N_s is number cells in series and N_p is the number cells in parallel.

Hence the objective function using the Equations (1) to (4) is formulated as given below:

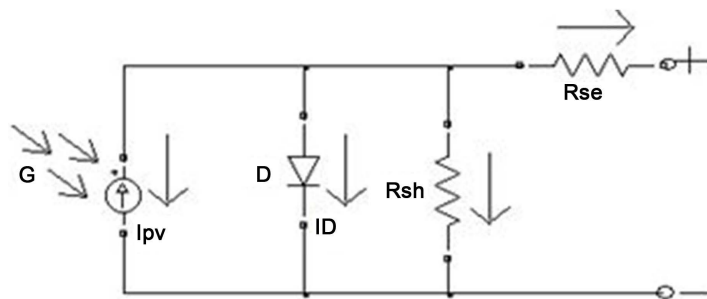


Figure 1. The equivalent circuit of a PV cell.

$$\text{Minimize } Y = \sqrt{\sum_{m=1}^n U(V_m, I_m, \phi)^2} \quad (5)$$

where

$$U(V, I, \phi) = I_{pv} - I_o \left(e^{\frac{V + IR_{se}}{a + V_T}} - 1 \right) - V \frac{IR_{se}}{R_{sh}} - I. \quad (6)$$

3.2. GSA Implementation for Optimal Design of PV Model

The detailed description of the algorithm to extract PV model parameters is presented below and the pictorial flowchart is shown in **Figure 2**.

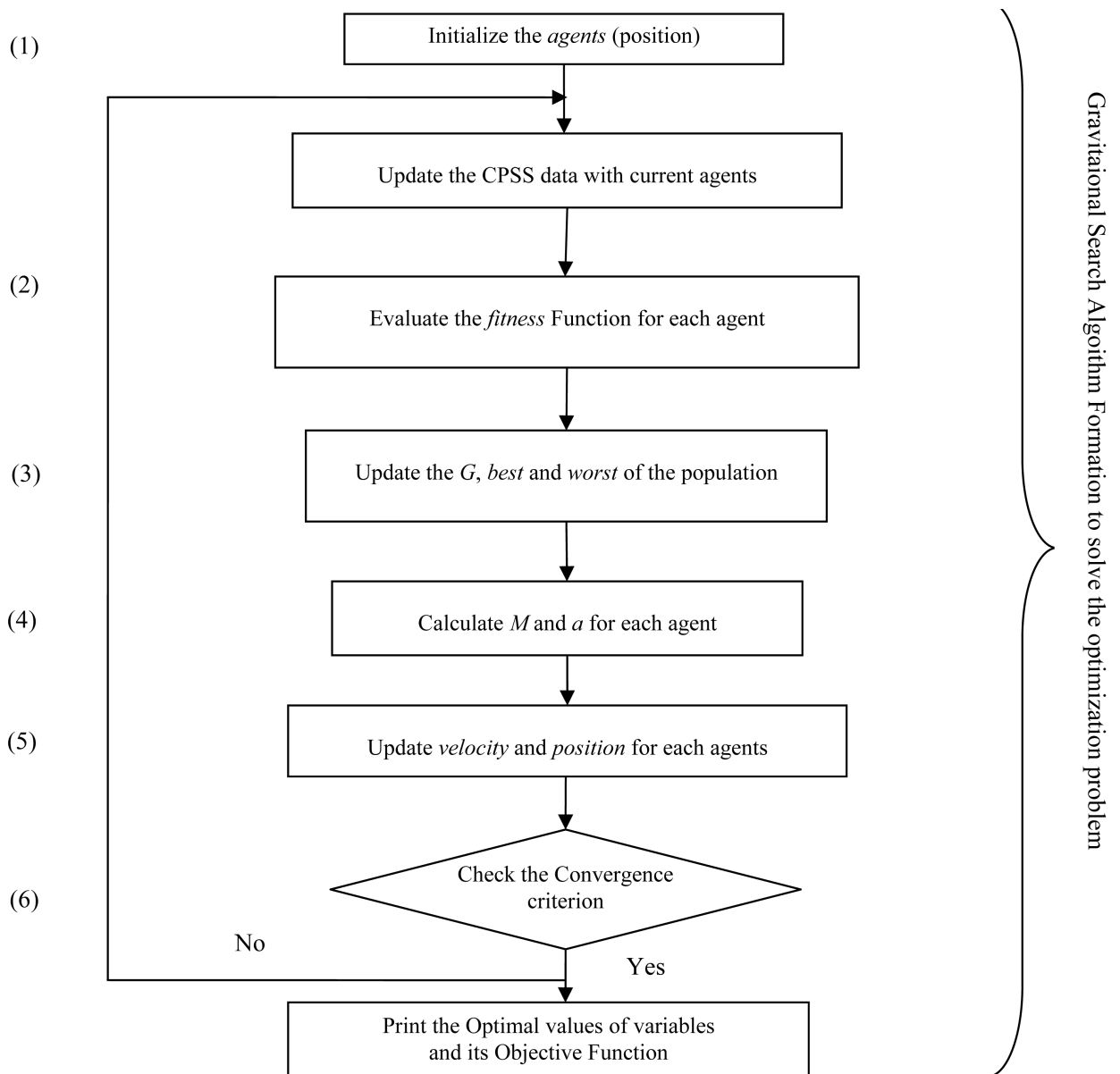


Figure 2. Pictorial flowchart.

3.2.1. Position

A set of values for the I-V characteristics serves as the input data for the GSA. The parameters that are extracted by optimization are I_{pv} , R_{sep} , R_{sh} and a are evaluated as X_k in GSA.

Considering a system with N agents (masses), Position of the K^{th} agent is defined by,

$$X_k = [x_k^1, x_k^2, \dots, x_k^d, \dots, x_k^N], \text{ for } k = 1, 2, 3, \dots, N \tag{7}$$

where x_k^d —Position of the K^{th} agent in d^{th} dimension.

3.2.2. Fitness Evaluation

The fitness value of each agent x_k is evaluated using Equation (6). The best and worst value of each generation with respect to time were calculated using,

$$\text{best}(t) = \min_{l \in \{1, \dots, N\}} Y(t) \tag{8}$$

$$\text{worst}(t) = \max_{l \in \{1, \dots, N\}} Y(t). \tag{9}$$

3.2.3. Gravitational Constant

Gravitational constant (G) is initialized at the beginning and at the later stages and is calculated as a function of time (t) (to reduce the time control strategy).

$$G(t) = G(G_0, t). \tag{10}$$

3.2.4. Force

During a time “ t ”, the force between the agents “ k ” and “ l ” with respect to mass is given as,

$$F_{kl}^d = G(t) \left[\frac{M_{pk}(t) \times M_{al}(t)}{R_{kl}(t) + \varepsilon} \right] (x_l^d(t) - x_k^d(t)), \tag{11}$$

where, (all the values are with respect to specific time “ t ”);

$M_{pk}(t)$ —Passive gravitational mass of agent k ;

$M_{al}(t)$ —Active gravitational mass of agent l ;

ε —Small constant;

$G(t)$ —Gravitational constant;

$R_{kl}(t)$ —Euclidian distance between two agents k and l . It is given by,

$$R_{kl}(t) = X_k(t), X_l(t)_2. \tag{12}$$

3.2.5. Total Force

The total force acting on a particle k at d^{th} dimension is given by,

$$F_k^d(t) = \sum_{l=1, l \neq k}^N rand_l F_{kl}^d(t), \tag{13}$$

where, $rand_l$ —Random number between the intervals [0-1].

K_{best} is a function of time, with the initial value K_0 at the beginning and decreasing with time in such a way, at the beginning, all agents apply the force, and as time passes, K_{best} is decreased linearly and at the end there will be just one agent applying

force to the others. Therefore, Equation (11) could be written as,

$$F_k^d(t) = \sum_{l \in K_{best}, l \neq k}^N (rand_l F_{kl}^d(t)), \quad (14)$$

where, K_{best} —Set of first k agents with the best fitness value and biggest mass.

3.2.6. Gravitational and Inertial Mass

Gravitational and Inertial masses are calculated by using the following equations (assuming gravitational mass is equal to inertial mass),

$$M_{ak} = M_{pk} = M_{kk} = M_k, \text{ for } k = 1, 2, 3, \dots, N, \quad (15)$$

$$m_k(t) = \frac{fit_k(t) - worst(t)}{best(t) - worst(t)}, \quad (16)$$

$$M_k(t) = \left[\frac{m_k(t)}{\sum_{j=1}^N m_j(t)} \right], \quad (17)$$

where, $Y_k(t)$ —Fitness value of the k^{th} agent at time t .

3.2.7. Acceleration

By the law of motion, the acceleration of the agent k in d^{th} direction at time t is found out by using the following relation,

$$a_k^d(t) = \left[\frac{F_k^d(t)}{M_{kk}^d(t)} \right], \quad (18)$$

where, $M_{kk}^d(t)$ —Inertial mass of the agent i .

3.2.8. Updating of Velocity and Position

Velocity can be updated by summing the current velocity and its acceleration. Similarly, the position of particles can be updated by adding its previous position and its velocity.

$$v_k^d(t+1) = rand_k \times v_k^d(t) + a_k^d(t), \quad (19)$$

$$x_k^d(t+1) = x_k^d(t) + v_k^d(t+1), \quad (20)$$

where, $rand_k$ —Random number between the intervals [0-1]. Random numbers are used to give a randomized characteristic to the search.

3.2.9. Convergence Criterion

To obtain the best solution for the global optima, this algorithm stops its searching for the best solution by maximum iterations given for the optimal PV design problem.

4. Results and Discussion

The PV modelling method accuracy is validated by measured parameters of selected PV modules. The experimental (I and V) data is extracted from the manufacturer's data-sheet [15]. Three PV modules (SM55, ST36 and ST40) of different technologies are utilized for verification; these include the mono-crystalline and thin-film types. The specifications of the modules are given in **Table 1**. For GSA method, the simulation is done

Table 1. Specifications for the three modules used in the experiments.

Parameter	Mono-crystalline SM55	Thin film ST40	Thin film ST36
I_{sc}	3.45	2.59	2.68
V_{oc}	21.7	22.2	22.9
I_{mp}	3.15	2.41	2.279
V_{mp}	17.4	16.6	15.8
$K_v, m/^{\circ}C$	-0.077	-0.1	-0.1
$K_j, m/^{\circ}C$	1.38×10^{-3}	0.26 mA	0.32 mA
N_s	36	42	42

using MATLAB R2010b with Intel Core i3 CPU @ 2.53 GHz processor, 3 GB RAM under windows 7 environment. And the SM55, ST36 and ST40 PV modules are used for simulation study. The parameters settings in GSA are: Agents-100, Iterations-100 and Power of R-1. The results obtained using the proposed GSA method is compared with DE in a judicial way.

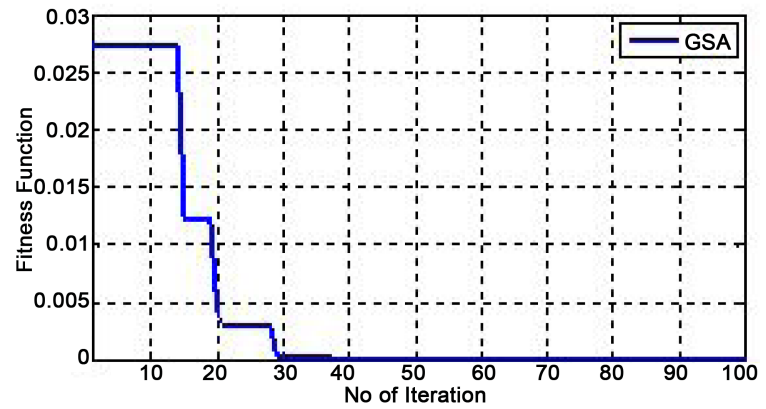
Fitness Value and Optimized Parameter Values by GSA

Simulation results are obtained by executing the proposed GSA method at 1000 W/m^2 and $25^{\circ}C$ temperature for 25 times. The GSA method obtains the global optimal value of objective function as 5.847×10^{-12} , 9.6421×10^{-12} and 5.1656×10^{-12} for SM55, ST36 and ST40 PV modules respectively. Also, for experimental validation, the data is significantly fewer compared to the DE and R_s -model [10] as shown in Table 2. Among the 25 runs, best values are taken as the model parameters. From these results, it is evident that GSA outperforms DE in optimizing the objective function, which shows the effectiveness of GSA method. GSA tends to find the global optimum faster than other algorithms and hence has a higher convergence rate [9] [10]. Even, GSA proves its fast computational ability by returning those results within 29 - 31 seconds. GSA could be the unique algorithm faster than all other optimization techniques in these kinds of applications [9] as shown in Table 3. The convergence performance of each module is shown in Figures 3(a)-(c) by selecting its best one out of 25 runs.

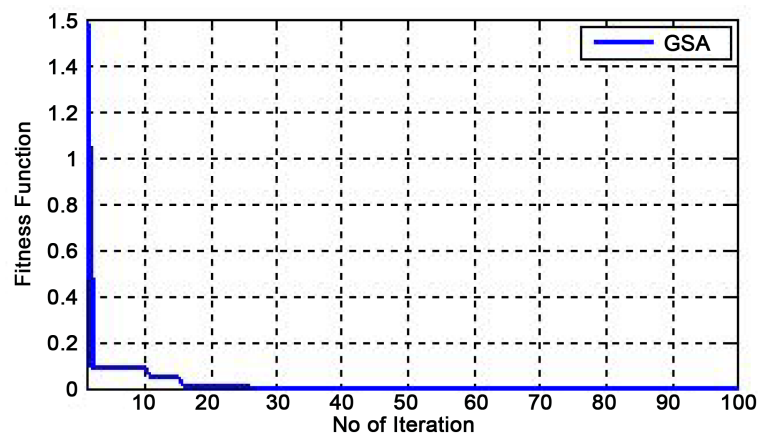
Figures 4(a)-(c) and Figures 5(a)-(c) show the I-V and P-V curves for SM55, ST36 and ST40 respectively, for different levels of irradiance and temperatures. It can be seen that the I-V and P-V curve obtained by proposed model strongly agrees to the experimental data for all types of modules. In particular, the proposed model is very accurate at all irradiance and temperature levels.

5. Conclusion

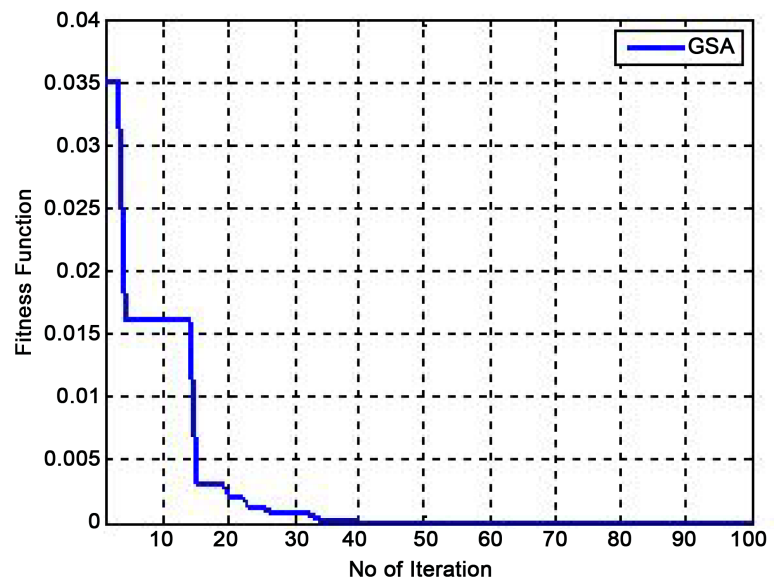
This paper presents a powerful GSA method for extracting solar cell parameters. Number of parameters extracted is limited to four *i.e.* I_{pv} , a , R_{se} and R_{sh} . The GSA method has been successfully applied to the PV modules SM55, ST36 and ST40 under different temperatures and solar insulations. The results obtained using GSA are better when



(a)



(b)



(c)

Figure 3. (a) Convergence performances of the fitness function with GSA for PV module ST40; (b) Convergence performances of the fitness function with GSA for PV module ST36; (c) Convergence performances of the fitness function with GSA for PV module SM55.

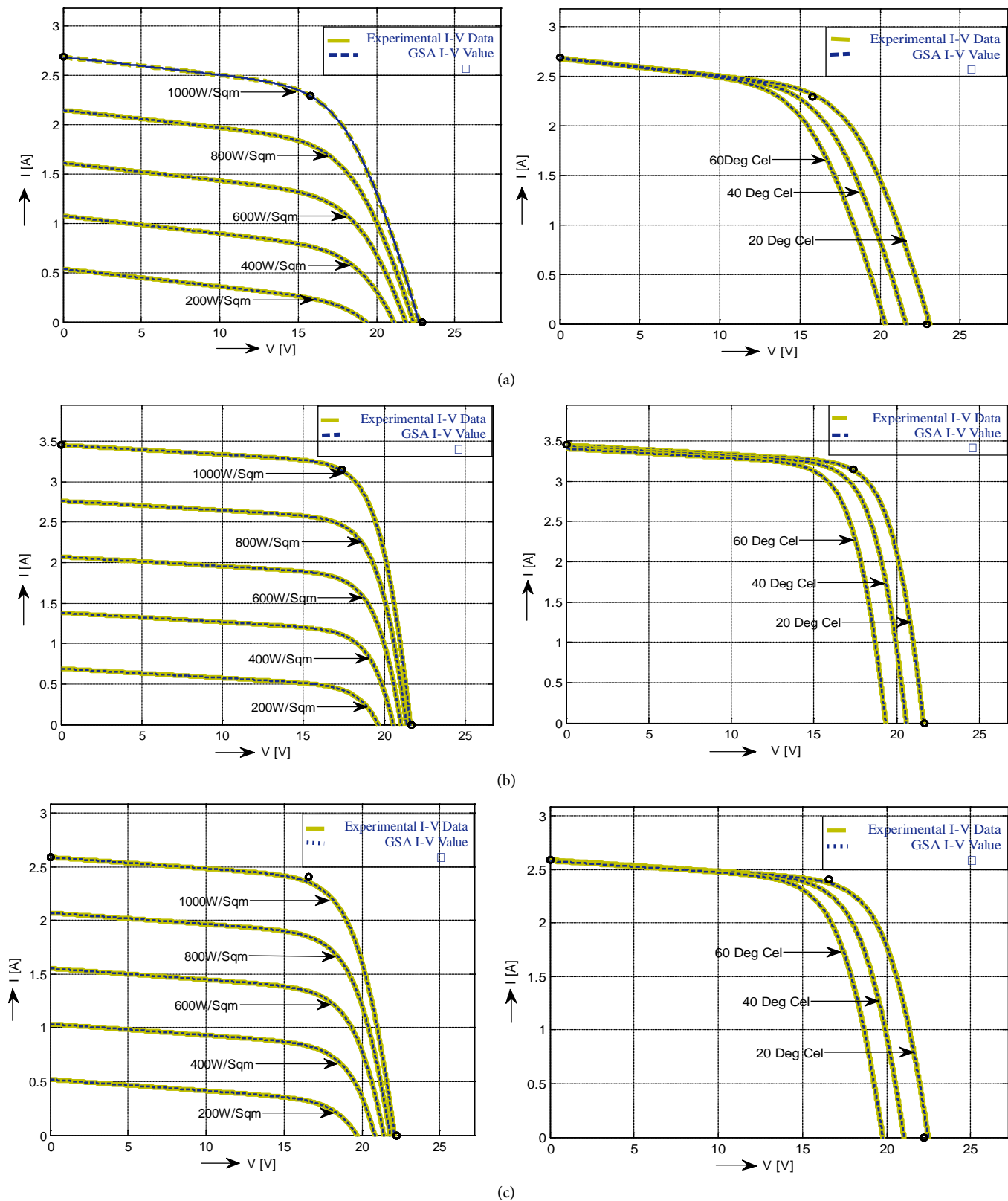


Figure 4. (a)-(c) I-V curves for different irradiation and temperature levels (a) ST36 (thin film); (b) SM55 (monocrystalline); and (c) ST40 (thin film).

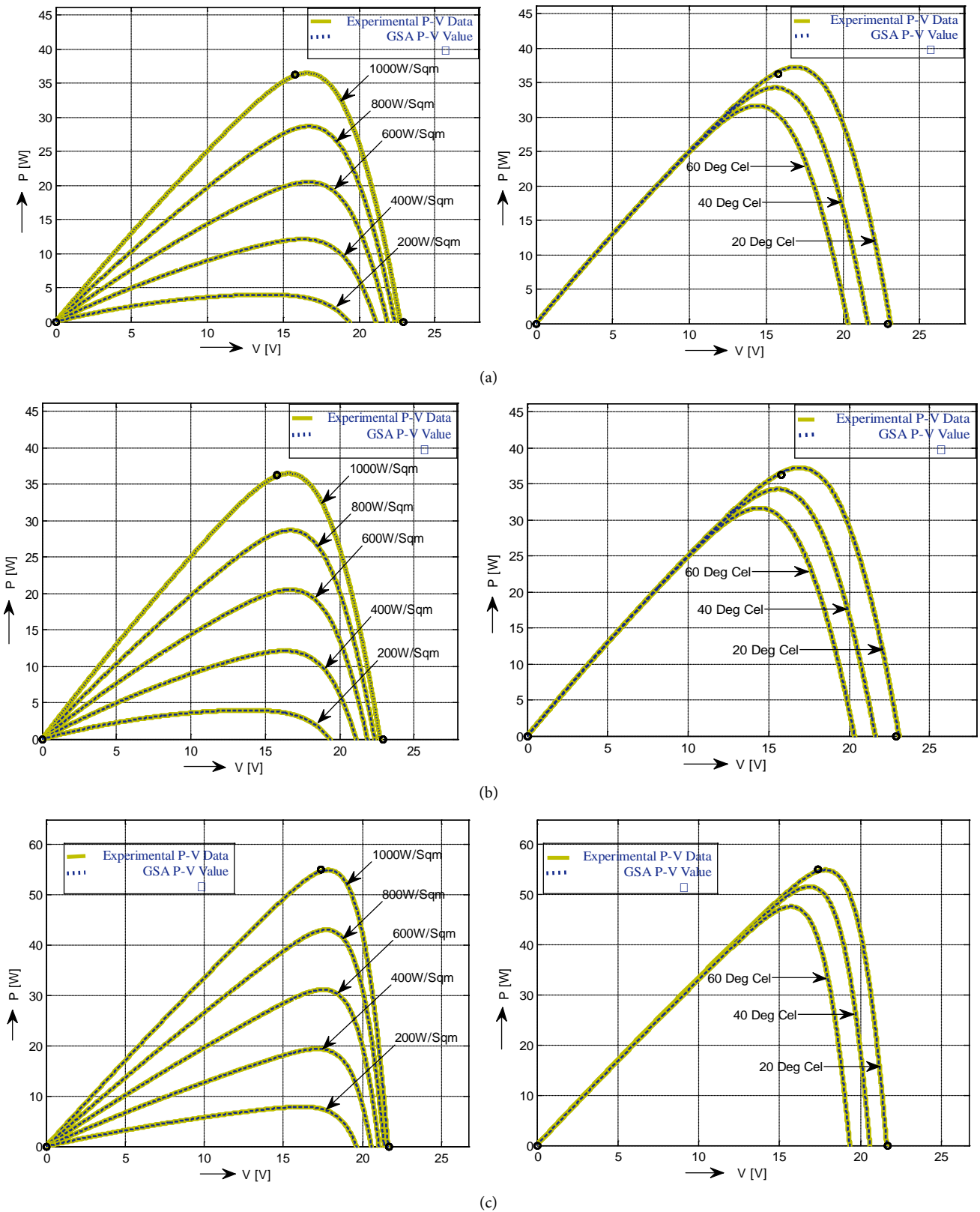


Figure 5. (a)-(c) P-V curves for different irradiation and temperature levels (a) ST36 (thin film); (b) SM55 (monocrystalline); and (c) ST40 (thin film).

Table 2. Comparison of computation time using various methods with proposed method GSA for one run.

Parameters	P-DE [7]	B-E [7]	PSO [7]	GA [7]	GSA
Time (Sec)	119	119	148	601	32

Table 3. Results for extraction of parameter by GSA for various types of modules (best result for 100 runs).

Parameters/module	SM55		ST36		ST40	
	GSA	P-DE [7]	GSA	P-DE [7]	GSA	P-DE [7]
I_{pv}	3.45 A	3.45A	2.689A	2.71A	2.6A	2.68A
a	1.1182	0.86	1.2171	2	1.1136	1.06
R_{se}	0.2458 Ω	0.56 Ω	0.4109 Ω	1.46 Ω	0.4610 Ω	1.42 Ω
R_{sb}	86.1164 Ω	4.9K Ω	110.4652 Ω	182.6 Ω	95.3439 Ω	440.6 Ω
Fitness function J	5.847×10^{-12}	2.4×10^{-2}	9.6421×10^{-12}	2.6×10^{-2}	5.1656×10^{-12}	2.5×10^{-2}

compared to DE and R_s -model. Further, the computational time is comparatively low using the proposed method which allows the possibility of real time application of the algorithm towards various modules under different environmental conditions.

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